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# ABSTRACTS / RÉSUMÉS

## TRACE ELEMENT GEOCHEMISTRY OF MAGNETITE AND ITS RELATIONSHIP TO MINERALIZATION IN THE GREAT BEAR MAGMATIC ZONE, NWT, CANADA — PRELIMINARY FINDINGS

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The Paleoproterozoic Great Bear magmatic zone is the focus of ongoing exploration for iron oxide copper-gold (IOCG) mineralization. Examples include the Sue-Dianne and NICO deposits. This project aims to characterize the nature and geochemistry of the fluids responsible for the mineralization in these deposits and other similar prospects in the southern part of the region.

Petrographic and hand specimen descriptions of 45 samples provides a preliminary paragenetic sequence for the DAMP, FAB, and Nori prospects and the NICO and Sue Dianne advanced exploration projects. Mineralization at DAMP, FAB and Sue Dianne (Cu±Ag, U) are hosted by brecciated felsic volcanic rocks and characterized by an early stage of hematite and magnetite, followed by the deposition of chalcopyrite, bornite, and chalcocite as the main Cu ore minerals. The FAB showing contains two generations of magnetite; an older phase disseminated on the breccia lithoclasts and a younger phase found as the matrix to the breccia and veins. At Nori (Cu-Mo-U), tourmaline-biotite-uraninite veins crosscut the Treasure Lake metasedimentary rocks and also have two generations of magnetite; early phase disseminated in the wall rock and a later phase occurring in veins with K-feldspar coeval with molybdenite, uraninite, and chalcopyrite mineralization. At the NICO (Au-Bi-Co-Cu) deposit, the ore minerals are hosted by hydrothermally altered metasedimentary rocks of the Treasure Lake Group. Several generations of magnetite have been recognized and include pre- (strata bound magnetite replacement), syn- (magnetite in arsenopyrite-bearing veins, vein selvages and breccias, and/or strongly overprinting the host metasedimentary bedding) and post-mineralization (late-stage magnetite veins) episodes. Thus, magnetite is found in all the mineral showings and advanced exploration projects within this area, and it is often closely related to mineralized rocks.

We present the results obtained by an electron microprobe analyses and suggest that the trace elements in magnetite, especially V, have a significant variation between the different prospects and advanced exploration projects. Furthermore, local variations in V and Co, can be used to distinguish between pre- and syn-mineralization magnetite. This study indicates that the trace element signature of magnetite may be a suitable tool for mineral exploration in the GBMZ. Future analytical investigations utilizing ICP-MS will be carried out to constrain the results reported here.

## THE INFLUENCE OF THE OTTAWA-BONNECHERE GRABEN ON NEOTECTONICS, CONTEMPORARY SEISMICITY, AND SEISMIC HAZARD

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The Ottawa-Bonnechere Graben (OBG) is a major weakness in the integrity of the Canadian Shield and influences the contemporary pattern of seismicity. The largest historical earthquake was magnitude 6.2 at Timiskaming in 1935. One of the younger tectonic disturbances near the OBG was the passage of Western Quebec over the Great Meteor hotspot. This likely caused the

migrating domal uplift of western Quebec leading to the erosion of overlying Cambrian-Devonian platform sediments that are still preserved in the Ottawa Valley where they were downfaulted into the OBG (similar rocks are preserved by downfaulting at the north end of Lake Timiskaming, and seismicity suggests that the OBG structure might extend 400+ km NW of Mattawa to include a linear cluster of deep earthquakes near Cochrane). There was ~1 km of uplift and erosion at Montreal (evidence: xenolithic Devonian rocks in Montereian volcanic throats) and the domal uplift is hypothesized to have caused extensional reactivation of existing pre-Cambrian and early rift faults near its NW-SE path ~110 m.y. ago. Carbonatite dykes were intruded into Ottawa floor buckles, and offset bore holes in Ottawa-area excavations. While indirect (shaking) evidence for postglacial paleo-earthquakes is known from the Alfred region (Aylsworth) and from near the north end of Lake Timiskaming (Adams), and there have been some postulated young faults (Eyles, Fenton/Adams) at the north end of Lake Timiskaming, no seismogenic postglacial fault has yet been proven. Understanding the origin and evolution of the OBG would be beneficial to contemporary hazard estimation. Current models for seismic hazard estimation consider that the current clustered activity will continue, but that large earthquakes will occur (and therefore have already occurred!) anywhere along the OBG.

## CONSTRAINING THE ORIGIN OF METAL ENRICHMENT IN THE BUSHVELD COMPLEX, SOUTH AFRICA: A FLUID AND MELT INCLUSION STUDY OF PEGMATITES BELOW THE MERENSKY REEF

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Pegmatites in the Bushveld Complex occur as veins and pipes comprised of quartz-andesine-biotite intergrowth. Mineral thermometry indicates minimum equilibration temperatures of 610-740°C, corresponding to the recrystallization (or alteration) of the surrounding cumulate wall rocks during pegmatite formation. Mossbauer spectroscopy and wet titration determination of the Fe<sup>3+</sup>:Fe<sup>2+</sup> ratios in biotite grains constrain the *f*O<sub>2</sub> during biotite crystallization to ΔFMQ±1. The δ<sup>37</sup>Cl values for biotite range from -0.15‰ to 0.84‰, consistent with a mantle source for the Cl. Laser <sup>40</sup>Ar/<sup>39</sup>Ar dating of biotite grains indicates that the pegmatites crystallized from 2044 (±23) Ma to 2023 (±12) Ma. The range in crystallization age indicates that late stage volatile activity persisted in the intrusion for a considerable period of time. The cores of the pegmatites may contain base metal sulfides with inclusions of precious metal minerals including melonite [(Ni, Pd) Te<sub>2</sub>] and hessite. Normative abundance patterns for the pegmatite sulfides are most similar to those of the Platreef, showing a marked enrichment in Pd and Au relative to Pt (Pd:Pt > 8), Cu enrichment relative to Ni (Cu:Ni > 20) and significant depletion in Ir.

Quartz and plagioclase within the pegmatites contain primary fluid inclusions, ranging from early low salinity two-phase aqueous to late, ultrahigh salinity (nearly anhydrous; >98 wt% NaCl

equivalent) halide melt inclusions composed of NaCl-CaCl<sub>2</sub>. Later generations of secondary halite-bearing inclusions [28.4-35.3 wt% NaCl equiv.; T<sub>h</sub>=115-259°C (by halite dissolution; n=58)] and halite-undersaturated [15.4-20.5 wt% NaCl equiv.; T<sub>h</sub>=128 and 320°C (by vapour-out; n=7)] were observed. Silicate melt inclusions containing a high K rhyodacitic liquid are also present. Co-entrapment of halide and silicate melt in single inclusions was observed, confirming that the silicate melt was saturated in a saline volatile phase. Trace element modeling shows that the pegmatites formed by very low degrees of fractional crystallization (~1 vol%) of the silicate liquid trapped in the inclusions. Analyses of single melt inclusions by LA-ICP-MS indicate high concentrations of Pd and Au (0.2-0.6 ppm range) at the time of their entrapment. These observations provide direct evidence that relatively oxidized halide melt-saturated silicate residues of magmatic origin were PGE-bearing at the time of their entrapment. Ore metal ratios in the melt inclusions and pegmatite sulfides are consistent with the bulk metal ratios of the pyroxenite cumulates below the Merensky Reef. This suggests that metals were scavenged from those cumulates.

#### U-Th-<sup>4</sup>He DATING OF CARBONATES: A REVIVAL? THE CASE OF THE BEAR CAVE FLOWSTONE, NORTHERN YUKON, CANADA

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Bear Cave, on the Arctic Circle in the north-western Yukon Territory, hosts rare, high latitude speleothem. Isolation from glacial advance has allowed for the preservation of a 68 cm thick flowstone (BC1), likely of Tertiary age. Unique deposits such as these attract interest in their potential for paleoenvironmental and paleoclimatic reconstruction at high latitude, and their insight into the conditions in Beringia prior to the establishment of permafrost. Dating this speleothem formation is critical in order to elucidate paleoclimatic variations inland at high latitudes. Initial <sup>230</sup>Th/<sup>234</sup>U/<sup>238</sup>U dating was unsuccessful as the system was at secular equilibrium, thus the age is greater than 400 ka. U-Th-<sup>4</sup>He has been used in the past for dating corals and was explored to obtain an absolute age on the flowstone from Bear Cave. Samples of primary unaltered calcite were crushed to a powder and gas was extracted by stepwise heating to 700°C at GEOTOP-UQAM. <sup>4</sup>He measured was calibrated against a pure <sup>3</sup>He spike using a quadrupole mass spectrometer at the University of Tokyo. Significant release of <sup>4</sup>He observed between 400 and 600°C suggests the retention of radiogenic helium in the carbonate grains. The contents of <sup>238</sup>U and <sup>232</sup>Th were measured on separate aliquots by TIMS at GEOTOP. Additional experiments were carried out at the MAPL Noble Gas Laboratory-University of Ottawa for comparison on a replicate section (BC1-4Base). Gas extraction was carried out by step heating crystal separates in ultrahigh vacuum from 50 to 600°C, where the helium isotopes were measured on a MAP215-50 noble gas mass spectrometer. Experiments also confirmed that <sup>4</sup>He is retained at ambient conditions. U and Th concentrations were measured on residual material by ICP-MS. Results from MAPL were similar to those reported at GEOTOP. <sup>4</sup>He range was found to be from 2.05 × 10<sup>-8</sup> to 3.18 × 10<sup>-7</sup> ccSTP/g. The <sup>238</sup>U content varies between 0.194 and 0.271 ppm and <sup>232</sup>Th ranges between 1.35 and 7.81 ppb. Resulting U-Th-<sup>4</sup>He calculated age for BCI-4Base is 9.70±0.70 Ma (GEOTOP), and

9.35±0.52 Ma (MAPL). These ages are congruent to those derived for other sections in the profile of the flowstone. Future work will be focused on refining the procedure to improve the chronology on the BC1 flowstone. Nevertheless, preliminary data from the present study support a revival of the U-Th-<sup>4</sup>He chronology and its applications in paleoclimatic reconstructions of other Tertiary-aged speleothems.

#### FORMATION OF THE CENTENNIAL UNCONFORMITY-RELATED URANIUM DEPOSIT IN THE SOUTH-CENTRAL ATHABASCA BASIN, CANADA

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The Centennial U deposit is situated in the south-central Athabasca Basin (Canada), and straddles the unconformity between early Paleoproterozoic to Archean metasedimentary and metavolcanic rocks and granitoids, and the clastic sediments of the Paleoproterozoic Athabasca Group. Although it has most characteristics of a unconformity-related uranium deposit, the Centennial deposit is atypical in that it is not directly associated with an EM conductor (there is a paucity of graphite in the basement) or with a major reverse fault zone; it is distal from a major fluid conduit (~300 to ~400 m from the Dufferin Fault), it has low Ni, Cu, Co, Zn, and Pb contents, and contains an unusually large amount (up to 5 %) of secondary uranyl minerals. Additionally, a network of diabase dykes and sills is observed at Centennial, seemingly intruding the main U mineralization of massive uraninite based on the relatively sharp contacts between the diabase dyke and the high-grade ore.

The pre-ore alteration assemblage at Centennial includes kaolinite, illite, and sudoite, which have been formed by fluids with isotopic and chemical compositions that are comparable with those from other sandstone-hosted unconformity-type U deposits in the Athabasca Basin. Pre-ore illite-related fluids have δ<sup>18</sup>O of ~3‰ and δD of approximately -40‰, whereas pre-ore chlorite-related fluids have δ<sup>18</sup>O between 1.7 and 4.3‰ and δD between -18 and 1‰.

Laser ablation ICP-MS U/Pb dating of the various U phases indicates that initial mineralization, represented by disseminated uraninite found directly to the north of the Centennial deposit s.s., occurred at ca. 1.6 Ga. The main ore, represented by massive and strongly altered uraninite, followed at an unknown time. A minor (<5%) unaltered uraninite formed from the local remobilization of the main massive uraninite at ca. 380 Ma. The main uranyl mineral, uranophane, formed last, at ca. 2 Ma. The recurrence of local U re-mobilization might have been facilitated by the persisting high permeability of the sandstones in the area due to the presence nearby of the major Dufferin Lake fault and to the emplacement of the diabase dykes.

The usefulness of Pb isotopes for exploration is demonstrated at the Centennial deposit, with strongly radiogenic Pb signatures closely related to the deposit and with common Pb signature observed at a distance of a few km from the deposit.

#### A COMMON MAGMATIC SOURCE FOR SULFUR IN VARIOUS BASE AND PRECIOUS METALS DEPOSITS, TORUD-CHAHSHIRIN RANGE, NORTH-CENTRAL IRAN

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The Torud-Chahshirin Range (TCR) in north-central Iran is covered mostly by Tertiary volcanic-plutonic rocks, underlain by Paleozoic-Mesozoic sedimentary rocks, and a metamorphosed Precambrian basement. The Tertiary rocks are high-K, calc-alkaline to shoshonitic in nature, and are characterized by depletions in HFSE and HREE, and enrichments in LILE and LREE on con-

ventional plots, implying a continental arc setting. Many base and precious metals deposits occur in TCR some with ancient mining records. The TCR has been under systematic exploration in the last 10 years. Four deposits, Cheshmeh-Hafez (Pb>Cu>>Au-Ag), Gandi (Pb-Zn>Cu-Au+Ag), Qoleh-Kaftaran (Pb>>Zn>>Cu-Ag), and Chah-Mosa (Cu only), are selected as representatives of the various deposits in TCR, for sulfur isotope studies. Qoleh-Kaftaran includes several galena-sphalerite-chalcopryrite bearing quartz-barite veins hosted in andesitic lava flows and a quartz-monzodiorite pluton. Cheshmeh Hafez consists of four main quartz veins containing galena and subordinate chalcopryrite, sphalerite, bornite, pyrite, and tetrahedrite in basaltic andesite and dacite. Gandi consists of numerous small veins of quartz containing variable galena, sphalerite, barite, pyrite and chalcopryrite in pyroclastic rocks. Chah-Mosa, consists of chalcocite-bearing quartz veins and veinlets in a shallow porphyritic quartz-monzodiorite intrusion.

Some 30 samples from the four deposits were analyzed for sulfur isotope values at the GG-Hatch Lab, University of Ottawa. The  $\delta^{34}\text{S}$  values for Gandi (galena-sphalerite), Cheshmeh-Hafez (galena-chalcopryrite), Chah-Mosa (chalcocite), and Qoleh-Kaftaran (galena-sphalerite) vary between -1.4 to -5.2, +0.5 to -1.3, -5.4 to -7.5, and -6.4 to -9.1 per mil, respectively. The  $\delta^{34}\text{S}$  values for ore fluids in equilibrium with the sulfide minerals fall in the range -1.3 to -7.5, -1.6 to +4.1, -0.3 to -5.1, and -5.5 to -9.1 per mil, respectively. The  $\delta^{34}\text{S}$  values for barite from Gandi and Qoleh Kaftaran vary between +15.0 to +16.0, and +8.3 to +9.4 per mil, respectively.

The ore and gangue minerals, textures, hydrothermal alterations, and  $T_{\text{H}}$  values, are typical of epithermal systems. Considering the large isotopic fractionation for sulfide-sulfate pairs at epithermal temperatures, the occurrence of barite in Gandi and Qoleh-Kaftaran accounts for the isotopically light sulfides in the two deposits. In spite of the distinct variations in the host rocks and the ore minerals, no significant differences exist in the  $\delta^{34}\text{S}$  values for the four deposits. The  $\delta^{34}\text{S}$  values suggest a magmatic origin for sulfur, and emphasize the role of magmatic fluids in the formation of epithermal systems.

#### APPLICATION OF SINGULAR VALUE DECOMPOSITION TO ESTIMATING GRAIN SIZES FOR CRYSTAL SIZE DISTRIBUTION ANALYSIS

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We explored the application of singular value decomposition (SVD) for the direct measurement of 3 dimensional grain sizes for crystal size distribution (CSD) analysis. To test and verify results, we used data sets of irregular grain shapes taken from simulated microstructures in which each grain is represented as a clusters of points (unit cells). The microstructures were generated from growths of prisms (1:1:5), plates (1:5:5), and cuboids (1:3:5), respectively, using governing equations for nucleation rate ( $N=e^{(at)}$ ) and growth rate ( $G=\Delta L/\Delta t$ ). The prisms, plates and cuboids became irregular grains because of competition for growth space in the microstructure. We used the ellipsoid algorithm of Moshtag (2006) which employs SVD to find the three semi-axes (radii) for an ellipsoid that approximates each cluster of grain points. However, the size and shape of the ellipsoid depends upon a subjective parameter (error term) that controls the number of points to be contained within the ellipsoid. The crux of the problem then dealt with avoiding "eye ball" subjectivity in selecting the best ellipsoid for each grain. CSDs from various size ellipsoids (error terms) were compared to CSDs predicted by the governing equations, and the best results were obtained from ellipsoids that were completely inscribed within the grains. Although such ellipsoids appeared smaller than their grains, they had one diameter that

yielded CSD slopes that compared favorably with the predicted CSD slopes for the grains. For grains derived from prisms the ellipsoid long diameters yielded a CSD slope of -0.16 compared with the predicted of -0.17, for grains derived from plates the ellipsoid intermediate diameters yielded a CSD slope of -0.29 compared to the predicted -0.28, and for grains derived from cuboids the ellipsoid intermediate diameters yielded a CSD slope of -0.32 compared to the predicted -0.33. These results need to be confirmed with other datasets, but results suggest that a specific diameter, that is dependent on the crystal shape, may be a good indicator of grain size. Work is in progress on finding a numerical method for selecting the key diameters independent of knowledge of crystal shapes. We anticipate that real application of this method will follow advances in grain resolution using high energy X-ray tomography.

#### MICROBIAL Fe-REDUCTION IN MINE WASTE ENVIRONMENTS

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Microbial reduction of iron oxyhydroxides (FeOOH) is a significant biogeochemical process linked to a myriad of critical environmental consequences: from the cycling of inorganic elements, to the transformation and remineralization of organic compounds in both natural and engineered systems. Given that FeOOH are important sorbents for metals in the geomeia, microbially mediated reductive dissolution of Fe-oxyhydroxides can have a profound impact on the mobility of metal contaminants. Mine waste environments are ideal sites for the activities of Iron Reducing Bacteria (IRB) as current mining practices produce significant waste residues rich in associated metals, solid-phase FeOOH and organic matter. Our combined field and laboratory investigations within a mine waste environment showed a progressive dissolution of amorphous FeOOH linked to IRB metabolism, with concomitant release of metals held within these FeOOH mineral phases. Moreover, laboratory experiments assessing IRB-controlled FeOOH dissolution showed that cold temperature ( $\sim 4^\circ\text{C}$ ) is the key control on this processes, promoting Fe(III)-respiration driven apparently by cold-adapted microorganisms. Water chemistry, substrate mineralogy, culture-dependent and independent techniques of mine residue microcosms under controlled laboratory conditions were used collectively to track FeOOH reduction, and identify the likely key microbial players driving this process. These results and their implications for mine waste environment metal dynamics will be discussed.

#### Au-As-Cu-Sb ORE-FORMING SYSTEM IN THE BAOGUTU GOLD DEPOSIT, WEST JUNGGAR (NORTH XINJIANG, NW CHINA)

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The Sb-bearing minerals, usually coexisting with native gold, are common in Sb-Au or Au-Sb hydrothermal deposit. Most of the Au-Sb hydrothermal deposits are mesothermal or epithermal, hosted in black shale or in limestone, as these rocks could contribute enough sulfur [1, 2]. Relatively alkaline and slightly reducing hydrothermal conditions provided by limestone favor transportation of Au and Sb are essential for the formation of Au-Sb deposits, while decrease of pH is the major controlling factor for co-precipitation of stibnite and native gold [3]. Sulfur activity might play an important role in the co-precipitation of native gold and antimony minerals (stibnite, berthierite) in the intrusion-related gold system. Native antimony generally coexists with native gold or aurostibite in gold deposit [4]. It is scarce to find native



antimony coexisting with stibnite, because their stable fields are separated by berthierite field. Here we describe antimony minerals (stibnite, ullmannite, native antimony, tetraedrite), coexisting with native gold, found in the Baogutu hydrothermal gold deposit (west Junggar, NW China).

The west Junggar is an important constituent of the central Asian metallogenic region [5, 6, 7], which is characterized with occurrence of several ophiolite belts, contacting with the Lower Carboniferous volcanic-sedimentary strata (LCVS) via faults. The LCVS is mainly composed of coarse tuff sandstone with alternating layers of tuff, tuff siltstone with basalt and siliceous locally. Post-collisional granitic plutons with ages of 295-310 Ma [8] intruded into the LCVS.

One medium-sized copper deposit formed in the porphyry body. Molybdenite separated from this porphyry copper deposit was dated to be 310 Ma by Re-Os method [9]. The Baogutu gold mine, occurring 15 km SW from the porphyry copper deposit, is a typical hydrothermal gold deposit hosted in the LCVS. The tuff and tuff siltstone are the wall-rocks of most gold-bearing quartz-sulfide veins. Most of the gold-bearing quartz-sulfide veins are lensoid or ribbon-like. Some veins reach 400 m in depth with length of 10 m to 150 m. More than twenty gold-bearing veins are exposed on the surface, while the buried lodges are the major ore-bodies mined presently.

The ore-forming process of the Baogutu gold deposit can be divided into three paragenetic stages based on the cross-cutting relationships and mineral assemblages. Gold-bearing fine-grained quartz-sulfide veins, formed at stage II, cross-cut the coarse-grained quartz-sulfide veins formed at stage I. Native antimony-bearing calcite veins, formed at stage III, always cut through the mineral assemblages formed at stages I and II. The stage II is the major period for gold deposition. The native gold crystallized in stage II is the major Au-bearing mineral. Native antimony in the Baogutu gold deposit, coexisting with calcite, stibnite and ullmannite, formed only in stage III. It contains 96-97% Sb, 2.0-2.5% As, and trace contents of S, Fe, Cu, Pb, Au and Ni.

## STIBIOCLAUDETITE ( $\text{AsSbO}_3$ ) IN THE GREENBUSHES PEGMATITE, WESTERN AUSTRALIA

Anderson, A.J., St. Francis Xavier University, Antigonish, NS B2G 2W5 Stibioclaudeite, a new mineral discovered at the Tsumeb mine, Namibia, is here documented in polyphase inclusions within spodumene from the lithium zone of the Greenbushes mine, Western Australia. Stibioclaudeite and associated arsenic- and antimony-bearing phases were identified using of Raman spectroscopy, optical microscopy, and by selective focused ion beam (FIB) milling and SEM energy-dispersive x-ray analysis. Stibioclaudeite occurs sporadically in spodumene-hosted inclusions as small (typically  $>6 \mu\text{m}$ ) crystals, with or without quartz, zabuyelite and cookeite. Other arsenic- and antimony-bearing daughter minerals in spodumene- and tourmaline-hosted inclusions include arsenolite ( $\text{As}_2\text{O}_3$ ), claudetite ( $\text{As}_2\text{O}_3$ ), native arsenic, senarmontite ( $\text{Sb}_2\text{O}_3$ ), and rare stibnite ( $\text{Sb}_2\text{S}_3$ ), schneiderhohnite ( $\text{Fe}^{2+}\text{Fe}^{3+}_3\text{S}_5\text{O}_{13}$ ), getchellite ( $\text{AsSbS}_3$ ) and pääkkönenite ( $\text{Sb}_2\text{AsS}_2$ ). Native arsenic also occurs as discrete solid inclusions in spodumene.

Stibioclaudeite-bearing polyphase inclusions represent the products of a trapped carbonate-rich magmatic fluid that exsolved from the pegmatite-forming melt during crystallization. The bulk composition of individual inclusions was modified by back reactions with the host mineral and by protracted necking during and after daughter mineral precipitation. The occurrence of native arsenic, arsenolite and senarmontite, and scarcity of arsenic and antimony sulfides in the polyphase inclusions, indicates extremely

high activities of arsenic and antimony species, low  $f_{\text{S}_2}$ , and highly reducing conditions.

## PETROLOGY AND GEOCHEMISTRY OF THE MOOSE II LITHIUM-TANTALUM PEGMATITE DEPOSIT, NWT

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The Moose II rare-metal granitic pegmatite is located approximately 115 km east-southeast of Yellowknife, NWT, along the north shore of the Hearne Channel of Great Slave Lake. It is a north-trending dyke, approximately 430 m long and up to 61 m wide, dipping moderately to the west, discordantly hosted within metasedimentary rocks of the Archean Yellowknife Supergroup. This deposit is a historical producer of lithium and tantalum (1946 – 1954).

This highly fractionated pegmatite is characterized by a narrow (up to 8 cm wide), discontinuous border zone, a poorly defined fine-grained wall zone, several coarse-grained intermediate zones, and massive quartz and amblygonite-montebrazite core zones. The intermediate zones contain albite – quartz – muscovite – K-feldspar  $\pm$  spodumene  $\pm$  amblygonite-montebrazite. The megacrystic spodumene (up to 1 m in length) forms normal to the wallrock contact in the outer zones of the pegmatite. Columbite-tantalite crystals, up to 2 cm in length, are found in many zones of the pegmatite, and are intimately associated with saccharoidal albitic zones and muscovite-rich greisen zones as platy or radiating needle-like crystals. Accessory phases include: petalite, apatite, graphite, cassiterite, lithiophilite, tourmaline, beryl, and lazulite. Detailed field mapping characterized the complex mineralogical zonation of this dyke, reflecting the different distribution and disposition of rock-forming and accessory minerals.

The whole-rock geochemical results of 56 channel, chip, and bulk samples indicate that the pegmatite is peraluminous (A/CNK ranges from 1.0 to 1.6), sodium-rich, with a very low concentration of Fe, Ca, Mg, Ti, and Mn, and elevated concentration of Ta, Nb, Rb, and Cs. The average  $\text{Na}_2\text{O}/\text{K}_2\text{O}$  is 2.8; the sodium enrichment is attributed to the abundance of cleavelandite (albite) throughout the dyke, and to the presence of discrete units of saccharoidal albite. Throughout the pegmatite, the concentration of Ta ranges from 3 to 770 ppm (averaging 110 ppm), and Nb ranges from 3 to 1520 ppm (averaging 127 ppm), with the highest values of Ta and Nb found within the secondary greisen zones. Lithium concentration reaches a maximum of 2.731 wt.%  $\text{Li}_2\text{O}$ , averaging 0.436 wt.%  $\text{Li}_2\text{O}$ . Calculation of monazite and zircon saturation temperatures is consistent with crystallization below 600°C. The whole-rock geochemistry has allowed the classification of the Moose II pegmatite as a spodumene-subtype of the complex family of rare-element LCT-type pegmatites.

## INSIGHTS INTO UNDERSTANDING THE CARBON-URANIUM ( $\pm$ SULFUR AND BORON) GEOCHEMICAL SYSTEM ALONG A RETROGRADE P-T-T PATH FROM 600°C TO 250°C: NEW CONSTRAINTS WITH IMPLICATIONS FOR U/C-TYPE URANIUM DEPOSITS

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Unconformity-type (U/C-type) uranium deposits of the ca. 1.75 Ga Athabasca Basin are the world's highest-grade uranium deposits. Most of these deposits have common characteristics that researchers attribute their genesis to some variation of the diagenetic-hydrothermal model, which invokes the mixing of highly saline, oxidized, basinal brines with variably reduced basement fluids between 150 to 220°C. However, unresolved issues still exist in the understanding of the uranium source, the flow paths of the

mineralizing fluids, the nature of the reductant, and the role of graphite and carbonaceous matter in the genesis of these deposits.

In the Athabasca Basin, many of the U/C-type uranium deposits are rooted within/near reactivated high-strain zones hosted by graphitic pelitic gneisses and graphitic/carbonaceous fault zone rocks. Many types, habits, and generations of graphite and spatially associated carbonaceous matter are found in these high-strain zones. Researchers noted the presence of carbonaceous matter and solid bitumen within the alteration and ore zones of these deposits, leading to the hypothesis that the destruction of graphite and the formation of hydrocarbons, such as methane, were the main reducing agent in their genesis. Other researchers have argued on the basis of isotopic constraints and geochemical modeling that this hypothesis should be rejected and graphite is non-reactive in this 150 to 220°C range, and have appealed to other potential reducing agents. However, all of the larger, high-grade deposits in the Athabasca Basin are spatially associated with graphitic lithologies, and within many of these, we have identified graphite alteration. Moreover, recent research indicates that the carbonaceous matter (i.e. CM buttons) records “a complex fluid-geochemical-uranium remobilization history”.

The purpose of this paper is to provide new insights into our understanding of the carbon-uranium ( $\pm$  sulfur and boron) geochemical system. Results from field, petrography, geochemistry, Raman spectroscopy, and synchrotron X-ray studies of graphitic pelitic gneisses and graphitic/carbonaceous fault zone rocks are presented and interpreted in light of recently published thermodynamic calculations of a cooling C-O-H fluid-graphite system. It is observed that graphite/carbon is consumed or precipitated along the retrograde P-T-t path of basement lithologies from 600 to 250°C. We also note that there are significant differences for carbon precipitation and/or accumulation within closed versus open fluid system conditions. The authors have also considered a mineralogically and chemically evolving unconformity breached by C-U-bearing reactivated faults. Finally, these constraints on the different carbon forms/states (graphite, CM, and methane) have implications for reducing uranyl sulfate solutions and precipitating uraninite.

#### **MINERAL EXPLORATION LEARNING EXPERIENCE AT THE UNIVERSITY OF SASKATCHEWAN: WHY, HOW, AND OUTCOMES**

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As part of the Geology program at the University of Saskatchewan, undergraduate students can take a one semester course in Mineral Deposits. The focus of the course is to provide an overview of models for magmatic and hydrothermal mineral deposits, but there is limited time to consider in detail the applicability of these models for exploration. In 2003, a new term project, an “exploration game”, was initiated to allow undergraduate students to use what they learn in the lecture component of the course to develop an exploration strategy for a particular commodity. The aim was to allow the students to consider all aspects of the “real life” exploration industry.

The teams consist of up to five students, and the commodities that have been targeted have been uranium, gold, diamonds, nickel, PGE, REE, chromium, VMS copper-zinc, porphyry copper, Li-Be pegmatites, and iron. They are provided with a small budget of \$1M, which they must use to develop a one-year exploration program for their commodity. They must use their understanding of mineral deposit types to target a suitable unstaked area. Given the budget most teams have concentrated on regions within Canada, although teams have also chosen target areas in Australia,

Argentina, and Iran. For each commodity, they must consider the appropriate techniques they would employ to identify potential mineralization and alteration, such as field mapping, geophysics, geochemistry, and drilling. Regulatory, environmental, and community relations issues must also be considered if necessary.

At the end of the semester, each team is required to present their idea for a geological target and the rationale for their choice, the exploration techniques they would use, and an overview of their budget in a 20-minute powerpoint presentation. The presentation is given by one student, chosen by the team, while the other team members provide support during the following question period. The mineral exploration community in Saskatoon are invited, and each year up to 20 industry representatives attend varying in seniority and experience. The industry representatives subsequently send comments on the presentations and target ideas to assist me in choosing the team that will receive the “virtual \$1M”. The success of the project has led to an increase in the number of students actively pursuing employment in the mineral exploration industry, and this presentation will include comments from previous team members and the industry community as well as an overview of the target areas chosen over the years.

#### **GEO-FOCUSED SITUATIONAL AWARENESS IN ROBOTIC PLANETARY MISSIONS: LESSONS FROM AN ANALOGUE MISSION AT MISTASTIN LAKE IMPACT STRUCTURE, LABRADOR, CANADA**

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Planetary exploration relies on robotic missions. However, remote data provides different information than the immersion that field geologists experience on site. We observed geo-focused issues of reduced situational awareness during a Canadian Space Agency-funded analogue mission at Mistastin Lake impact structure, Labrador, Canada. A field team collected data under the direction of a remote mission control team (2,000 km away), who had never visited the field site.

Mission control encountered difficulties related to scale, relief, and geological detail, which the field team did not. Interpreting scale in images proved difficult, even with measurement data (numbers don't carry the same impact as that experienced in the field). Relief was difficult to intuit from available data, even with stereo images. Finally, mission control missed several geologically interesting details the field team identified on their first day's walk around. Together, these affected mission control's ability to interpret geology.

Most of these issues are also related to time constraint problems. Time was required to upload data. Remote data interpretation is less intuitive, so took longer. Subsequent data collection had to be discussed, prioritized, and re-quested. Resolution improvements required repetition of this time-consuming cycle. Miscommunication, between mission control and the field, resulted in wasted cycles. In contrast, the field team absorbed and processed visual information intuitively (modifying distance, view angle, etc. to improve observations), made group or unilateral decisions quickly, and followed up on those instantly. As a result, the field team observed and interpreted more geology than mission control.

Several techniques may be helpful in mitigating these situational awareness issues. Extensive training programs, to instill an intrinsic sense of scale from numerical values, could be developed and employed. Stereo camera data collected from various angles could improve fidelity. Finally, the different timelines of robotic



missions need to be recognized and embraced. Robots take longer than humans to complete tasks, but robotic missions last months or years (not days/weeks). Analogue missions need to incorporate this aspect into their testing methodologies.

#### **REVISED BEDROCK GEOLOGY OF THE SOUTHERN ANTIGONISH HIGHLANDS, NOVA SCOTIA, CANADA**

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Detailed (1:10 000-scale) bedrock mapping of the southern Antigonish Highlands in Avalonian northeastern mainland Nova Scotia, combined with U-Pb geochronology and petrological studies, have resulted in major changes to previously inferred geological relationships in the area. The most extensive unit, the Keppoch Formation, forms the core of the southern highlands and consists of rhyolitic to dacitic flows and tuffs with minor andesitic tuff and cherty siltstone. It grades upward into laminated cherty siltstone to wacke with minor rhyolitic to basaltic tuff of the James River Formation which outcrops along the northern and southern flanks of the highlands. The Chisholm Brook Formation consists dominantly of basaltic flows and tuff with rare rhyolitic tuff and flows, and laminated cherty siltstone. These three units have been intruded by probably coeval ca. 618-603 Ma calc-alkaline, "I-type", dioritic to syenogranitic plutons. Of less certain age is the unconformably overlying Bears Brook Formation which consists of red arkosic sandstone to conglomerate with minor basaltic to rhyolitic tuff and flows, and rare laminated cherty siltstone.

The West Barneys River plutonic suite is a previously unrecognized assemblage of medium- to coarse-grained syenite to alkali-feldspar granite and gabbro which outcrops over an area of about 100 km<sup>2</sup> in the central part of the map area. A syenite sample yielded a middle Ordovician U-Pb (zircon) age of 469.4 ± 0.5 Ma. Magma mixing and mingling textures indicate a co-genetic relationship between the felsic and mafic lithologies. The intermediate to felsic rocks are in part peralkaline and have characteristics of A-type granitoid suites. Preliminary data indicate that the gabbroic rocks have compositions characteristic of continental within-plate tholeiite. The plutonic suite and its host rocks are intruded by numerous mafic and felsic dykes and sills, indicating on-going extension after pluton emplacement. The structural evidence combined with the overall distribution of these older units suggests the southern Antigonish Highlands form a broad east-west domal feature with the Ordovician plutonic suite forming the core.

Unconformably overlying the older units is quartz-rich, locally fossiliferous sandstone to granule conglomerate and rare limestone that is tentatively assigned to the Early Silurian Beechill Cove Formation, the basal unit of the Arisaig Group. This unit is conformably overlain by grey to black fossiliferous wacke, siltstone, and slate assigned to the Ross Brook Formation. Unlike the older units, the units of the Arisaig Group have not been intruded by mafic or felsic sills and dykes.

#### **DISTRIBUTION AND MOBILITY OF TOTAL PETROLEUM HYDROCARBONS IN SOILS: CASE STUDY OF THE SOUTH PARS GAS COMPLEX, NORTHERN PERSIAN GULF**

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Hydrocarbon contamination has been recognized as one of the most serious environmental threats arising from the exploration,

refining and transport of oil and gas resources. In terrestrial environments, the quality of soil, in terms of biological or physical and chemical properties, would be altered as a result of hydrocarbon contamination. This work discusses the distribution of total petroleum hydrocarbons (TPH) contamination in soil within areas of the South Pars Gas Complex (S.P.G.C.), located on the northern shore of the Persian Gulf. To assess the potential risk to groundwater, in situ contaminant mobility was examined in vertical soil profiles. Two series of soil sampling were conducted at 40 and 15 points, respectively. TPH was determined in accordance with standard methods of TPH analysis. The maximum detected concentration was 1300 +80.36 mg/kg, originating from a leaking underground waste line. Significant levels of TPH were also detected at solid waste stabilization and disposal sites, a liquid waste storage area, fire training area and in the vicinity of the oil separation unit (API). Groundwater sampling followed by total organic carbon (TOC) analysis was also performed. Although the groundwater samples did not show any evidence of contamination, vertical contamination profiles clearly demonstrated that the groundwater contamination is possible to occur in the near future, if no remedial measure is taken immediately. Since the refineries have been brought to production for the last 5 years, it is necessary to monitor the increasing industrial activities in the area. Therefore, the regulation should address cleanup standards and the preventive and remedial guidelines for petroleum hydrocarbon contamination in soil and/or groundwater.

#### **WHERE IS THE MAGNETIC CRUST OF MARS?**

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The strong magnetic anomalies over the southern hemisphere of Mars have been interpreted in terms of strong magnetization of Martian crust. Estimates of depth to Curie temperature of viable magnetic mineral at about 4 Ga imply that the potentially magnetic layer must have been in the upper 70 km of the crust, and that the lower ~10 km must have been effectively demagnetized by viscous decay. The observation that the floors of the giant impact basins Hellas, Isidis and Argyre are non-magnetic has been related to impact demagnetization of the pre-existing magnetized crust. The rock magnetic measurements show appreciable demagnetization at pressures higher than 3 GPa. Accordingly, an impact producing a crater of diameter larger than 200 km is expected to demagnetize almost the entire magnetic crust and create a magnetic anomaly observable at satellite altitudes. Besides the northern lowland which is likely demagnetized by the giant Borealis impact, and the Tharsis bulge which is formed after the cessation of the core dynamo of Mars, an extensive ancient area in the southern hemisphere, south of 30S, extending from west of Hellas to east of Argyre show no appreciable magnetic anomalies associated with craters. We investigate all of the craters and some of the Quasi Circular Depressions (QCD) larger than 200 km in diameter over this area. Using high resolution MOLA topography and the most recent JPL gravity model (jgmro-1102b), we determine the undulations of Moho and the thickness of the crust beneath each of the craters and QCDs. The majority of the craters and some of QCDs have distinct mantle plugs directly beneath, suggesting that impacts have effectively disturbed the crust. We extracted the vertical component of the magnetic field over these craters and QCDs from Mars Global Surveyor magnetic data at 400 km altitude, and used covariance analysis to derive the most reliable magnetic anomalies. We also extracted the Electron Reflectometer magnetic data at 185 km altitude over these features. However, none of these features show magnetic anomaly at satellite altitudes, emphasizing that the ancient crust in this vast area has not been appreciably

magnetized by the core dynamo prior to the impacts. Also, detailed investigation of the magnetic anomalies surrounding Hellas, Isidis and Argyre basins reveals that the surrounding crust actually is not continuously magnetized. The magnetic anomalies are associated with localized magnetic source bodies. This seems to be the case elsewhere, except in Cimmeria and Sirenum regions, implying that Martian crust as a whole may not be continuously magnetic and magnetic anomalies are due to localized magnetic bodies.

#### **GIANT IMPACTS CRIPPLE CORE DYNAMOS OF SMALL TERRESTRIAL PLANETS**

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Large impacts not only create giant basins on terrestrial planets but also heat their interior by shock waves. We investigate the impacts that have created the largest basins existing on the planets: Utopia on Mars, Caloris on Mercury, Aitken on Moon, all formed at ca. 4 Ga. We determine the impact-induced temperature increases in the interior of a planet using the “foundering” shock heating model of Watters et al. (2009). The post-impact thermal evolution of the planet is investigated using 2D axis-symmetric convection in a spherical shell of temperature-dependent viscosity and thermal conductivity, and pressure-dependent thermal expansion. The impact heating creates a superheated giant plume in the upper mantle which ascends rapidly and develops a strong convection in the mantle of the sub-impact hemisphere. The upwelling of the plume rapidly sweeps up the impact heated base of the mantle away from the core-mantle boundary and replaces it with the colder surrounding material, thus reducing the effects of the impact-heated base of the mantle on the heat flux out of core. However, direct shock heating of the core stratifies the core, suppresses the pre-existing thermal convection, and cripples a pre-existing thermally-driven core dynamo. It takes about 17, 4, and 5 Myr for the stratified cores of Mars, Mercury, and Moon to exhaust impact heat and resume global convection, possibly regenerating core dynamos.

#### **LATERALLY ACCRETING, DEEP-MARINE SINUOUS CHANNELS — INITIATION, DEPOSITION AND TERMINATION**

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Deep-marine sedimentary rocks of the Neoproterozoic Windermere Supergroup are superbly exposed at the Castle Creek study area in east-central B.C. Here channel complex 2 exposes a network of vertically-stacked and laterally-offset, sharp-based deep-marine, sinuous channel fills. Channels are sharply bounded on their outer bend side by an erosion surface that separates coarse-grained channel fill strata from (older) fine-grained levee deposits in which sandstone injections are common. The inner bend, or “point bar” side of the channel consists of well developed channel lateral accretion deposits, or LADs, that are inclined up to 7-12° toward the channel base. Grain size changes little obliquely-upward along an individual LAD, or vertically upward through the channel fill. LADs consist of two repeating and interstratified kinds: coarse-grained LADs consisting of strata up to granule conglomerate, and fine-grained LADs composed of thin- to medium-bedded finer-grained turbidites. The rhythmic intercalation of coarse- and fine-grained LADs is interpreted to be related to episodic changes in the nature of sediment transport and deposition within the local channel bend. This history of alternating coarse and fine-grained sedimentation was repeated several times in the channel bend as it migrated laterally. Commonly, lateral channel migration was terminated abruptly in one of two ways:

incision by a younger sinuous channel, or detachment related to gravitational sliding. In at least one example, incision is made evident by an extensive mudstone-clast breccia zone separating the channel fills. Clasts were likely sourced from fine-grained deposits that had accumulated in the older channel fill following channel deactivation. Erosion associated with rejuvenation of the channel fairway formed the breccia horizon, which then is overlain by LADs of the younger channel fill. Channel fills truncated by slide detachment are characterized by sharp surfaces that tend to cut obliquely downward and across the mudstone-rich upper part of the LADs and then sole-out in the lower amalgamated sandstone part at the base of the channel fill. Gravitational instability was most likely enhanced by the steep angle of the lateral accretion surfaces, the intercalation of sediment of contrasting mechanical strength, and possibly also the reduction of transport activity within the channel. Collectively, the lithological characteristics of sinuous channel fills and the recognized styles of channel termination may provide help in understanding some puzzling seismic attributes from deep-marine sinuous channel systems.

#### **ORE CHARACTERISTICS AND GENESIS IN CHAH MOSA DEPOSIT, TORUD-CHAHSHIRIN RANGE, NORTH-CENTRAL IRAN**

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The Chah Mosa is located in Torud-Chahshirin Range in ~120 km south of Shahrood in Semnan province. The Tertiary Torud-Chahshirin Magmatic Range (TCMR) in north Central Iran, hosts several base and precious metal deposits. The Chah Mosa copper deposit in central part of TCMR occurs as quartz-chalcocite veins and veinlets in a porphyritic quartz-monzodiorite and includes: Two major types of veins are distinguished: a) Chalcocite-bearing milky quartz veins, with distinct comb textures, 1-5 cm thick and 1-100 metre long; b) Chalcocite-bearing grey quartz veinlets, <2 cm thick, few centimeters to few meters long. Chalcocite is the main hypogene sulfide mineral, associated with minor bornite, digenite, and pyrite. The sulfide minerals are partially to completely oxidized at surface to form malachite, azurite, and hematite. The deposit is currently mined in small open pits, the average copper assay being 2.3% Cu. The ore contains, on average, 226 g/t Pb, 202 g/ton Zn, 8 g/ton Ag, and 0.02 g/ton Au. The monomineralic character of the ore might be attributed to the low concentrations of reduced sulfur in the hydrothermal fluid, or monometallic nature of the ore fluids. In the former case, chalcocite preferably consumed much of the sulfur in the ore fluid, leaving insufficient sulfur for other sulfide minerals to form. The ore-related alteration consists of a clay-chlorite-calcite assemblage superimposed on a regional chlorite-carbonate alteration. Fluid inclusion studies on three ore-bearing quartz samples indicated wide variations in the homogenization temperature (148 to 287°C) and salinity (0.4 to 10.4 wt percent NaCl equivalent). The  $\delta^{34}\text{S}$  values for chalcocite samples from chalcocite-bearing grey quartz veinlets fall in the range -5.4 to -7.5 per mil. The  $\delta^{34}\text{S}$  values of  $\text{H}_2\text{S}$  in equilibrium with chalcocite vary between -0.3 to -5.1 per mil, consistent with a magmatic source of sulfur. The homogenization temperature and salinity data is characteristic of epithermal environment. However, the ore mineralogy is not common for an epithermal system. Mineralization at the Chah Mosa deposit might be related to an evolved magmatic fluid which separates from a hypersaline liquid related to a porphyry copper type mineralization and then ascends to the lithocap. This type of mineralization could be attributed to transition from porphyry to epithermal environment.

**THE GEOLOGICAL SETTING, COMPOSITION, AND ORIGIN OF THE FRASER LAKES ZONE B GRANITIC PEGMATITE-HOSTED U-Th-REE MINERALIZATION, WOLLASTON DOMAIN, NORTHERN SASKATCHEWAN, CANADA**

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The Fraser Lakes granitic pegmatite-hosted U-Th-REE mineralization is located in the Wollaston Domain of northern Saskatchewan, about 25 km from the southeastern edge of the Athabasca Basin. The pegmatites intrude the highly deformed, unconformable contact between Paleoproterozoic Wollaston Group metasedimentary gneisses and underlying Archean orthogneisses. Zone B pegmatites are concentrated within a NNE-plunging antiformal fold nose, and are sub-parallel to the dominant gneissosity in the host rocks, evidence for a strong structural/metamorphic control on their location.

Zone B radioactive pegmatites can be separated into two groups based on their U and Th contents, Th/U ratios, and location within the fold nose. Those in the western part of the fold are U and Th-enriched (Th/U ~1; with up to 2460 ppm U and 1100 Th), while those in the eastern part are Th+LREE-enriched with up to 7310 ppm Th, 700 ppm U (and Th/U typically >5), 4410 ppm La, 9050 ppm Ce, and 3590 ppm Nd. The main U-Th-REE minerals in the uraniferous pegmatites include uraninite, uranothorite, zircon, and allanite, while those in the thorium- and LREE-enriched pegmatites include monazite, uranothorite-thorite, and zircon with rare allanite.

The Th- and LREE-enriched pegmatites tend to be more similar in composition to the pelitic gneisses than the uraniferous pegmatites. The uraniferous pegmatites contain more SiO<sub>2</sub> and less TiO<sub>2</sub> than the Th- and LREE-enriched pegmatites, and likely represent more highly evolved/fractionated melts. Both groups of granitic pegmatites show strong linear trends away from pelitic gneiss compositions on major element Harker diagrams; indicating a possible compositional relationship between the pegmatites and pelitic gneisses.

The strongly peraluminous to weakly metaluminous character of the pegmatites suggests that they formed by partial melting of a metasedimentary source. Since the pegmatites do not show a direct connection to migmatitic leucosomes in the pelitic gneiss host rocks, it is likely that the melt required for them to form was generated at depth. The melts would have travelled up the structural/lithological discontinuity between the Archean orthogneisses and Wollaston Group metasedimentary rocks to the level of emplacement, where they crystallized to form pegmatite bodies. During transport, the melts would have undergone assimilation-fractional crystallization processes, causing enrichment of the granitic pegmatites in incompatible elements (especially U, Th, and REEs).

The origin of the Fraser Lakes granitic pegmatites is similar to that for other granitic pegmatite/leucogranite-hosted uranium deposits, including the alaskite-hosted deposits at Rossing (Namibia), and the numerous uraniferous granitic pegmatite occurrences in the Grenville Province.

**FORAMINIFERAL DISTRIBUTION IN THE SEYMOUR BELIZE INLET COMPLEX, BRITISH COLUMBIA: IMPLICATIONS FOR HOLOCENE PALEOCEANOGRAPHIC RECONSTRUCTION**

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The Holocene distribution of agglutinated foraminifera and freshwater thecamoebians was reconstructed from two piston cores collected from glacier-carved Frederick and Alison sounds in the Seymour-Belize Inlet Complex (SBIC), British Columbia coast. The sedimentary record archived in these late Holocene cores was characterized by unevenly distributed massive and laminated intervals interrupted by occasional slumps and turbidites.

In the Frederick Sound core, the faunal assemblages are overwhelmingly dominated by the foraminiferal species *Eggerella advena*. In the Alison Sound core, thecamoebians as a group are more abundant than any individual foraminiferal species. Cluster analysis identified the presence of four foraminiferal/thecamoebian biofacies; *Eggerella advena* Biofacies, *Eggerella advena-Recurvoides turbinatus-Spiroplectammina biformis* Biofacies, Thecamoebian spp. Biofacies and the *Eggerella-advena-Thecamoebian* spp. Biofacies. In both cores, these biofacies are characterized by a low Shannon Diversity Index (SDI) (0.064-1.55) indicating that the foraminifera lived in an unfavourable habitat. The predominance of low-oxygen tolerant agglutinated foraminifera and absence of calcareous fauna indicate that oxygen was the main environmental stresser, which exhibited considerable control on the late Holocene foraminiferal distribution in the SBIC. Abundant organic matter in the core sediments provide additional evidence of the low oxygen conditions that precluded most organisms that might have utilized this rich food resource. The presence of varying proportions of freshwater thecamoebians throughout the cores is a result of soil erosion from the adjacent nearby shore in these narrow fjords and subsequent reworking of the nearshore sediments into deep water.

A moderate upcore increase in the abundances of the glaciomarine indicator species *Spiroplectammina biformis*, *Recurvoides turbinatus*, *Portatrochammina bipolaris* and *Cribrostomoides jeffreysii* within the *Eggerella advena-Recurvoides turbinatus-Spiroplectammina biformis* Biofacies and *Eggerella-advena-Thecamoebian* spp. Biofacies suggests a subtle shift to cooler bottom water conditions in the late Holocene. Development of these relatively cold bottom water conditions seems to have been coeval throughout the SBIC becoming established at ~2,860 cal yr BP in both the Frederick Sound and Alison Sound cores,

**A 1200-YEAR RECORD OF PALEOCEANOGRAPHIC AND PALEOCLIMATIC VARIABILITY FROM THE SEYMOUR-BELIZE INLET COMPLEX, CENTRAL COASTAL MOUNTAINS REGION OF BRITISH COLUMBIA**

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Foraminiferal biofacies and trace elements distribution patterns were utilized to investigate variation in regional paleoceanography and paleoclimate through the last ~1200 years, as archived in a freeze core (VEC0A13) from Mereworth Sound (MSFC) in the Seymour-Belize Inlet Complex (SBIC). Ocean circulation patterns

in the SBIC are strongly linked to precipitation, which is closely linked to the relative strength and position of the Center of Action (COA) of the Aleutian Low (AL) and North Pacific High. The MSFC was comprised of monotonous massive mud and silt sediments interspersed with minor sandy intervals. The fossiliferous upper portion (after ~1300 A.D. AD) was found to be sandier than the poorly fossiliferous lowermost section (~820-1300 AD). A down core increase and higher concentrations of aluminosilicate related elements (e.g. Al, Ca, Ti, K and Mg) particularly prior to ~1300 AD, are consistent with the predominance of mud sediments in the basal portion of the core (~820-1300 AD).

Cluster analysis of the quantified foraminiferal results identified four biofacies: *Haplophragmoides bradyi*-*Eggerella advena*-*Stainforthia feylingi*, *Buccella frigida*, *Buccella frigida*-*Criboelphidium excavatum*, and *Buccella frigida*-*Haplophragmoides bradyi* Biofacies, which characterized subtly different depositional environments in sediments deposited after ~1300 A.D. It can be generally stated though that the dominance of marine calcareous foraminifera indicate that higher oxygen and cooler temperature prevailed for a significant proportion of the core deposited after ~1300 years A.D. The high concentrations of redox sensitive elements and general absence of foraminifera in the basal portion of the core ~820-1300 AD suggests that deposition of this part of the MSFC occurred under warm, low-oxygen bottom water conditions. This basal core interval likely corresponds to the Medieval Warm Period (MWP). The reduced oxygen conditions likely came about as a result of diminished precipitation in the SBIC catchment as the COA of the AL progressively moved westward over time, resulting in significantly reduced estuarine circulation and only infrequent incursions of oxygenated open water into the SBIC basin. The overlying fossiliferous ~1300-1500 AD interval corresponds to the onset of the Little Ice Age (LIA). During this time the COA of the AL migrated further to the East, which in the SBIC resulted in higher levels of precipitation, which greatly enhanced estuarine circulation and frequent incursions of cold, well oxygenated ocean currents into the bottom waters and development of a diverse calcareous foraminiferal fauna.

#### THE FRACTIONATION OF Nb AND Ta: A POWERFUL TRACER OF SILICATE DIFFERENTIATION

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Niobium (Nb) and tantalum (Ta) are both highly lithophile high-field-strength elements that occur in a pentavalent state with nearly identical effective ionic radii; thus, the two elements are traditionally regarded as geochemical twins and are not expected to fractionate significantly during magmatic processes. Two major empirical observations, however, challenge this view. First, all accessible Earth reservoirs are subchondritic. The currently proposed chondritic Nb/Ta ratio of  $19.9 \pm 0.6$  is significantly higher than those of continental rocks, mantle-derived basalts, and the sub-continental lithosphere. It has been proposed that the 'missing' Nb resides in the core, subducted eclogitic slabs in the deep mantle, or a combination of the two. Second, the degree of fractionation between Nb and Ta during silicate differentiation is much higher than expected. There is agreement that fractionation of Nb and Ta most likely occurs somewhere in the subduction zone magma factory, but there is currently no consensus on the process.

With respect to the first observation we report new high-precision Nb and Ta data for a suite of chondritic meteorites, including Orgueil. The new data yield a very consistent Nb/Ta of  $21.55 \pm 0.27$  for chondrites with smooth REE patterns. This finding reinforces the apparent Nb/Ta mass imbalance in the silicate Earth. Eoarchean metasedimentary and metabasaltic rocks have much

lower Nb/Ta (~14-16), which suggests that the missing Nb either sits in the core or that the early terrestrial differentiation event evident in  $^{142}\text{Nd}$  isotopes was also capable of strongly fractionating Nb from Ta, for example in a Ti phase.

With respect to the second observation, we report new data for greenschist facies basalts from the 1.9 Ga Flin Flon Belt. Some of these have very high Nb/Th (up to 33) and Nb/Ta (up to 18.5) ratios that anti-correlate with LOI. This suggests that relative to Nb, Th and Ta might be more soluble in metamorphic fluids. During dehydration of oceanic slabs, Ta may be preferentially transferred to the mantle wedge and that the generally low Nb/Ta of continental arc magmas is an expression of this process.

The high-field-strength elements are widely considered as immobile but high-precision data show that even pentavalent cations can be differentially mobilized in geological environments, leaving behind important chemical clues that are beginning to be understood.

#### A PERMEABILITY STUDY OF CRYSTAL-BEARING STROMBOLI BASALTIC MAGMAS: IMPLICATIONS FOR STROMBOLI ERUPTIONS

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In-situ bubble formation and growth in crystal-bearing Stromboli basaltic magmas were studied with X-ray microtomography at high (1.85 micron voxel edge length) and low (5.46 or 7.81 micron voxel edge length) resolution. The effects of crystals on bubble sizes and distributions were investigated and compared to previous experimental studies of bubble size distributions in crystal-free samples and to natural scoria from Stromboli. The permeabilities of vesicular crystal-bearing Stromboli basaltic run products were determined using lattice-Boltzmann simulations and laboratory measurements. The permeability and porosity are related by a power-law:  $k(\Phi) = 2.04 \times 10^{-20} \Phi^{5.24} \text{ m}^2$ . Such permeabilities are approximately 1 to 2 orders of magnitude higher than those in crystal-free Stromboli basaltic melts in the porosity range of 31.6 to 55.3%. Crystal-bearing run products can easily form large bubbles due to coalescence, and do not form foams consisting of multiple, partially coalesced bubbles that are generally observed in aphyric samples. The larger bubbles in the crystal-bearing samples contribute to the higher permeability values.

Our experiments show that the presence of crystals produces high bubble number densities in the degassing magma, and that the bubble number density in crystal-bearing samples can decrease significantly during short durations of bubble growth. We propose that normal Stromboli explosions are driven by the high bubble number density of crystal-rich magma. The higher permeability in crystal-bearing samples implies highly efficient degassing in the shallower, crystal-rich, Stromboli magma body that supplies the normal Strombolian activity and sustains passive degassing. This degassed, high density magma is known to sit above the crystal-poor, volatile-rich magma body that produces paroxysmal eruptions yielding low crystallinity pumice. We suggest that this degassed scoriaceous magma body acts as a cap that allows bubbles to accumulate and form a foam layer at the top of the volatile-rich pumice magma body, potentially resulting in a more-violent paroxysmal explosion.

## **GEOLOGICAL SETTING OF THE LALOR LAKE Zn- AND Au-RICH VMS DEPOSIT, SNOW LAKE, MANITOBA, CANADA**

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This presentation gives the results of an investigation of the geological setting of the Hudson Bay Mining and Smelting Company Limited (HBMS) Lalor Lake deposit. The deposit setting is discussed in terms of its stratigraphic position and relationship to a large, well exposed, footwall alteration system. An important and surprising outcome is identification of an angular discordance (60-45°) between strata in the hanging wall and underlying rocks that host the Lalor Lake, Chisel Lake and North Chisel Zn-rich VMS deposits. This angular discordance is interpreted to be a structural discontinuity, most likely a pre-metamorphic thrust fault following the top of the deposits. The similar stratigraphic and structural setting of the nearby Chisel and Chisel North mines strongly suggests that all three deposits are part of the same, large-scale VMS system and share the same hangingwall thrust fault. In contrast, the nearby, more Cu-rich Photo Lake deposit is part of the structural hanging wall (thrust sheet) above the Lalor deposit. This investigation of the Lalor Lake deposit has dramatically modified previous understanding of the regional geology and interpreted setting of the Snow Lake VMS deposits.

## **3-D IMAGING OF GEOMATERIALS: X-RAY MICROTOMOGRAPHY APPLIED TO VOLCANIC EJECTA**

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Geology is a three-dimensional (3-D) science. We are not merely interested in the surface of objects but desire knowledge of their shapes, orientations and distributions in 3-D, whether we are looking at bedded strata on an outcrop and are measuring the strike and dip, or trying to understand the "twists and turns" of an igneous intrusion or a vein of precious ore. Often, however, we must content ourselves with a two-dimensional (2-D) sample, such as a thin section, because of the difficulty of making 3-D measurements. In many cases 2-D samples provide us with a wealth of information and are sufficient for our studies, but in other cases they fail and a true 3-D investigation is necessary, especially when quantitative data are desired. Stereologic techniques can be used to convert some 2-D measurements into 3-D, but they are often applicable only to objects of similar shape that are topologically convex (i.e. tangents to the surface do not penetrate the object). Thus, in many geological cases true 3-D measurements are a necessity. With the advent of synchrotrons and laboratory microfocus x-ray sources, x-ray computed microtomography has become an easy-to-use tool that allows the rapid acquisition of 3-D imagery at spatial resolutions routinely approaching 1 micron (and in some cases at sub-micron resolution), albeit with the restriction that the higher the resolution the smaller the sample. The reconstructed volumes allow us to quantitatively measure the true 3-D sizes, shapes and spatial orientations of phases in our samples. We have been applying 3-D microtomography to the study of experimentally produced bubbles and of vesicles in natural volcanic rocks in order to better understand the mechanisms involved in magma degassing and the relationship between bubble formation and volcanic eruptions. The reconstructed volumes allow us to view crystal and bubble textures

directly in 3-D and to measure their 3-D size distributions. But, more than producing "pretty pictures" we can correlate the 3-D data with other measurements and also use the reconstructed volumes as input into models for the prediction of the behavior of geological materials. In particular, we have been actively modeling the permeability of vesicular magmas using lattice-Boltzmann techniques and are now beginning to model the strength of magmatic foams based upon 3-D microtomographic imagery.

## **DETAILED CHEMOSTRATIGRAPHY OF THE NEOPROTEROZOIC RAPITAN IRON FORMATION, WITH EMPHASIS ON THE REE+Y, Mo, AND U**

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Neoproterozoic iron formations represent an unusual and apparently final reoccurrence of this sediment type, deposited following a more than one-billion-year hiatus. Despite the unusual and possibly unique environmental parameters that led to their formation, Neoproterozoic iron formations have strongly influenced depositional models for iron formations of much greater antiquity and play a crucial role in many ideas regarding the surficial evolution of the Precambrian Earth. These proposals have been put forward using a surprisingly slim database of geochemical data for Neoproterozoic iron formations. One of the most recognised and well-known of these is the Rapitan iron formation of northwestern Canada. In this study, a suite of high-quality trace element data from the Rapitan iron formation was used to reconstruct the configuration and redox evolution of the Rapitan basin. Complete, shale-normalized REE+Y patterns demonstrate that the basin was well connected with the open ocean, demonstrating several diagnostic features of seawater, such as elevated Y/Ho and Gd/Gd\* ratios. Local granitoid catchments also supplied dissolved REE+Y, mainly evident in the subdued shale-normalized La anomaly, suggesting partial basin restriction. Molybdenum and U systematics are very well behaved, but are unrelated to Fe and Mn contents. Combined Mo and U data indicate a partly restricted, or 'silled' basin. In contrast to modern analogues of such basins, (e.g. the Cariaco Basin of Venezuela), the stratigraphic association of glaciogenic clastic rocks requires the consideration of ice cover in attempts to construct a depositional model. Based on the Mo and U metal stratigraphy, we propose that the Rapitan iron formation was deposited in either of the following two basin configurations: (1) an ice-capped, stagnant, open-marine basin in which long-term redox stratification helped develop euxinic and ferruginous water masses; or (2) a combination of a silled basin and ice cover, in which permanent restriction at depth was magnified by ice-capping of the basin. Regardless of the preferred model, the absence of a positive Eu anomaly in the Rapitan iron formation suggests that the open ocean was fully ventilated by this time.

## **LASER ABLATION WITH FULLY SIMULTANEOUS ICP-MS DETECTION**

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Inductively coupled plasma mass spectrometry is a widely used analytical method for the elemental analysis and the measurement of isotope ratios in geochemistry and is extensively used for the fingerprinting of rocks, minerals and ceramics. The combination of such an analytical instrument with Laser ablation as a sample introduction system has several advantages. Potential errors and contamination problems are eliminated with a direct measurement of the sample. Also spatially resolved information can be obtained.

Sequential detection of the elements has several disadvantages when using laser ablation as a sample introduction system.

Fluctuations and noise of the laser ablation system as well as flicker noise from the plasma are limiting precision and accuracy of the analytical results.

A completely new detector placed in the focal plane of double focusing sector field mass spectrometer in Mattauch Herzog Geometry offers now the possibility to fully simultaneously record the signals of all isotopes of the inorganically relevant mass range from a permanent ion beam. This offers new possibilities for the simultaneous determination of element ratios across the complete inorganic relevant mass range as well as simultaneous determination of multiple isotope ratios out of one measurement. When working with transient signals, the full duty cycle applies to all elements selected and a potential signal skew can be eliminated.

The technologies of this new detector together with the mass spectrometer setup and the advantages for Laser Ablation are discussed.

#### **IMPROVED UNDERSTANDING OF SEAFLOOR HYDROTHERMAL SYSTEMS USING THE NEPTUNE CANADA CABLED OCEAN OBSERVATORY**

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Steve Scott's interest in modern seafloor hydrothermal systems and sulfide deposit genesis was partly generated by volcanic venting and hydrothermal deposits along the Endeavour Segment (2200m), Juan de Fuca Ridge, offshore BC. Earlier submersible studies are now supplemented by NEPTUNE Canada (NC), the world's first regional cabled ocean observatory, transforming our understanding of biological, chemical, physical, and geological processes at the spreading ridge and shelf to deep sea relationships across the tectonic plate. Real-time continuous monitoring and archiving ([www.neptunecanada.ca](http://www.neptunecanada.ca)) captures the temporal nature, characteristics, and linkages of these natural processes in ways previously impossible.

NC is instrumenting two of five vent fields – Main Endeavour Field (MEF) and Mothra. At MEF, temperature-resistivity probes, high-resolution digital camera (or HDTV), McLane remotely activated fluid sampler and short-period seismometer were installed in 2010. At Mothra, temperature-resistivity probe, microbial incubator, McLane fluid sampler and high-resolution digital camera will be deployed in 2011/12. Many instruments from University of Washington, Rutgers University and PMEL/NOAA were modified to be network compatible. In 2010, two trans-ridge cables were successfully laid connecting to 41 instruments, two junction boxes, and three interface adapters. Data flowed satisfactorily for a month before the MEF connection failure. A regional circulation experiment characterizes hydrothermally driven water mass movement; one of four mooring arrays was installed north of MEF, with acoustic three-dimensional current meters at 10, 50, 125 and 250 m above the seafloor, measuring temperature and salinity variations. A bottom pressure sensor accurately measures local tides. A broadband seismometer will characterize the overall seismicity to understand linkages between local tectonics and biological and oceanographic phenomena. A novel Cabled Observatory Imaging Sonar System (COVIS) installed at MEF to acoustically image, quantify and monitor seafloor hydrothermal flow on timescales of hours (response to ocean tides) to weeks-months-years (response to volcanic and tectonic events) to advance understanding of these interrelated processes.

This Endeavour and later Middle Valley instrumentation will quantitatively document real-time complex interactions among volcanic, tectonic, hydrothermal and biological processes. New users and instruments are welcomed to utilize the infrastructure's expansion capacity.

#### **RESEARCH FRONTIERS ADDRESSED BY CABLED OCEAN OBSERVATORIES: PERSPECTIVES FROM NEPTUNE CANADA**

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Cabled ocean observatories are transforming the ocean sciences. Examples are drawn from North America, Europe and Asia, but in particular from NEPTUNE Canada (NC) as the world's first regional cabled ocean observatory, off British Columbia's coast. Its final set of the initial 130 instruments, being deployed in 2011-12, will result in over 400 data streams. Continuous power and high bandwidth facilitates real-time integrated data on physical, chemical, geological, and biological gradients at temporal resolutions relevant to the dynamics of the earth-ocean system through a range of environments, particularly the deep ocean frontier. This allows discrimination between short and long-term events, interactive experiments, real time data and imagery, and complex multidisciplinary teams interrogating a vast database over the observatory's 25-year design life.

NC's observatory nodes at the coast, continental slope, abyssal plain, and ocean-spreading ridge are in 100-2660m water depths. Principal research frontier themes are: plate tectonic processes and earthquake dynamics; dynamic processes of seabed fluid fluxes and gas hydrates; regional ocean/climate dynamics and effects on marine biota; deep-sea ecosystem dynamics; and engineering and computational research.

The building of this \$100M facility integrates hardware, software, and people networks. Hardware progress includes: installation of the 800km powered fiber-optic backbone (10kV DC and 10Gbsec communications); innovative technological development of Nodes and Junction Boxes; acquisition/development/testing of Instruments; development of mobile instrument platforms such as Vertical Profiler and Crawler; and integration of over a thousand components into an operating subsea sensor system. Software and hardware systems are developed for acquiring, archiving, and delivering continuous, free, open, real-time data through the Internet (about 60TB/yr); the web environment combines this data access with analysis and visualization, collaborative tools, interoperability, and instrument control. A network of scientists and technicians are contributing to the process along with thousands of data users.

Cabled observatories are yielding new knowledge and scientific interpretations, including: ocean/climate change, ocean acidification, recognizing and mitigating natural hazards, non-renewable and renewable natural resources. Frontier challenges are considerable: new scientific inquiry, technical innovations, maximizing educational/outreach activities. Socio-economic benefits include applications in sectors such as sovereignty, security, transportation, data services, and public policy.

#### **OXIDE GOLD DEVELOPMENT ABOVE VOLCANOGENIC MASSIVE SULFIDE DEPOSITS: EXAMPLES FROM THE ARABIAN-NUBIAN SHIELD**

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Oxide gold deposits above VMS deposits form during weathering and interaction with the groundwater table under arid and temperate conditions, and add considerable value to the economics of mining the deposit. Classic examples are found in the Neoproterozoic Arabian-Nubian shield, including at Bisha in western Eritrea, in the Ariab district of northeast Sudan, and at Al Hajar in southern Saudi Arabia. The oxide gold cap at Bisha has 1.08 M oz Au and 4.66 M oz. Ag in 4.8 M tonnes of hematite-dominant, with lesser kaolinite-alunite-sulfate ore (M+I) from the surface to ~35 m depth. It is underlain by a supergene copper zone (7.5 M tonnes

@3.96% Cu, M+I+I), and a primary Cu-Zn sulfide zone (26.4 M tonnes, 0.7 g/t Au, 47.5 g/t Ag, 0.99% Cu, 0.22% Pb, 5.72% Zn, M+I+I). In the Ariab district, at least ten VMS deposits are overlain by kaolinite-alunite-sulfate dominant oxide gold caps that have produced >2.2 M oz. Au. The Hassai South deposit is a large (>20 M tonnes), planar, moderately-dipping sulfide lens currently be evaluated at depth. The mined oxide ore in the upper 120 meters contained native gold, electrum, calaverite, petzite, tellurides of lead, silver and bismuth, native copper, copper oxides and carbonates, anglesite, cerussite, and smithsonite. Iron oxides and chalcocite were redistributed for several tens of meters to either side of the original sulfide lens into sericite-chlorite schists. The pre-mining surface had massive, brecciated and re-brecciated hematite-goethite-silica formed a 2-20 m-thick cap. Significant native gold is present along fractures and in cavities in the oxide material at surface.

In this environment, much gold and lead remains in the oxide caps, whereas copper is more widely distributed, and zinc may be nearly absent. Gold is found along fractures and in cavities in oxides, sulfates and carbonates, and tends to bind to oxide mineral surfaces. Gold may migrate in solution, released from the dissolution of sulfides and sulfosalts; or it may be transported physically if native gold grains are sufficiently large. Lead liberated from sulfides is commonly locked in low solubility anglesite. Copper oxides and chalcocite may cement surface gravels above bedrock and above the groundwater table. Sulfide zinc may form smithsonite, or it may be washed out of the near-surface environment. Manganese contents are variable. At Bisha, the surface gossan is depleted in Mn, whereas exhalites along strike are significantly enriched in Mn, reflecting original Mn distribution on the paleo-seafloor.

#### **THE INFLUENCE OF CANADA AND STEVE SCOTT IN THE BUILDING OF PORTUGUESE EXPERTISE IN MASSIVE SULPHIDE DEPOSITS AND MARINE GEOLOGY**

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The influence of Canada and Steve Scott on the development of Portuguese VMS expertise has been immense. It all started in the late 1970's, when the first Portuguese PhD students in the topic of VMS deposits (and the Iberian Pyrite Belt) went to London, Ontario to work with Bill Fyfe, Dick Hutchinson, Bob Hodder and Rob Kerrich.

From then on the links never ceased to strengthen. The above Canadians, accompanied by Fred Longstaffe (and others) and yes, Steve Scott, started visiting Portugal rather frequently. At the same time, the development of a Portuguese scientific team on VMS generated the more and more frequent appearance of Portuguese scientists in international meetings. A high turning point was an UMI meeting in Estes Park, Colorado, back in 1993, co-convened by Steve. Since then, the influence of Steve over our group continued to grow.

Another key event was leg 193 of the Ocean Drilling Program, in the early 2000's, to Papua New Guinea, very close to Nautilus Minerals Solwara 1 deposit, which will soon become the first deep sea VMS mining operation ever. Steve was one of the scientists responsible for the discovery of the target, Pacmanus. Because of ODP rules, only one scientist from the discovery team could be co-chief scientist in the expedition. The second co-chief had to be invited from a different group. The choice ended in a Portuguese scientist. Steve sailed as a "simple" scientist. What a fantastic opportunity to get to know Steve better, both as a scientist and as a colleague! A second Portuguese, Alvaro, an ore mineral-

ogist, sailed as well. Steve and Alvaro spent as much time as they could over the reflection microscope, finding rare minerals and fluid pathways.

After Leg 193 Steve became a member of the International Advisory Committee of our research center, Creminer. We have very strong links with engineers, who better than Steve to help us communicate with them? Indeed Steve, over the years, produced many extremely useful comments and suggestions.

Many of us benefited from Steve's formal lecturing. Several groups of Portuguese graduate students went to Brest (France) year after year to attend the Mineral Deposits Course co-organized by Steve.

Last but not least, Steve is now in charge of a post-doc from Portugal, Filipa. She will speak for herself, I will only comment that the Steve's participation in our growth continues. Many thanks, Steve, may the force be with you.

#### **PETROLOGICAL, GEOCHEMICAL, AND PETROGENETIC ANALYSIS OF THE LATE-TECTONIC GRENVILLIAN URANIFEROUS LAC TURGEON INTRUSIVE COMPLEX, QUEBEC**

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The Lac Turgeon Intrusive Complex (LTIC), along the north shore of the St. Lawrence Seaway in the Grenville Province of Quebec, is host to pegmatite-related uranium mineralization. The main zone has inferred resources of 44 million pounds  $U_3O_8$ , averaging 0.012%  $U_3O_8$ ; isolated occurrences have up to 0.38%  $U_3O_8$ . The intrusion lithologies include granite, pink pegmatite, and white pegmatite all of which are heterogeneous in texture and have irregular contacts. The main accessory minerals include biotite, muscovite, zircon, ilmenite, hematite, and magnetite with minor apatite, uranophane, uraninite, monazite, and xenotime. U-Pb monazite dating for the granite, white pegmatite, and pink pegmatite yielded ages of  $1004.2 \pm 4.1$  Ma,  $1001.9 \pm 4.2$  Ma, and  $998.3 \pm 5$  Ma, respectively. This age corresponds to the terminal stages of the Ottawa Orogeny (1080-1020 Ma) of the Grenville Orogenic Cycle that is associated with extension and uplift.

The LTIC is characterized as peraluminous ( $A/CNK > 1$ ) with high  $SiO_2$  (65-85 wt.%) and most samples are calc-alkaline to alkali-calcic, have  $K_2O > Na_2O$ , and have low  $P_2O_5$  and  $TiO_2$ . The white pegmatite has lower CaO, FeO, and MgO compared to the other phases and is more fractionated with elevated Rb/Sr and Rb/Ba and decreased Rb/Cs, K/Rb, and Zr. The chondrite-normalized REE patterns for the white pegmatite have a less pronounced, negative Eu/Eu\*, and lower  $\Sigma REE$  (average 34 ppm) compared to the other phases (average 142 ppm for the granite and 94 ppm for the pink pegmatite). The LaN/LuN is similar for all lithologies ( $2.1 \pm 2.1$ ); however, the REE profile is relatively flat reflecting apatite and monazite fractionation. The LTIC is extremely evolved as reflected by Rb/Sr (average  $5.8 \pm 14.0$ ), Rb/Ba ( $2.7 \pm 6.4$ ), and Zr/Hf ( $20.1 \pm 7.2$ ) fractionation ratios and Zr ( $108 \pm 194$  ppm) and Rb ( $247 \pm 107$  ppm) abundances. The zircon-, monazite-, and apatite-saturation temperatures decrease from the non-mineralized granite, pink pegmatite, to the white pegmatite with averages for the LTIC of 690°C, 805°C, and 702°C, respectively. The LTIC is characterized as an A-type granite with a crustal origin followed by additional fractionation.

The U and Th content is highly variable (<2-4485 ppm and 0.7-620 ppm, respectively) with U/Th ratios ranging between 0.28 and 25. The average U/Th for the LTIC is 2.3 (+4.0/-1.5; based on log transform data). In most samples, uraninite is accompanied increased accessory mineral content explaining the close relationship between U and La, Ce, Zr, and Y.



## IMPACT OF PYRITE ON THE MOBILIZATION OF ANTIMONY IN THE MINING ENVIRONMENT

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Antimony (Sb) is considered carcinogenic and has been targeted as a priority pollutant by the USEPA, the European Union and the Canadian government. The mobilization of Sb can be of concern in mesothermal gold deposits where stibnite, a primary Sb-bearing sulphide, often occurs in association with pyrite and arsenopyrite. The presence of the latter sulphide minerals with relatively high redox potentials can affect the dissolution rate of stibnite due to galvanic interactions, and potentially enhance the release of Sb. The objective of this presentation is to show the impact of pyrite on the oxidative dissolution of stibnite in three different systems: a rock sample, binary mixtures of ground minerals and mine wastes. The first experiment investigated the weathering of stibnite with included pyrite exposed in a polished section. Detailed spectroscopic characterization revealed preferential oxidative dissolution of stibnite at the interface with pyrite, while the pyrite remained unaltered. In a second study, finely ground pyrite and stibnite were mixed in various ratios and the mixtures were subjected to leaching in flow-through columns. Similar to what was observed in the polished section with a pyrite-stibnite assemblage, an increased oxidation rate of stibnite was noted in the presence of pyrite, with a greater accumulation of solid-phase Sb-oxide products in the systems containing higher pyrite inputs. These two studies provide evidence that, in oxygenated environments where stibnite is in close contact with pyrite, galvanic interactions can enhance the oxidation of stibnite and the mobilization of Sb. In some mine wastes, however, such close contact with pyrite may not be present due to the overall low content of sulphides (<5% in mesothermal gold deposits) and possible isolation of the liberated stibnite grains by insulating silicates. This aspect was evaluated in a third study using pyrite-amended gold mine wastes in which stibnite (<1 wt.%) is the main Sb-bearing mineral. Results from these ongoing leaching column experiments will be discussed from the perspective of their significance in mine waste management.

## LOW-TEMPERATURE HYDROTHERMAL ALTERATION AT THE WORLD-CLASS GOLD-RICH VMS LARONDE-PENNA MINE, ABITIBI, QUÉBEC: AN OXYGEN ISOTOPE STUDY

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The oxygen isotope compositions of metamorphosed, hydrothermally altered, mafic to felsic volcanic and volcanoclastic rocks hosting the world-class Archean LaRonde-Penna gold-rich VMS deposit, Abitibi, Canada, exhibit a large range ( $\delta^{18}\text{O} = 6.5$  to  $22.0\text{‰}$ ). Basalt and andesite have lower average  $\delta^{18}\text{O}$  values ( $x = 10.8\text{‰}$ ) whereas felsic rocks have higher average  $\delta^{18}\text{O}$  values ( $x = 11.1$  to  $13.2\text{‰}$ ). A correlation between  $\delta^{18}\text{O}$  values and  $\text{SiO}_2$  or  $\text{Zr/TiO}_2$  suggests that only a 2‰ variation in  $\delta^{18}\text{O}$  values can be ascribed to fractional crystallization. Whole rock samples interlayered in massive and semi-massive sulfide zones 5, 6, 20N and 20S have  $\delta^{18}\text{O}$  values ranging from 9.6 to  $22.0\text{‰}$ . Despite large ranges in  $\delta^{18}\text{O}$ , the various metamorphosed hydrothermal alteration facies affecting mafic to felsic rocks have average values that are similar (ca.  $12.7\text{‰}$ ).

On a camp scale, a decrease of  $\delta^{18}\text{O}$  values downward in the volcanic sequence, from  $\sim 13$  to  $\sim 10\text{‰}$ , is interpreted to reflect higher temperatures at depth within the hydrothermal system that

formed the massive sulfide lenses. An up-section profile, in the immediate footwall of 20N zone, of  $\delta^{18}\text{O}$  values in an undifferentiated rhyodacite-rhyolite unit with constant  $\text{Zr/TiO}_2$ , displays an increase of  $\delta^{18}\text{O}$  values from 13‰ to 14‰, followed by decrease to values near 12‰ beneath the massive sulfide lens. Along this pattern of  $\delta^{18}\text{O}$  values, the concentration of MnO increases gradually in the footwall of the 20N massive sulfide lens. Decrease in  $\delta^{18}\text{O}$  values in Mn-rich altered rocks in the immediate footwall of the sulfide lenses may indicate zones of higher temperature up-flow, although there is no correlation between  $\delta^{18}\text{O}$  values and MnO.

Water-rock reaction modeling requires temperatures below  $100^\circ\text{C}$  to explain the high  $\delta^{18}\text{O}$  values of altered volcanic rocks assuming oxygen isotope exchange between water with  $\delta^{18}\text{O}=0\text{‰}$  and initial rock with  $\delta^{18}\text{O}=7\text{‰}$ . Alternatively, the high  $\delta^{18}\text{O}$  values of altered volcanic rocks were achieved by reaction of a fluid with an initial  $\delta^{18}\text{O}$  up to 5‰ at temperatures below  $200^\circ\text{C}$ . Initial fluid  $\delta^{18}\text{O}$  values up to 5‰ indicate either a fluid reservoir where high temperature exchange under lower water-rock ratios, or mixing of seawater near (0‰) with magmatic water exsolved from felsic magmas (7‰; c.f. Iberian Pyrite Belt). The very high  $\delta^{18}\text{O}$  values ( $>17\text{‰}$ ) quartz-rich volcanic rocks interlayered with massive sulfides likely indicate low temperature ( $<100^\circ\text{C}$ ) hydrothermal silica precipitation as a result of cooling and mixing with seawater at or near the sea-floor.

## FROZEN HEAT: UNEP GLOBAL OUTLOOK ON METHANE GAS HYDRATES

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The United Nations Environment Programme via its collaborating center in Norway, UNEP/GRID-Arendal, is undertaking an assessment of the state of the knowledge of methane hydrates. Global reservoirs of methane gas have long been the topic of scientific discussion both in the realm of environmental issues such as climate change and as a potential energy resource for development. Our rapidly evolving scientific knowledge and technological development related to methane hydrates makes these formations increasingly prospective to development. In addition, global demand for energy continues, and will continue to outpace supply for the foreseeable future, resulting in pressure to expand development activities, with potential environmental and social impacts. Understanding the intricate links between methane hydrates and 1) their role in natural systems including the global carbon cycle, 2) their sensitivities to climate variations such as global warming, 3) the key drivers (e.g. economic drivers; resource scarcity; geopolitical drivers) associated with their evaluation as a possible source of natural gas, and 4) the environmental and societal impacts of possible development, are key factors in making good decisions that promote sustainable development.

As policy makers, environmental organizations and private sector interests seek to forward their respective agendas, there is a clear and imminent need for an authoritative source of accessible information on various topics related to methane hydrates. The 2008 UNEP Annual Report highlighted methane from the Arctic as an emerging challenge with respect to climate change and other environmental issues. Building upon this foundation, the Global Outlook on Methane Gas Hydrates aims to provide a multi-thematic overview key aspects of the current methane hydrate debate for both land-based Arctic deposits and those in the marine environment. Although based on the latest scientific work produced by leading experts, the style and language are designed for a general audience. This Outlook will span a range of themes that include: the history of gas hydrates science, natural systems, human impacts, exploration and extraction technologies, sustain-

able economics, resource efficiency and policy perspectives and challenges.

UNEP/GRID-Arendal's mission is to provide environmental information, communications and capacity building services for information management and assessment. Established to strengthen the United Nations the UNEP, our focus is to make credible, science-based knowledge understandable to the public and to decision-makers to promote sustainable development. We are dedicated to making a difference by exploring how environmental information impacts on decision-making and the environment. We seek to bridge the gap between science and politics.

#### **UNEP PACIFIC MARINE MINERALS AND DEEP SEA MINING ASSESSMENT**

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The exploitation of deep sea marine minerals, including poly-metallic sulphides formed at hydrothermal sites, is now a near term prospect. A number of private sector and State-sponsored interests are actively examining these potential resources, having identified them as partial replacements to dwindling land based reserves. Exploration work in the Exclusive Economic Zones of many Pacific Island States has increased dramatically over the past decade, with key sites having undergone advanced exploration work and environmental impact assessments, leaving them on the verge of development. Despite this upsurge in commercial activity, most Pacific Island States have not concurrently developed the specific policy, legislation and regulatory framework necessary for the governance and sustainable development of deep sea mineral deposits.

UNEP/GRID-Arendal, along with the Pacific Islands Applied Geoscience Commission, is seeking to bridge the gap between science and policy as it pertains to deep sea mineral resources. Building upon its experience linking environmental protection, socio-economic issues and sustainable resource development, UNEP/GRID-Arendal aims to initially produce a regional Pacific Islands deep sea minerals assessment that would serve as a model for an eventual global assessment. Key themes to be addressed include: 1) a synthesis of scientific knowledge pertaining to the geology of deep sea marine minerals, 2) an examination of potential adverse environmental impacts of improperly regulated development and 3) an examination of the socio-economic benefits and consequences of marine mineral resource development.

This regional assessment is targeted primarily at decision makers tasked with developing national policies for regulating deep sea mineral resource development. It is thus formulated as a standalone compilation providing a concise, science-based foundation upon which balanced policy development can take place, incorporating input from all appropriate stakeholders. Secondary target groups include: 1) private sector and commercial interests logistically supporting the development work, and 2) the local communities which, through good governance, could ultimately benefit economically from development activities, but who alternately could, under poorly regulated regimes, suffer from the effects of the degradation of their environment.

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#### **THE UNEP SHELF PROGRAMME: MEETING THE NEEDS OF DEVELOPING STATES**

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The key challenge for developed coastal states working towards a submission for Article 76 of the United Nations Convention on the Law of Sea (UNCLOS) remains the collection and interpretation of scientific evidence needed to support their conclusions. Countries with the means to develop large scale initiatives have invested many resources into getting the job done. Developing states and small island developing states (SIDS), however, face great challenges in addressing this issue as many lack the institutional and financial capacity so readily available to richer nations. With the May 2009 submission deadline having affected most of these states, a different "rush" ensued and continues to this day; one that is dedicated to ensuring that no state gets left behind in this historical process.

The UNEP Shelf Programme (USP) is the access point to a collaboration of international organisations with expertise in marine geosciences and maritime law. It was established in response to a United Nations resolution, stating that the United Nations Environment Programme (UNEP), working through the Global Resource Information Database (GRID) system, should work in conjunction with the Intergovernmental Oceanographic Commission of UNESCO (IOC) and the International Hydrographic Organisation (IHO), to store and handle research data from the outer continental margin, with a view to serving the needs of coastal States, and in particular developing countries and small island developing States, in their compliance with article 76 of the Convention.

The UNEP Shelf Programme, implemented by UNEP/GRID-Arendal, is assisting numerous states in Africa, the south Pacific and Latin America amongst other regions. The Programme is mostly dedicated to facilitate developing state's access to public marine geoscientific data through a One Stop Data Shop (OSDS) compiled by the Programme over the past 4 years. In addition, the USP provides technical and practical training and advice to the national teams working on the delineation projects. The Programme strives to increase its effectiveness when training national teams by organizing multistate training workshops targeting large regions.

#### **FAULT-MEDIATED MELT ASCENT IN A NEO-PROTEROZOIC CONTINENTAL FLOOD BASALT PROVINCE, THE FRANKLIN SILLS, VICTORIA ISLAND, CANADA – IMPLICATIONS FOR Ni-SULFIDE AND PGE MINERALIZATION**

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The Neo-Proterozoic Franklin Large Igneous Province on Victoria Island, Canada, is characterized by continental flood basalts and a sill-dominated feeder system. Field relationships indicate that there were ephemeral fault-guided transfer zones that allowed magma to jump up-section to form higher-level intrusions. In the corner regions where the magmas move up-section, roof rocks are characterized by unusually wide and intense contact metamorphic haloes, implying significant magmatic throughflow, favourable

for Norilsk' type Ni-S mineralization. The geometric constraints suggest that the conduits may have opened episodically, and would be ephemeral, closing when magma pressure waned. The episodic nature of conduit opening events can account for pulsed ascent of crystal slurries, and explains the rarity of exposed feeder conduits in the geological record. Residual oxide-sulfide-saturated fluids expelled from the feeder sill during roof subsidence would have been channelled by the fault, and reacted with contact-metamorphosed roof rocks to form skarns.

#### **MICROBIAL ARSENIC RELEASE FROM HISTORIC GOLD MINE TAILINGS, NOVA SCOTIA**

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Gold mines frequently have high natural arsenic (As) concentrations in tailings and nearby streams and groundwater. The optimal remediation plan should therefore protect the local population from health risks associated with ingesting arsenic-rich solids or waters. The speciation of arsenic is important in the assessment and remediation of contaminated sites. The reduced As(III) species of arsenic are known to be more toxic and mobile than the oxidized As(V) species. The present study focused on understanding the biotic controls on the release of arsenic from two extremely contaminated abandoned gold mine tailings sites in Nova Scotia.

Arsenic reducing bacteria communities were identified in the tailings using gene specific polymerase chain reaction (PCR), whereas sequencing allowed the identification of specific reducers belonging to the Geobacteraceae and Prolixibacteraceae genus. The microbial activity of these metal reducing bacteria was further assessed using anaerobic microcosms containing tailings samples and deoxygenated surface water from the same sites. Differences in the rates of arsenic reduction and iron reduction were found in geochemically distinct tailings samples.

These results have implications for remediation efforts at these sites, including the use of a geosynthetic clay liner which would raise the anaerobic boundary, and liming, which would increase the pH. Both of these methods could potentially increase the rate of microbial reduction and trigger the release of soluble reduced arsenic into the surrounding environment.

#### **REMOTE PREDICTIVE MAPPING OF BEDROCK GEOLOGY USING IMAGE CLASSIFICATION OF LANDSAT AND SPOT DATA, WESTERN MINTO INLIER, VICTORIA ISLAND, NWT**

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Image classification of Landsat-7 and SPOT-5 data was used to analyze and map the bedrock geology of a part of western Minto Inlier on Victoria Island. The image data set consisted of two SPOT scenes and the corresponding area on the Landsat data. Based on the existing geology map, the main lithological units exposed in the study area include the Minto Inlet, Wynniatt, Kilian, and Kuujjua Formations of the Shaler Supergroup which are unconformably overlain by the Cambro-Ordovician succession. The Franklin magmatic event is represented by Natkusiak Formation basalts and the related gabbro-diorite sills and dykes intruded into the sedimentary strata. Digital image processing techniques were used to mask out the water, ice, and the main part of the vegetation to enhance the images and obtain a better discrimination between various lithological units. Six bedrock classes including diabase, basalt, carbonates of Wynniatt Fm, Kuujjua sandstone, evaporates of Minto and Kilian Formations, and Cambro-Ordovician carbonates together with six surficial classes including the vegetation, were defined mainly based on the spectral diversity observable in

the Landsat image as well as expert knowledge. The separability of training areas was measured using both the Jeffries-Matusita and Transformed Divergence statistic and the maximum likelihood algorithm was used for classification. The resulting classified images for both Landsat and SPOT data were very similar in terms of the regional distribution of lithological classes, as reflected by fairly high classification accuracies for both imageries. Diabase and basalts, despite having a similar mineralogical composition are spectrally distinct throughout most of the study area especially on Landsat image. The Carbonates of Cambro-Ordovician succession were also successfully separated from carbonates of the Wynniatt Fm where the later was unconformably overlain by the former. Complicating spectral signatures of overlying glacial sediments and/or other overburden materials and spectral similarities between some of the lithologies caused poor classification in some areas. Generally the Landsat imagery provided better spectral separability between most of the lithological units than the SPOT imagery because of its higher spectral resolution. However, in certain areas where the spectral separation between different lithologies is not dependant on the SWIR channels, the SPOT imagery provided a better classification because of higher spatial resolution.

#### **VOLCANIC STRATIGRAPHY, CHEMOSTRATIGRAPHY, AND HYDROTHERMAL ALTERATION OF FELSIC VOLCANIC SEQUENCES OF THE MOUNT BRITAIN FORMATION THAT HOST THE RESTIGOUCHE VOLCANOGENIC MASSIVE SULFIDE DEPOSIT, BATHURST MINING CAMP, CANADA**

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The Restigouche deposit is a Zn-Pb-rich stratiform type VMS deposit hosted by Middle Ordovician felsic volcanic rocks of the Mount Britain Formation, in the Bathurst Mining Camp of New Brunswick, Canada. The Mount Britain Formation at the Restigouche deposit comprises 11 lithostratigraphic units of three volcanic cycles that are assigned to six chemostratigraphic units A, B, C, D, E, and F, based on their immobile-element lithogeochemistry. Sulfide mineralization was associated with the Cycle I volcanism that generated high temperature feldspar-phyrlic, dacitic-rhyolitic, lava flows that make up the footwall stratigraphy. Lithic-lapilli tuffs of Cycle II make up the hanging wall rocks for the Restigouche deposit and the predominantly explosive nature of volcanism associated with deposition of Cycle II rocks may have terminated the ore forming hydrothermal system.

Mass balance calculations show gain and loss of major-elements, such as Si, Fe, Mg, Ca, Na, and K, and trace-elements, such as Zn, Pb, Rb, Sr, Ba, La, and Ce. The litho-geochemical variations in the rocks are alteration-related and are controlled by distribution of sericite, Fe-Mg-chlorite, and pyrite. Three hydrothermal alteration zones are recognized. Zone 1 is an intense, proximal type sericite-Fe-chlorite-pyrite alteration and has a spatial and genetic association with pyrite-Fe-chlorite-quartz±chalcopyrite stockwork veins in the footwall rocks. Zone 2 is also deposit-related alteration with moderate to strong, distal sericite-quartz±Fe-Mg-chlorite-pyrite alteration in the immediate hanging wall and distal footwall rocks. Zone 3 is a distal seawater-related alteration with weak sericite-quartz alteration, in the upper parts of the hanging wall rocks.

## **EARLY DIAGENESIS OF PERIODIC PRECIPITATION OF PYRITE IN ANOXIC MARINE SEDIMENT**

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Pyrite formation is a key process linking several biogeochemical cycles involving sulphate content in sea water and transformation of iron in marine sediment during early diagenesis. The presence of pyrite aggregates is commonly associated with the existence of decaying organic matter in an anoxic environment. One such intriguing pyrite aggregate is observed in a sapropel sediment as a periodic precipitation pattern characterized by a spatial distribution of pyrite bands.

We study the formation of such "Liesegang" pyrite bands in aging sapropel sediments by means of early diagenetic reaction-transport modelling coupled with pyrite precipitation kinetics that incorporates nucleation, growth and ripening.

The model reproduces the essential features of the observed bands. The results show that the main factors controlling the formation of distinct precipitation bands, their number and distribution over the sediment layer are: availability of organic matter, sulfate, iron, bacteriological decomposition kinetics as well as pH.

The properties of pyrite formation depends critically on sediment history and such a model can be used to constraint the paleo-environmental deposit conditions.

## **BIOMONITORING FOR ENVIRONMENTAL LEAD EXPOSURE IN CHILDREN FROM PRE-1970s HOUSING IN ST. JOHN'S, NEWFOUNDLAND AND LABRADOR**

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Older residential neighbourhoods in St. John's, NL, have lead levels in soil and house dust above health-based guidelines, primarily related to the past use of leaded paint and coal-burning. Soil-lead levels are sufficiently high to warrant public health concern, especially for young children who are more sensitive to the health effects of lead. Previous studies in St. John's have established a relationship between higher residential lead levels and older housing stock and identified housing age categories where children are expected to be at risk of elevated blood lead levels (BLLs). In summer 2010, 250 children between 6 and 72 months old living in St. John's were recruited to participate in a cross-sectional biomonitoring study using BLLs to determine whether there is an increased exposure for children to residential lead in older potentially contaminated housing stock. Concurrent measurement of residential lead levels in the participants' homes permit a preliminary evaluation of possible exposure sources. The environmental dataset comprises of 1040 tap water samples, 417 soil samples, 2392 indoor dust samples, 345 indoor and outdoor paint samples, and 124 samples of home-grown garden produce. Our analyses specifically address whether there is a relationship between children's BLLs and the levels of environmental lead in St. John's and attempts to identify the potential sources and pathways of lead exposure in different aged housing stock. Information documented through a questionnaire survey will help interpret BLLs in households where correlation with measured lead exposure is weak. Our presentation will report preliminary findings.

## **SEISMIC DETECTION OF DEEP-SEATED VMS DEPOSITS: LESSONS FROM THE BATHURST MINING CAMP, NEW BRUNSWICK, CANADA**

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Geophysical exploration of volcanogenic massive sulfide (VMS) deposits has relied traditionally on non-seismic methods such as electromagnetic and potential field techniques. However, the increasing ambiguity of these methods with depth makes seismic reflection methods favorable for targeting deep-seated (>1000 m) VMS deposits. Here, we present seismic signature of a deep-seated VMS deposit from the Bathurst Mining Camp on surface 2D and 3D seismic data, and on three-component Vertical Seismic Profiling (VSP) data. Surface 2D and 3D seismic data from Halfmile Lake successfully allowed the detection of a hidden 6.5 Mt massive sulphide deposit at a depth of about 1200 m known as the Deep zone. The massive sulphide lens is located on the southern flank of an over-turned antiform also associated with smaller and shallower mineralized deposits. The Deep zone displays remarkable characteristics on surface 3D seismic data which include: (1) a large and asymmetric semicircular diffraction signature relative to the location of the Deep zone, indicating that the deposit does not lie at the center of the diffraction in time slices (2) amplitude variations along the diffraction, with the highest amplitudes occurring at the northern flank of the diffraction and (3) two zero-amplitude segments that might be an indication of phase reversal or an effect from the shape of the VMS deposit. Multi-component VSP data confirms presence of wave-mode converted seismic signal at the Deep zone, including P-P, P-S, S-P and S-S wave-modes. S-P and P-S images generated from a prestack migration of the surface 3D data also confirm mode-conversion processes at the Deep zone. We further present results from three 2D seismic profiles in the Brunswick No. 6 area, which image several sequences of reflective and transparent zones representing a series of faults juxtaposing various formations of the Brunswick Belt. A reflective package, related to the Brunswick horizon, the main ore bearing horizon in this camp, is also observed on all the three profiles down to 3 km depth. Two other sets of deep reflections imaged on all profiles in the 5-8 km depth range are interpreted as thrust sheets suggesting that the Brunswick belt may extend down to a maximum depth of 8 km.

## **THE METAL-SILICATE PARTITIONING OF Re AND Pt: CONSTRAINING Os ISOTOPE SYSTEMATICS IN THE UPPER MANTLE**

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We have conducted metal-silicate partitioning experiments for Re and Pt over a range of temperature, pressure,  $f_{O_2}$  and  $f_{S_2}$  with the aim of better understanding their behaviour during core formation and the resulting Re/Os and Pt/Os ratios in the primitive upper mantle (PUM).  $^{187}\text{Re}$  and  $^{190}\text{Pt}$  decay to  $^{187}\text{Os}$  and  $^{186}\text{Os}$  with half lives of ~42 and ~450 Byrs respectively. Measured  $^{187}\text{Os}/^{188}\text{Os}$  and  $^{186}\text{Os}/^{188}\text{Os}$  in mantle xenoliths reveals insignificant deviation from chondritic values and thus provides time-integrated evidence for a mantle which has evolved with chondritic Re/Os and Pt/Os ratios (Meisel et al., 2001, Brandon et al., 2006). The question remains however, as to whether the chondritic pattern of these highly siderophile elements (HSE) is the result of core-metal segregation at high temperature and pressure, or is instead the product of some post-core-formation process. This question may be answered if metal-silicate partition coefficients ( $D_{\text{met/sil}}$ ) of Re, Pt and Os at conditions relevant to core formation are known. Several obstacles have hindered the acquisition

of this data, most notably the formation of dispersed metal inclusions which make analyses of silicate run products hard to interpret. This obstacle has been overcome here through the addition of Au, which coats the HSE of interest, physically but not chemically isolating it from the silicate melt. This appears to suppress formation of metal inclusions in most cases, allowing straightforward analyses of silicate glasses by laser ablation inductively coupled mass spectrometry. Pt solubility may suffer a further complication involving the use of graphite capsules in high pressure experiments. Previous solubility experiments under carbon saturated conditions are seen to contain CO vesicles that are spatially associated with exsolved Pt-inclusions (Cottrell and Walker, 2006). This raises the possibility of Pt dissolution as carbide or carbonyl species and makes investigation of carbon as a means to enhance Pt solubility an important experimental goal. To assess the magnitude of any carbon effect, experiments have been conducted for both Re and Pt in which graphite capsules are substituted for an HSE+Fe alloy. Dmet/sil for Re obtained here and for Os from Brenan & McDonough (2009) predict chondrite normalised PUM abundances to be less than observed and suggest a Re/Os ratio following core formation of  $\sim 7$ , over 70 times the value required to reproduce measured mantle  $^{187}\text{Os}/^{188}\text{Os}$ . Experiments are ongoing, however, Re data thus far appear to preclude mantle HSE ratios being set solely by core formation at elevated temperature and pressure.

#### **PETROGRAPHY AND GEOCHRONOLOGY OF THE PELE MOUNTAIN QUARTZ-PEBBLE CONGLOMERATE URANIUM DEPOSIT, ELLIOT LAKE DISTRICT, CANADA**

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Uranium deposits older than about 2,200 Ma are generally hosted within quartz-pebble conglomerates and are a major source of uranium. Genesis of these deposits is controversial and genetic models for these include hydrothermal, detrital/placer and modified placer. Petrography of the uranium mineralogy from the Pele Mountain Quartz-Pebble Conglomerate uranium deposit of the Elliot Lake district, Canada shows the dominant uranium minerals are thorite ( $[\text{Th,U}]\text{SiO}_4$ ) and brannerite  $((\text{U,Ca,Ce})(\text{Ti,Fe})_2\text{O}_6)$ . Uranium-lead (U-Pb) and lead-lead (Pb-Pb) isotopic analyses of galena, thorite and brannerite were obtained using secondary ion mass spectrometry (SIMS). Galena has a Pb-Pb age of  $2659 \pm 27$  Ma, whereas thorite and brannerite have U-Pb ages of  $2467 \pm 2$  Ma and  $2243 \pm 2$  Ma, respectively. The Archaean age of galena represents the age of the source rock, which is most likely Archaean pegmatites or granites. The sub-rounded textures along with the U-Pb age of the thorite, which is older than the main conglomerate bed of the Matinenda Formation ( $\sim 2350$  Ma), suggests a detrital origin. The Pb-Pb ages of thorite range from  $2453 \pm 25$  Ma to  $1782 \pm 125$  Ma and can be attributed to Pb loss during the Blezardian and Penokean Orogenic events. The various ages of heavy minerals older than depositional age of the Matinenda formation indicates multiple sources for detritus. The brannerite, which replaces rutile, has a U-Pb age that is consistent with fluid events associated with the Blezardian Orogeny, and is likely of hydrothermal origin. Pb-Pb ages of brannerite are  $1325 \pm 106$  Ma and  $1013 \pm 61$  Ma and can be associated with Pb loss during the Grenvillian Orogeny. Thus, the Pele Mountain Quartz-Pebble Conglomerate uranium deposit is interpreted to be a modified placer-type deposit.

#### **COMPARATIVE PLANETOLOGY AND CANADA'S REQUIRED HUMAN CAPACITY**

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The more we learn about other planetary bodies, the more we learn about Earth and its history – and to fully understand the geological history and evolution of other planets in our Solar System, we need to understand Earth. This may seem obvious but when rover-geologists were sent to Mars, there were scientific surprises! Some of these discoveries have sent shock waves into our current scientific thinking that are so profound, they generate an abundance of questions tackled by planetary scientists worldwide ... but many of the questions have yet to be answered. We do occasionally answer some burning questions, but dozens of new ones are created every time, and some paradigm shifts simply cannot be addressed without great leaps in technology that can only happen here, on Earth. The Moon still holds secrets from Earth's past that have yet to be discovered. And so we live in an exciting new era of Planetary Sciences that offers tremendous opportunities to Canadian scientists and engineers in many fields of expertise, but also calls for greater collaboration, and for stable, vigorous R&D partnerships between academia, industry, and government.

In this talk, we will describe the challenges faced by the Canadian Space Agency in this new decade and beyond, as it seeks to train and maintain the highly-qualified workforce required to successfully meet the needs of space missions. The timelines involved with space missions (1-2 decades) do not adapt well to graduate student projects, and are difficult to design around them. The space-based and terrestrial industries also have important roles to play in qualifying science instruments and mission infrastructure for space flight. Government can, and should, be a full partner, encouraging the sharing of best practices at all levels, and playing a complementary role to all other Canadian stakeholders so that we, as a nation, can participate with our international partners in these major human and robotic endeavours.

#### **LITHOSPHERIC EVOLUTION OF CENTRAL NUNAVUT: TOWARDS A 4D SYNTHESIS**

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Effective exploration of the North requires understanding of lithospheric architecture integrated with models of its evolution. Here we interpret mantle SKS splitting and receiver function (RF) data for a large number of earthquakes in the light of evolving tectonic models for the Hudson Bay region as a step towards a 4-D synthesis of lithospheric evolution in this region.

Geological constraints and crustal deformation ages based primarily on in situ monazite geochronology suggest that assembly of the core of Laurentia initiated with microcontinent collisions (Hearne at 1.9 Ga, Meta Incognita/Sugluk at 1.87 Ga) on the southeastern flank of the Rae craton following north-dipping subduction. Outstanding questions are the location and nature of boundaries between these blocks in Hudson Bay as well as between intra-Rae domains with different economic potential.

Fourteen of sixteen teleseismic stations around Hudson Bay have fast SKS directions ( $260 \pm 20^\circ$ ) indistinguishable from the direction of recent plate motion. A second, northeast-oriented anisotropy is recorded by four stations in the north-central Rae and by stations on Southampton and Coats islands, indicating the latter are likely underlain by Rae mantle. However, recently published higher crustal seismic velocities on Coats Island versus Southampton Island and Rae crust in general suggest that Rae mantle is overthrust to the northwest by Meta Incognita/Sugluk crust.

A similar geometry, with Rae overthrust by Hearne, is obtained from a strong RF discontinuity (070/30°) above Rankin Inlet. This discontinuity projects northward to the Chesterfield fault zone, a northwest-vergent thrust that exhumed high-P rocks with 1.9 – 1.87 Ga cooling ages and is interpreted to have been driven by arrival of Meta Incognita/Sugluk microcontinent. Consistent SKS directions (50 ± 20°) along the southern flank of the Rae may have formed during this convergence or may outline a distinct Archean domain of the Rae; mantle geochronology is needed to resolve this question. More northerly trending anisotropy (010°), and southeast-striking RF structure in the northernmost Rae stations are interpreted to reflect accretion of isotopically distinct proto-Rae blocks across NW-striking boundaries prior to the pan-Rae 2.6 Ga magmatic event.

## SEQUESTRATION OF CO<sub>2</sub> BY CARBONATION OF STEEL SLAG

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Owing to the environmentally safe and stable nature of the reaction products, mineral carbonation (mainly of olivine) is the favoured approach to CO<sub>2</sub> sequestration. A mineral with similar sequestration potential to olivine is larnite (Ca<sub>2</sub>SiO<sub>4</sub>), one of the main constituents of slag resulting from steel production. As the steel industry accounts for ~6% of global CO<sub>2</sub> emissions, carbonation of this readily accessible material presents a great opportunity for the industry to reduce its carbon footprint.

This preliminary study investigates reactions taking place during the dissolution and carbonation of steel slag. Experiments were conducted on 2-3 mm diameter steel slag grains consisting of larnite (Ca<sub>2</sub>SiO<sub>4</sub>), calcium ferrite (Ca<sub>2</sub>Fe<sub>2</sub>O<sub>5</sub>), and Mg-wuestite ((Mg,Fe)O). A H<sub>2</sub>O-CO<sub>2</sub> fluid mixture (XCO<sub>2</sub> = 0.05) was pumped through a flow-through reactor containing these grains for 3 to 7 days. Temperature ranged from 120°C to 200°C, the pressure was 150 bar and the flow rate was 3.00 mL/min.

The fluid chemistry consistently involved initially high concentrations of Ca, reaching maxima between 1.59 and 2.25 mmol/L, and generally lower concentrations of Si, reaching maxima between 0.34 and 3.03 mmol/L. After attainment of a steady state, concentrations of Si approached or exceeded concentrations of Ca, with values between 0.13 and 0.28 mmol/L and between 0.01 and 0.05 mmol/L, respectively. Magnesium and iron concentrations were consistently low, never exceeding 0.09 mmol/L. The ranges in peak concentrations of Ca and Si are believed to reflect retrograde and prograde solubility of calcite and quartz, respectively.

The reacted steel slag grains have three distinct zones: a) the un-reacted core, composed of the slag-forming minerals; b) the reaction layer, which consists of Ca-carbonate and -phosphate phases that replaced the larnite grains during interaction with the CO<sub>2</sub>-bearing fluid; and c) the porous aluminum and iron oxide framework around the edge of the grain resulting from dissolution of the carbonate and phosphate phases. Mg-wuestite is present throughout the grains, indicating that it was inert during fluid-slag interaction.

These experimental results demonstrate the potential of steel slag to sequester CO<sub>2</sub>. Although previous studies (mainly on olivine) emphasize the necessity for small grain-size to ensure reaction completion (armouring of larger grains by silica and carbonation, inhibits further reaction), this study shows that comminution of the slag is unnecessary because dissolution of the calcium ferrite surrounding larnite crystals provides pathways for the fluid to react with the larnite. This finding highlights an im-

portant economic advantage of using steel slag as a carbonation material.

## EVIDENCE FOR MULTIPLE FLUID EVENTS IN THE PALEOPROTEROZOIC OTISH BASIN, QUEBEC: THE CAMIE RIVER UNCONFORMITY-RELATED URANIUM PROSPECT

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The Paleoproterozoic Otish Basin, Quebec, hosts several uranium prospects that were discovered in the 1970s and 1980s, but have since received little attention and remain under-explored. The Camie River U prospect is one such prospect that has been the focus of revitalized U exploration in the Otish Basin. In this study, the Camie River U prospect, which shows similar characteristics to high-grade unconformity-related U deposits, is the focus of a comprehensive basin analysis in the western Otish Basin.

Conglomerate and sandstone of the Indicator Formation, which were deposited in at least six depositional sequences, display a northeastward increase in the proportion of braid plain/delta deposits, and a southwestward increase in the proportion of braided channel and bar deposits. Strata were affected by insignificant early diagenetic compaction and cementation. This allowed the formation of regional peak diagenetic aquifers, which conducted fluids having δ<sup>18</sup>O and δ<sup>2</sup>H values similar to those of seawater-influenced basinal brines at 250°C.

U mineralization at Camie River occurred at 1721 ± 20 Ma based on a <sup>207</sup>Pb/<sup>206</sup>Pb date obtained by laser ablation of uraninite, which coincides with the ca. 1730 Ma Otish Gabbro intrusion. The intrusive event promoted circulation of U-bearing basinal brines, triggering U mineralization at several locations in the western Otish Basin.

Subsequent fluid alteration events occurred between ca. 1670 and 1410 Ma based on mineral paragenesis and <sup>40</sup>Ar/<sup>39</sup>Ar dates of muscovite. Metamorphic fluids having high δ<sup>18</sup>O values and temperatures around 300°C accompanied 1.2 – 1.0 Ga Grenville orogenesis and sub-greenschist-grade metamorphism in the Otish Basin, but were present at low water/rock ratios at Camie River and therefore produced little alteration. Post-Grenville uplift of the Otish Basin likely produced late, low-T alteration minerals that have been influenced by recent meteoric water.

Radiogenic Pb and the characteristic trace elements Mo + W + Nb have preferentially dispersed from the mineralization along fault zones, fractures, and depositional sequence boundaries, and can be used to explore for Camie River-style U mineralization. This study extends the unconformity-type U deposit model to basins as old as 2.0 Ga that are underlain by Archean metasedimentary basement rocks.

## ALONG AND ACROSS STRIKE VARIATIONS IN THE LATE TRIASSIC NICOLA ARC AND RELATIONSHIP TO ALKALIC PORPHYRY Cu-Au DEPOSITS, QUESNEL TERRANE, BRITISH COLUMBIA

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Most Alkaline porphyry Cu-Au deposits in British Columbia are hosted by the Late Triassic Nicola group and laterally equivalent Takla group of Quesnellia representing an oceanic arc assemblage (Nicola Arc) extending over 1300 km along strike. The Nicola Arc between Mount Milligan (55° Lat. N) and Copper Mountain (49°

30° Lat. N) is subject of this study. Here the arc assemblage is dominated by augite  $\pm$  plagioclase and analcime phyric basalts but can be subdivided into segments on the basis of subtle differences in physical properties, geochemistry and metallogeny.

Augite phyric basalts sampled in the Mount Polley and Lac La Hache area, where porphyry Cu-Au mineralization is considered broadly coeval with basaltic volcanic rocks, have magnetic susceptibilities from 20 to  $110 \times 10^{-3}$  SI,  $\text{Fe}^{2+}/\text{Fe}^{3+}$  ratios below 1.5 and contain magnetite inclusions in augite phenocrysts. In contrast, basalts from areas devoid of porphyry mineralization or where mineralization is  $>20$  Ma younger (e.g. Mount Milligan) have higher  $\text{Fe}^{2+}$  contents, an order of magnitude lower magnetic susceptibility and generally lack magnetite inclusions in augite phenocrysts. Geochemically, the difference between arc segments is subtle. Basalts around Mount Polley and Lac La Hache are slightly alkaline and are more sodic at given  $\text{SiO}_2$  than those from areas devoid of coeval mineralization. Mount Polley basalts have lower  $\text{Fe}_2\text{O}_3$  and MgO but higher  $\text{Al}_2\text{O}_3$ , and densities from 2.6 to 3 g/cm<sup>3</sup>, which are lower overall than for other areas (2.75 to 3.07 g/cm<sup>3</sup>). Carbon isotopes of secondary carbonates in basalts from Mount Polley range from  $\delta^{13}\text{C} = +1.7\text{‰}$  to  $-5.6\text{‰}$  (PDB) whereas in the other studied arc segments  $\delta^{13}\text{C}$  is  $<-6\text{‰}$ . The  $\delta^{18}\text{O}$  values of all analyzed carbonates vary between  $\sim 4$  and 21‰ (VSMOW) but most values from Mount Polley are higher than 15‰.

Magnetic susceptibility and  $\text{Fe}^{2+}/\text{Fe}^{3+}$  ratios indicate that arc segments hosting coeval alkalic porphyry Cu-Au mineralization are characterized by relatively oxidized and alkalic basalts. The negative  $\delta^{13}\text{C}$  values of the other studied areas may indicate a higher proportion of organic or magmatic derived C in the carbonates which contrasts the stable isotope composition of Mount Polley area basalts where the  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values are closer to those expected for marine carbonates. Thus, stable isotope signatures of secondary carbonate within marine basalts hosting mineralization at Mount Polley potentially indicate relatively oxidizing conditions and shallow water depth at the time of extrusion.

#### CHLORINE-36 AGE DETERMINATION FOR MYSTERY CREEK ROCK AVALANCHE, BRITISH COLUMBIA, CANADA

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The Sea to Sky Corridor has experienced hundreds of historic and prehistoric landslides. The most common types of historical landslides are rock falls and debris flows, which are relatively small in volume, but can be damaging. These types of failures are more common in the southern part of the corridor, between Horseshoe Bay and Porteau, where infrastructure has been built in close proximity to steep slopes. Farther north, fewer landslides have been reported historically, but those that have been recorded, are usually large and date to prehistoric time (e.g. Cheekye fan and Mystery Creek rock avalanche).

As part of a Geological Survey of Canada surficial geology and landslide inventory mapping study, Mystery Creek rock avalanche, near Whistler, British Columbia, was sampled for  $^{36}\text{Cl}$  dating. Samples were collected from three large flat boulders of quartz diorite in the rock avalanche deposit to confirm a correlation with the previously reported radiocarbon age of  $800 \pm 100$  years BP on charcoal. One sample revealed an age of 2400 years and the other two, 4300 and 4800 years, respectively. These new ages point to four possible interpretations: 1) Mystery Creek landslide is about 800 years old; 2) Based on the overlapping 2 sigma uncertainties, the rock avalanche took place between 2200 and

3600 yrs ago; 3) The rock avalanche deposit is 2400 years old and the other two blocks are too old; and 4) The rock avalanche is between 4300 and 4800 years old. We favour the second where the age range is broader and statistically significant for all three samples. Moreover, at this time, we favour discounting the radiocarbon age based on a greater number of samples analyzed for  $^{36}\text{Cl}$  analysis, which indicates an older age with the 2 sigma uncertainty. Thus, large landslides such as these remain a present-day hazard to infrastructure like the Sea to Sky Highway, the railway, and population.

#### DEVELOPMENT OF A MULTIDISCIPLINARY APPROACH TO UNDERSTAND THE GROUNDWATER FLOW SYSTEM OF THE SAINT-MATHIEU/BERRY ESKER, ABITIBI, QUÉBEC

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The last glaciation and ice retreat, which ended around 9 ka in Abitibi, left significant eskers consisting of glaciofluvial sand and gravel that are covered in part or totally by clay deposited in glacial Lake Ojibway. They represent aquifers supplying high quality groundwater to several municipalities and to a water bottling company. Despite the aquifer potential, uncertainties about the morphology of the underlying bedrock and the spatial distribution of the glaciolacustrine clay increase the challenge of getting an accurate understanding of the flow dynamics, which is needed by decision makers regarding economical and sustainable development of this water resource. One way to provide better understanding about groundwater resources is to develop a multidisciplinary characterisation approach to better understand these systems. With the integration of geological, geophysical, geochemical and hydrogeological methods, this project aims to develop an approach for the hydrogeological characterisation of aquifer systems associated with eskers. The aquifer of the Saint-Mathieu/Berry esker located near the city of Amos, which is exploited and has been initially characterized, is used as a natural hydrogeological laboratory for the development of the new approach. Well drilling is used to get geological and mineralogical information as well as installing piezometers to form three transects that were instrumented in 2010. These instrumented transects, which will be completed in 2011, will be used to follow groundwater evolution from the crest to the flank of the esker. Ground penetrating radar (GPR) will help to define the continuity of hydrostratigraphic units and water table between piezometers. Hydraulic parameters as hydraulic conductivity of the screened interval will be defined with slug tests. Concentrations of inorganic constituents,  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  in precipitation and groundwater, plus tritium/helium and  $^{14}\text{C}$  dating of groundwater, will be used to trace groundwater recharge and circulation as well as our understanding of flow dynamics and groundwater geochemistry evolution in the studied esker. This should allow the development of more realistic groundwater flow models that are important tools to quantitatively understand granular aquifers as eskers.

#### LINKING THE ORDOVICIAN L-CHONDRITE EVENT TO THE TERRESTRIAL CRATERING RECORD: A NORTH AMERICAN PERSPECTIVE

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Meteorite researchers have hypothesized that ca. 500 million years ago (Ma) a catastrophic breakup event took place in the asteroid



belt. This hypothesis received a major boost with the discovery of numerous L-chondrite meteorite fragments in limestone quarries in southern Sweden, preserved in situ across a section of Middle Ordovician stratigraphy (ca. 470 Ma). Several meteorite impact structures in Scandinavia have also been linked to this event, e.g., the 458 Ma Lockne crater in central Sweden.

With Earth moving through a dynamically evolving swarm of asteroid debris, the effects should have been global. Numerous, possibly large, impact craters should be linked to this event, particularly in North America with its large, stable, cratonic target area and a robust population of ~60 confirmed impact structures.

Here I specifically link the well-known Brent crater to this event, with a stratigraphically constrained age of 460-450 Ma and with a melt/breccia sheet that contains geochemical traces of an L-chondrite bolide. Among the ~32 confirmed and possible impact craters in Canada alone, there could be as many as 5-10 that are linked to the same broad event: Brent, Holleford, Skeleton Lake, Nicholson, Pilot Lake, Presqu'île, Couture, La Moinerie, and the large Slate Island structure in Lake Superior. Scattered and non-definitive K-Ar and Ar-Ar ages could extend this list to the very large Carswell structure, and perhaps the buried but unconfirmed Can-Am crater. Even if only the most likely subgroup of this list is indeed related to a ca. 470-440 Ma impact spike of L-chondrites, the proportion of impact craters linked to this event is very large (1 in 5?), as similarly suggested by the more limited sample of just the Swedish crater record alone.

A similar conclusion is reached for craters in the remainder of North America, where among ~30 confirmed craters the following could be linked to the same event: Ames, Calvin, Glasford, Glover Bluff, Newporte, Rock Elm and Versailles (again, a proportionally similar and very large subpopulation, as in Canada). Several of these structures have stratigraphically constrained ages in the 470-440 Ma interval.

It is concluded that the Ordovician L-chondrite event left a major imprint in the North American and global cratering record and, as recognized by Schmitz and coworkers, must have jarred the Earth system throughout much of the Middle and Late Ordovician. During this interval, the flux of large impactors must have been an order of magnitude higher than during the remainder of the Phanerozoic.

#### **THE OTTAWA-BONNECHERE GRABEN: A COMPLEX RIFT STRUCTURE SHAPED BY REACTIVATION**

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The Ottawa-Bonnechere Graben, first so named by Kay (1942), forms a marked, fault bounded, rift-like structure in eastern North America, extending from east of Montreal to Lake Nipissing and beyond. It has an overall WNW trend, at a high angle to reactivated Paleozoic rift structures such as the St. Lawrence rift system. In detail it has a more complex structural plan, consisting of left-stepping en échelon segments, with many major normal faults typically clockwise to the overall trend. This is particularly evident in the Ottawa area where the en échelon structure is highlighted by the zig-zag course of the Ottawa River and the sudden termination of the prominent basement horst of the Gatineau Hills. Some of the major faults (e.g. the Hazeldean) have a sigmoidal trace with maximum displacement on a central NW-trending segment, and displacement tapering off along strike in either direction.

The Lake Nipissing area presents perhaps the most complete "type section" of the rift structure, with 1) a ~30 km wide, normal fault-bounded valley, 2) exposures of major rift-parallel tholeiitic dykes ("Grenville swarm", ca. 590 Ma), 3) a subparallel, less widespread swarm of alkaline dykes (referred to here as the "Mat-

tawa dykes", perhaps ca. 580 Ma?), 4) central alkaline intrusions along the valley floor (nepheline syenites and carbonatites, ca. 577 Ma) that must have fed several alkaline volcanoes, and 5) numerous more localized and more irregular mafic and ultramafic lamprophyre dykes proximal to the central intrusions. Similarities to the modern East African Rift are striking.

Ages of magmatism, the overall trend of the graben, and the eastward convergence of the Grenville dyke swarm to a focal region east of Montreal (the Sutton plume?), support the model of a failed rift arm of latest Neoproterozoic age, related to a rift-rift-rift triple junction and opening of Iapetus ocean, as proposed in early papers by Kumarapeli, and Burke.

Yet, most of the obvious normal faults and the physiography of the graben are post-Ordovician in age, and if there was a Neoproterozoic graben structure, its suprastructure was removed by erosion and planed off prior to transgression of Ordovician platform sediments across the area. Hence Kay's original suggestion that the graben is a much younger structure. There are no Neoproterozoic rift basalts or alkaline volcanics, nor any rift clastics, preserved along the axis of the graben, and Grenville dykes are exposed at some depth below the paleosurface.

This argues for an elevated terrestrial graben (again similar to the East African rift) during the latest Neoproterozoic, major erosional levelling during the Cambrian, finally followed by (thermal?) subsidence and marine transgression in the Ordovician. Only afterwards did a major phase of extension and reactivation form the normal faults that now define the "graben".

#### **STUDY OF THE MATRICES OF PRISTINE TAGISH LAKE SPECIMENS USING TEM**

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Tagish Lake is an ungrouped Type 2 carbonaceous chondrite (CC) with affinities to CIs and CMs. In an effort to further characterize the Tagish Lake (TL) CC and understand its history, we expand on our previous efforts to understand the prominent macroscopic variations in pristine samples, investigating whether the macroscopic variations are mirrored at the sub-micron level in the matrix of each sample. Such observations can add an additional parameter in establishing an overall mineralogical framework for determination of the degrees of alteration of this meteorite.

We examined specimens 5b, 11i, and 11h, representing the range of macroscopic variation within the pristine TL suite. A total of four focused ion beam (FIB) sections were made from polished probe mounts: one each from 5b and 11h, and two from 11i (11i-1 is from the matrix and 11i-2 from a lithic clast). An FEI Nova 600 FIB-SEM at the Naval Research Laboratory was used to make electron-transparent cross-sections (~10 µm wide). All FIB sections were examined at NRL with a 200 keV JEOL 2200FS transmission electron microscope (TEM) equipped with an EDS spectrometer and scanning-TEM (STEM) based bright- and high-angle annular-dark-field detectors.

The mineralogy of the three matrix samples is similar. All contain phyllosilicates with various degrees of order, identified as mostly saponite and serpentine with sinuous textures and sometimes intermixed with amorphous material; large (up to 3 µm) carbonate grains; and minor olivines. Fe-Ni sulfides are present in all samples; however, their abundance and shapes varies. For example, the 5b matrix contains more rod-shaped sulfides than other samples, whereas 11h matrix has relatively large bands of sulfide enrichments. We also note two significant observations. The first is a prominent serpentine 'flower' texture in section 11i-2, which

could provide clues to the growth conditions (e.g. redox) of this mineral. The second observation is the apparent inverse relationship between porosity and phyllosilicate abundance. The lithic fragment from specimen 11i (section 11i-2), which is more compact than the rest of the matrix on both sub-micron and micron scales, is also composed entirely of phyllosilicates. This suggests that lithic fragments of 11i could have experienced higher degrees of aqueous alteration than the rest of the matrix.

#### LANDSLIDE SUSCEPTIBILITY MAP OF CANADA

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Within Natural Resources Canada (Geological Survey of Canada), one objective of the Public Safety Geoscience Program is the provision of broad, high level information that summarizes the likelihood of threat from a variety of natural hazards to Canada's citizens and infrastructure. Landslides are especially important. In Canada, during the past 150 years, more individuals have died from landslides than all other natural hazards combined. Moreover, landslides are estimated to cost (direct and indirect) the country over \$200 million (CDN) annually. Unfortunately, no publically available, pan-Canadian expression of the potential threat from landslides currently exists. In response to these facts and issues, the Geological Survey of Canada has now developed a national scale (1:5 million) landslide susceptibility map to illustrate the significant variability that exists across the country with respect to the likelihood of slope instability.

In the absence of a national inventory of landslides, information used in the derivation of this map (GIS based) consisted of national scale data for the following parameters: vegetation, precipitation, permafrost, aspect, slope angle, distance to rivers, distance to coast (lakes and oceans), bedrock geology and surficial geology. Attributes within each parameter were assessed and classified (semi-quantitatively) according to several categories of significance (1-low to 6-high). For the classification, expert opinion was obtained during a workshop at which GSC landslide experts relied on their personal experience and professional knowledge as input to the attribute and parameter relevance regarding landslide hazards.

The final map, to be released as a GSC Open File map, provides an excellent "first approximation" characterization of landslide susceptibility for the diverse terrain scattered across Canada using a hot to cold (red to green) legend to illustrate the threat. At this scale, the classification is most useful in demonstrating regional trends. Local and site specific assessments cannot be reliably extracted from such a national scale map and require more diligent study and interpretation on a case by case basis.

#### NEARLY TWO BILLION YEARS OF HEARNE CRATON HISTORY EXPOSED IN MANITOBA'S FAR NORTH

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New bedrock mapping in Manitoba north of 58° revealed evidence of a protracted and complex geological history, and provides a much improved understanding of the regional geological context for the largest remaining frontier area of Manitoba. Supported by U-Pb geochronology and regional airborne magnetic and radiometric survey data through the Geological Survey of Canada's Geomapping for Energy and Minerals (GEM) program, bedrock mapping by the Manitoba Geological Survey has established a de-

tailed new lithostratigraphy for the Precambrian rocks of the Seal River Domain at the southeast margin of the Hearne craton.

Mesoarchean basement rocks that include remnants of Paleoproterozoic (up to 3.5 Ga) material have been discovered in a discrete crustal block in the Seal River Domain. Emplacement of a voluminous felsic plutonic suite occurred during the ca. 2.70 and ca. 2.57-2.55 Ga Neoarchean Hearne orogenic pulses and coincides in time with bimodal volcanic rocks that overlie the oldest basement. The dominantly granitic plutonic rocks can be subdivided, based on age and trace-element lithogeochemistry, into distinct magmatic provinces; volcanic-arc derived granitoid rocks to the east are separated from within-plate granitoid rocks to the west by the central supracrustal belt in the Great Island area. Consequently, a potential paleotectonic scenario suggests older and thicker Hearne craton crust towards the southeast, which, combined with its abundant mafic dike swarms, renders the cratonic portion east of Great Island favourable for diamond exploration.

Of particular importance for regional tectonic correlations as well as mineral exploration is a new chronology of four sedimentary sequences, the oldest of which is now recognized to be a ca. 2.70 Ga conglomeratic siliciclastic sequence that was dominantly sourced from Paleo- and Mesoarchean crust and contains U-Au-REE mineralization of possible paleoplacer-type. This early sedimentary sequence unconformably overlies a Neoarchean greenstone belt with known Au occurrences. The latter is dominated by mafic volcanic rocks that may be remnants of a complex arc/back-arc volcanic terrane that accreted with the Hearne basement between 2.7 and 2.6 Ga.

Provenance profiles for at least three separate, overlying marginal marine to deep marine siliciclastic sequences provide distinct provenance maxima and Paleoproterozoic maximum depositional ages of ca. 2.50, 1.98 and 1.88 Ga, respectively. These data provide new constraints for regional stratigraphic correlations with better-studied and explored successions in Nunavut (Hurwitz Group) and Saskatchewan (Wollaston Group), and a substantially upgraded conceptual framework for mineral exploration in Manitoba's far north.

#### GEOLOGICAL, ASTROBIOLOGICAL, AND ROBOTIC CRITERIA FOR SITE SELECTION FOR A MARS METHANE ANALOGUE MISSION

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Through its Analogue Missions program, the Canadian Space Agency is funding the Mars Methane Analogue Mission which is designed to simulate as closely as possible a micro-rover mission whose goal would be to detect, analyse, and determine the source of methane emissions on the surface of Mars. Site selection for the mission was done according to strict geological, astrobiological, and robotic criteria including mineralogical similarities to high-interest Martian targets, high likelihood of methane production (biogenic or abiogenic), and ability to safely deploy a rover. Based on these criteria, the Jeffrey Mine, an open pit asbestos mine near Asbestos, Québec, Canada, was selected for the mission and a preliminary visit was conducted in November 2010. One scenario for the presence of methane on the Martian surface is production through the weathering of serpentinites. This process could occur when serpentine, which often contains ferrous iron, releases hydrogen from the oxidation of ferrous iron to ferric iron

due to weathering. The released hydrogen can then react with dissolved CO<sub>2</sub> to produce methane. The mine, which is located in the Appalachian ophiolites in southern Quebec, contains both serpentinite (chrysotile bearing) and magnesium carbonate which are both associated with areas of enhanced methane production on Mars. This makes the Jeffrey Mine an excellent site for the analogue mission.

#### **THE DUVAY GOLD PROJECT: MULTIPLE DEFORMATION STYLES CONTROLLING GOLD MINERALIZATION AT A WIDE RANGE OF SCALES (TRES-OR RESOURCES LTD-TRS)**

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Geologic structures repeat from very small to very large scales. Structure mapping at the Duvay Gold Project, northern Abitibi greenstone belt, Quebec, reveals that multiple deformation styles occur from outcrop scale of a few 10s of centimetres to the project scale (roughly 800 by 200 m).

The Duvay Gold Project is being evaluated for its potential to host an economic gold resource by Tres-Or Resources Ltd. Considerable stripping, pit tests, and drilling since the 1930s has demonstrated coarse gold occurs across the property. Multiple deformation events at Duvay began with a compressional shear zone striking more or less west-northwest with dextral motion. This shear zone strikes east-west (090) and east-southeast (120) across the project area and carries gold, disseminated sulphides and only a little quartz. Preliminary surface samples have returned 1.1 grams per tonne (g/t) gold (Au) over 30 cm and 1.2 g/t Au over 50 cm. The anastomosing shear zones at 090 and 120 form roughly almond-shaped blocks with extensive deformation at the borders, and significantly less deformation in the interiors.

The compressional shear event was followed by extensional quartz veins striking north-south, and inclined vertically. Kinematic indicators again appear dextral. The extensional quartz veins carry coarse sulphides, iron oxide minerals and locally tourmaline. The compressional shear zone and subsequent extensional quartz veins strike over 800 m across the Duvay Gold Project. The same compressional and extensional deformation can be seen in rocks at the outcrop scale.

In addition to the two deformation events described above, north-east faults cut the Duvay deformation zone. These faults are associated with low-angle quartz planes, some of which carry coarse sulphides and perhaps gold. The fault plane, in at least two cases, appears to dip southeast, and may have a thrust component. It is not yet clear when these northeast faults formed relative to the compressional and extensional deformation events.

Intersections of these three deformation trends are potential points of enhanced gold mineralization. Historical gold results from the 1940s to the 1990s support this potential, including 402 g/t over 0.36 m, 76.8 g/t over 0.46 m and 34.6 g/t over 0.46 m.

Similar orientations of deformation trends mapped at the Duvay Gold Project describe regionally important gold-bearing structures of the Quebec Abitibi Province, including the Porcupine-Destor fault and the Cadillac break. Like Duvay, the regional shear zones form roughly almond-shaped blocks with greater deformation at their edges, and lesser deformation in the interiors.

#### **ALKALI PORPHYRY Cu-Au-PGE, Ag-Sb AND U MINERALIZATION IN ALKALINE AND ALKALINE-MAFIC MAGMATIC PROVINCES OF EASTERN ASIA**

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The age of ores, alkaline and alkaline mafic magmatic complexes and the sequence of their formation have been studied in four large provinces: Verkhoyansk fold-thrust belt/Yakutia, Aldan shield, SE Altai and NW Mongolia, Northern and Central Vietnam.

Several age intervals of ores and magmatic rocks formation are determined using isotope-geochronological investigations (U-Pb SHRIMP and Ar/Ar dating):

- 1) Early Mesozoic, 250-230 Ma (SE Altai-NW Mongolia, Kontum/Central Vietnam);
- 2) Late Mesozoic, 146-126 Ma (Aldan shield); 146-127 Ma, 120-115 and 107-98 Ma (Verkhoyansk/ Yakutia); 117-115 Ma (Kontum/Vietnam);
- 3) Cenozoic, 40-22 Ma (Northern Vietnam).

Alkali porphyry Cu-Au-PGE deposits associated with differentiated alkaline ultramafic complexes are localized in the Central Aldan and NW Vietnam. In addition, fluorite-barite-REE carbonate, gold and Au-U mineralization occur in these provinces.

The Ag-Sb-base metal, gold and Au-U deposits are linked with alkaline mafic complexes differentiated to different extent (from lamprophyre to syenite, occurred as dike swarms, explosion pipes and stocks), at that Ag-Sb-base metal mineralization is localized only in carbonaceous terrigenous sediments (SE Altai-NW Mongolia, Verkhoyansk belt/Yakutia), while gold and Au-U deposits related to more differentiated alkaline series occur in metamorphosed rocks of different ages (Kontum/Vietnam, Eastern Aldan and SE Altai/Russia).

Genetic link of these type deposits with alkaline mafic complexes is proved by temporal correlation of their formation (U-Pb SHRIMP, Ar/Ar), He, Pb and Sr isotope composition, and presence of ore elements (Ag, Sb, U, Pb) in the composition of magmatic fluids from minerals of alkaline mafic rocks (LA-ICP-MS data).

#### **THE INTERPLAY BETWEEN SERPENTINIZATION AND HYDROTHERMAL ACTIVITY AT MID-ATLANTIC RIDGE (MAR): CONSTRAINTS FROM RAINBOW, LOGATCHEV AND ASHADZE FIELDS**

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A discovery of peridotite-hosted active hydrothermal sites at MAR between 12°58'N and 36°13'N has encouraged comprehensive studies of feedback between OCCs and hydrothermal vents. Data on isotope geochemistry and melting degree of peridotites infer petrologic and geochemical heterogeneity and short wavelength segmentation of MAR. Mineralogical and chemical compositions of serpentinites and primary compositions of peridotites and gabbros reflect differences in magma generation and serpentinization conditions. A kinetic-thermodynamic simulation shows that serpentinization occurs effectively at 130–150°C after ~4800 years of interaction with a fluid at 3.5–4.5 km depths. Fluid inclusion, lead, helium and sulfur isotope studies of minerals revealed the differences between these fields. Fluid temperatures and salinity range from high-temperature (up to 370°C) to low-temperature (down 110-170°C) and from 4 to 26 wt % NaCl-equiv., respectively. The fluid salinity is two- to five-fold higher than seawater

salinity. Lead isotopic ratios of OCCs-related sulfides cluster near the North hemisphere reference line, but are enriched in radiogenic lead relative to basalt-hosted sites. They are homogenous within an individual site but vary from site to site. Sulfur isotopic compositions in OCCs-related minerals are richer in a heavy isotope that infers a contribution of seawater derived sulfur. The R/Ra values in fluids capsulated in inclusions indicate a relative prevalence of mantle-derived helium and an involvement of a minor radiogenic isotope. Fluid-peridotite interaction leads to the formation of weak serpentinite and phyllosilicates that may facilitate fracturing and enhancement of the rock permeability. Faulting of the rigid and cold lithosphere produced thereby drain lower crustal magmatic chambers and triggers the emplacement of shallow-depth gabbros intrusions. This results in conditions favorable for the “startup” of a hydrothermal circulation system. The seawater-peridotite interaction leads to formation the high-temperature and saline fluids due to hydration reactions. A further fluid evolution occurs due to its interaction with uncooled gabbroids and the contribution of magmatic volatiles. The rapid migration of fluid to the ocean floor results in its phase separation and mixing with seawater in the discharge zone.

#### **DIFFERENT VIEWS, DIFFERENT PERSPECTIVES: UTILIZING THE ATHABASCA BASIN 3D MODEL TO GENERATE NEW (OR SUPPORT OLD) IDEAS**

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The Athabasca Basin in northern Saskatchewan and Alberta hosts the world's largest high-grade uranium deposits and continues to be a highly prospective area exemplified by recent discoveries such as the Phoenix trend, Roughrider zone and J-zone. Similar interests in uranium-related research and development as well as similarities between the Athabasca Basin and Cariewerloo Basin in South Australia resulted in a Memorandum of Understanding (MOU) between Primary Industry and Resources South Australia and the Saskatchewan Ministry of Energy and Resources. One component of this MOU was the development of a 3-dimensional model of the Athabasca Basin to be a tool for further understanding of the host rocks for the deposits and ore-system processes. Using mainly drillhole data as well as geophysical images, outcrop maps and topographic data, a preliminary model of the Athabasca Basin was created using Paradigm's™ GOCAD® software. The objects currently in the model include surfaces representing the unconformity at the base of the Athabasca Group, the base of the overburden, the base of several Athabasca Group formations and the digital elevation model. The model also contains a group of surfaces representing major faults which were interpreted from basement and surface linear features. Additional objects such as uranium deposits, drillhole traces, mine locations and quaternary geology have also been incorporated into the model. In 3-dimensions the data can be scrutinised from a variety of perspectives, which allows the viewer to critically analyse their geological ideas. As the model is advanced it will continue to be the framework upon which additional datasets, such as geophysics, geochemical analyses, hydrological data, can be superimposed. One example is plotting drillhole geochemical data in 3D space. Changes in elemental abundances both downhole and across the basin can then be modelled at appropriate cut-offs. Adding geophysical datasets to the model also advances our knowledge of structural controls and how they played a role in basin development and basin stratigraphy. These and other datasets will ultimately aid in our understanding of a variety of processes, including fluid dynamics,

movement of structures, geochemical anomalies and ore-related alteration systems. This model represents a template for others, with the recognition that investigation of ore systems in 3D space is a tool that can be applied to other camps and deposit types. The primary goal is to provide a vehicle in which the critical aspects of a mineral system can be investigated in a user-friendly environment.

#### **ARSENIC-BEARING PHASES IN A SOIL PROFILE LOCATED ON A GEOCHEMICAL ANOMALY (FRANCE): EVOLUTION AND CONTRIBUTION TO ARSENIC IN SURFACE WATERS**

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Runoff and weathering of As-rich soils can lead to widespread contamination of water. There is thus a need to define soil properties that affect most the contamination of water by arsenic, in order to integrate these parameters into environmental risk assessments. The objective of this study was to determine the impact of weathering of As-bearing phases on the As mobility in soils collected from a natural geochemical anomaly in the St-Yrieix-la-Perche gold mining district.

Arsenic behaviour was studied in a soil profile at the bulk and particle scales, and the potential As transfer from solid phases to waters was evaluated by monitoring dissolved As in soil solutions and runoff. The As-bearing phase characterization was performed using Scanning Electron Microscopy (SEM) associated with Electron Probe MicroAnalyses (EPMA) and micro-Raman spectroscopy. The studied small subwatershed was located in the St-Yrieix-la-Perche district, the second most productive gold mining site in France, characterized by a high grade As-geochemical anomaly.

Arsenic concentrations in the soil profile showed a decrease from 1500 mg.kg<sup>-1</sup> in the 135-165 cm deepest soil horizon to 385 mg.kg<sup>-1</sup> in the 0-5 cm superficial soil horizon, suggesting As depletion during pedogenesis. At the particle scale, mineralogical characterization showed an evolution of As-bearing phases in the soil profile from (i) arsenates (Ba-rich pharmacosiderite) containing 14 to 26 wt.% As in the deepest soil horizon to (ii) As-rich Fe-oxyhydroxides (ferrihydrite-like) with 4 to 16 wt.% As in layers deeper than 100 cm to (iii) Fe-oxyhydroxides with less than 3 wt.% As (ferrihydrite, hematite and goethite) in the intermediate and superficial soil horizons.

Dissolved As concentrations in soil solutions showed an increase from 15 µg.L<sup>-1</sup> in the deepest soil horizon to 52 µg.L<sup>-1</sup> in the superficial soil horizon. These results coupled with the evolution of As-bearing phases towards less and less concentrated carriers suggest that As mobilization was mineralogically controlled. The greater As release in surface soil could also be explained by the increase in organic matter and colloidal fraction which may favour the As mobility. Therefore, natural weathering of As-bearing phases had an impact on the As release and can contribute to the contamination of surface waters by arsenic, mainly from the superficial soil horizon and runoff.

## **A PRELIMINARY GEOCHEMICAL INVESTIGATION OF THE ROUGHRIDER UNCONFORMITY – TYPE URANIUM DEPOSIT, ATHABASCA BASIN, SASKATCHEWAN**

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Unconformity-type uranium deposits in the Athabasca basin are commonly hosted in either the Athabasca Group sandstones (typically polymetallic) or the underlying basement (typically monometallic). Hathon Exploration Limited's Roughrider Deposit, although basement-hosted, exhibits a number of features common to basement-hosted deposits and also displays some attributes typical of sandstone-hosted deposits. A systematic petrographic and geochemical study of the deposit is currently being carried out to investigate its mineralogical characteristics, which will be used to decipher the nature of the fluid system responsible for its hybrid-like properties.

Three dimensional modelling of the clay alteration pattern indicates that a vertically elongate, illite-dominant zone is extensive and pervasive, encompasses mineralization, cross-cuts the paleoweathering profile, and extends into the overlying sandstone; in contrast, hydrothermal chlorite alteration is only developed in basement rocks proximal to mineralization. Preliminary geochemical analysis yields a positive linear correlation for U-W and a nearly mutually-exclusive relationship for U-Zn and U-Co. Five positive trends are discernible in the U-Th bivariate plot, and two positive linear correlations are observed for Zr-Hf. Three dimensional modelling of Zn and U indicates uranium mineralization overlies and rarely encroaches upon the anomalous ( $>0.1\%$ ) Zn zone. Mass balance analysis (assuming Al immobility) of paired altered versus fresh quartz arenite and granite samples suggests uranium enrichment with alteration. Sandstone alteration implies Bi enrichment and Mn, Fe, Ag, Mo, and Sn depletion, whereas granite alteration infers enrichment of Ag, V, Cr, and Sn, and Zr depletion.

The alteration pattern revealed, to date, suggests a focussed, vertical fluid flow associated with mineralization, with additional lateral fluid supply. The positive correlation between U and W suggests a basement source for U, although a basin source cannot be ruled out if the original sedimentary lithologies varied significantly from their present day remnants. The nearly mutually exclusive relationships between U-Zn and U-Co may indicate multiple fluid flow and mineralizing events with different fluid sources. This interpretation is further supported by the multiple positive trend lines between U and Th. The mass balance analysis indicates that the association of elements enriched or depleted is different for the basin and basement rocks. Zirconium appears to be depleted in the alteration of both basin and basement rocks, which is consistent with the observation that Zr is relatively low in the mineralized zone. Overall, preliminary data suggest that the mineralizing fluid system at Roughrider was complex, with the involvement of multiple fluids from different sources.

## **PETROLOGY, MINERALOGY AND GEOCHEMISTRY OF THE BEATTIE SYENITE, PORCUPINE-DESTOR FAULT ZONE, ABITIBI SUBPROVINCE, QUÉBEC**

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The Beattie Syenite is composed of three lenticular bodies of syenitic rocks that occur immediately north of the Porcupine-Destor fault zone in the town of Duparquet, approximately 32 km north of Rouyn-Noranda. The principal body is 3.3 km long and

425 m in width and is flanked by two smaller lenses to the south and southeast. The intrusion has yielded zircon ages of  $2682 \pm 1$  Ma and  $2682.9 \pm 1.1$  Ma and hosts in part the Au-mineralization of the Beattie mine, a major producer in the area from 1933 to 1956 (9.66 Mt at 4.88 g/t Au). A total of 5 principal petrographic units are here defined on the basis of field relationships, petrography, mineralogy, and textures:

- 1) The unaltered syenite unit is composed of 2-10% of euhedral feldspar phenocrysts (2-10 mm) in a finer-grained matrix. This unit, is characterized by a low degree of postmagmatic alteration, has unaltered phenocrysts of amphibole and titanite and is the only unit with relicts of pyroxene.
- 2) The Beattie syenite porphyry unit is composed of 2-10% of tabular euhedral feldspar phenocrysts (2-10 mm) set in a red feldspathic and aphanitic matrix. This unit is crossed by multiple generations of fractures, is locally strongly cataclastic, and has been subjected to intense hydrothermal alteration.
- 3) The Central Duparquet syenite porphyry unit occurs principally in the southeast body. It contains 2-25% of coarse equant euhedral feldspar phenocrysts (5-16 mm) in a red or sometimes grey aphanitic matrix.
- 4) The megaporphyritic syenite unit occurs exclusively in the southeast body and is composed of very coarse alkali feldspar phenocrysts, 1-6 cm across, in a red aphanitic matrix. The texture is locally glomeroporphyritic. Field relationships suggest that the unit was emplaced shortly after the Central Duparquet syenite porphyry unit.
- 5) The feldspar lath dyke unit occurs as numerous thin dykes, on the order of a few meters in width, that cross-cut all other petrographic units. The lath dykes display a characteristic trachytoid texture defined by the preferential alignment of alkali feldspar laths (1-3 cm) in a grey or red aphanitic matrix.

Preliminary petrographic and mineralogical studies demonstrate a series of hydrothermal events including the precipitation of albite, sericite, chlorite and carbonate minerals. Additionally, the alteration was accompanied by precipitation of sulphide minerals and gold. Electron microprobe studies also reveal a complex compositional zoning in all porphyritic feldspars. Whole-rock normalized REE patterns suggest that all the petrographic units are comagmatic.

## **MESOZOIC FAULTING ALONG THE ST. LAURENT RIFT SYSTEM: CONSTRAINTS FROM COUPLING (U-Th/He) AND AFT THERMOCHRONOLOGY**

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The St. Lawrence Rift System is a NE-trending, seismically active zone extending for ~1000 km along the Saint Lawrence River valley. It forms a half-graben that links the Ottawa-Bonnechere and the Saguenay River grabens. It is made up of Late Proterozoic-Early Paleozoic supracrustal faults commonly located at the contact between the Grenvillian basement to the northwest and Paleozoic strata of the St. Lawrence Lowlands to the southeast. The lack of strata younger than the Ordovician makes however difficult to determine precisely when the faults reactivated after post-Ordovician times. There are sparse but significant isotopic evidences for Mesozoic reactivation of the rift system in the Quebec City and Charlevoix areas. Apatite fission tracks (AFT) and

(U-Th)/He thermochronology are adequate tools to recognize thermal events related to fault movement of the upper crust. AFT ages recently measured along the St. Lawrence rift system and the Saguenay River graben suggest syn- to post- Jurassic normal faulting at ca. 200 Ma followed by tectonic inversion at ca. 150 Ma. Here we present new data obtained on apatite separated from Grenvillian basement rocks from the hanging wall and footwall of the Montmorency and Saint-Laurent faults at three different locations along the St. Lawrence rift system: Sault-aux-Cochons, Cap-aux-Oies and Montmorency Falls. Apatite grains for (U-Th/He) analysis were obtained from five granitic to charnockitic gneisses and an amphibolite of the Grenville basement. Apatite grains were isolated by standard heavy liquid and magnetic separation techniques and then selected under optical microscope. Particular care was taken in order to isolate apatite free of mineral and fluid inclusions. SEM analyses showed that some inclusions are monazite, a supplementary source of He to be avoided. Six samples were selected and analyzed for their  $^4\text{He}$  content using a static noble gas mass spectrometer in CRPG-Nancy and duplicated using a quadrupole mass spectrometer at GEOTOP-UQAM. U and Th contents were analyzed by ICP-MS at CRPG-Nancy. Preliminary results of U/Th/He analysis yield an age of  $137 \pm 12$  Ma for the hanging wall of St. Laurent fault and  $118 \pm 10$  Ma for a sample from the footwall, whereas AFT age data are older at  $149 \pm 16$  Ma and  $196 \pm 19$  Ma for the hanging wall and the footwall, respectively. These preliminary U/Th/He results are consistent with AFT ages of the area (i.e. as expected, U/Th/He ages are younger than AFT ages) but do not provide yet new constraints for the structural evolution of the St. Lawrence rift system.

#### **THE IMPORTANCE OF COLLABORATION TO PRESERVE HISTORICAL GEOLOGY COLLECTIONS: THE BRALORNE GOLD COLLECTION AS AN EXAMPLE**

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Mining operations provide a rare opportunity to view geology in an unobstructed way that is not naturally possible. The limited lifespan of mines means that the window of opportunity for building reference collections is limited and often an afterthought. As a cultural institution devoted to the preservation of geoscience resources it is our responsibility to convey the importance of collections to outside audiences and to create opportunities to build and acquire these collections. Historical geological collections are one of the strengths of the Royal Alberta Museum, home to a number of prominent collections including the Bralorne Gold Collection. This collection includes stunning gold specimens and is the largest collection of gold and related historical documentation from the Bralorne Mine, which operated from 1932-1971. The Bralorne Mine was the largest of a series of underground mesothermal gold mines in the Bridge River Valley that collectively produced 4 178 363 ounces of gold and is British Columbia's largest lode gold operation to date. The first report of placer operations in the area occurred in 1858 during the Fraser River Gold Rush. The first quartz claims were not staked until 1896 and sporadic attempts at mining were short-lived. A stable mine operation was finally brought in to production in the early 1930s and by 1933 a community of over 3000 blossomed. The Bridge River Valley mines proved to be a critical industry to the western Canadian economy at a time when the rest of North America was suffering through the Great Depression. The Bralorne Mine operated until 1971 but closed due to a number of factors, including the low price of gold and difficult mining conditions. Like so many mining towns, most of the residents left and buildings were dismantled or

fell into disrepair. The limited number of photographs, documents and geological specimens are the last record of this important period in Western Canadian History and is fortunately preserved in a few public collections in Canada. Periods of economic restraint can cause government financial priorities to shift away from cultural heritage initiatives. In times like these it is more important than ever to collaborate between government institutions and industry to ensure that the preservation of important geologic and historic resources continues. The Bralorne Collection at the Royal Alberta Museum is one example of how collaboration between public and private institutions succeeded to ensure the preservation of geoscience heritage.

#### **PALEOENVIRONMENTAL RECORD OF SUBMERGED SHORELINES AND COASTAL ENVIRONMENTS AT LIMAN TEPE, TURKEY**

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Changing Holocene sea levels significantly altered coastal environments worldwide and had a major influence on the settlement patterns of prehistoric peoples. At Liman Tepe, a long-occupied prehistoric coastal settlement in western Turkey, the configurations of submerged mid-Holocene (ca. 5-6 Ka) coastlines were investigated to guide the search for underwater Neolithic archaeological sites. Shoreline features were mapped on the shallow shelf area (4 km<sup>2</sup>) using a single-beam (200 kHz) echosounder and chirp (18-24 kHz) sub-bottom seismic profiler. More than 700-line km of bathymetric data were acquired and processed to a detailed digital bathymetric model (DBM). Changes in sea level and the coastal paleoenvironments were determined by detailed sedimentologic (lithofacies, grain size, magnetic susceptibility) and micropaleontologic analyses of marine sediment from 5 percussion cores (up to 4.7 m length).

The DBM shows a number of relict shoreline features and incised river channels (wadis) that extend into water depths of 8-10 m (b.s.l.). The most prominent paleoshoreline is marked by a major break in the slope in water depths of 10-12 m (b.s.l.). The sediment cores revealed a sequence of poorly-sorted pebbly shoreface deposits containing abundant shell and coralline fragments (Unit E shell hash) overlain by marine muds and silts (Units D-B) deposited in low-energy shallow marine and lagoonal/wetland environments. The contact between the pebbly sands and mud sequence is represented in seismic profiles by a high amplitude reflection that is continuous basin-wide. The reflector surface (top of Unit E) shows a number of northwest-trending ridges and terrace features that are interpreted as buried paleoshorelines.  $^{14}\text{C}$  dating of shell materials from uppermost buried beach ridge yielded a Late Neolithic age of  $3860 \pm 120$  cal BC. The laminated mud sequence (Unit C, D) overlying the beach deposits records the development of a shallow back-barrier lagoon. The lagoonal sediments transition at 60-80 cm to sandy, organic-rich muds containing abundant organic fragments (Unit D). Organic materials from just below Unit D yielded a  $^{14}\text{C}$  date of  $450 \pm 70$  cal BC. The transition is interpreted as the onset of construction of the Alexander causeway (ca. 334 BC) connecting the mainland with Karantina Island. Following the causeway construction the shoreline on the east side of the island prograded rapidly covering older barrier/lagoonal sequences with a >1 m mud drape (Unit B). The reconstructed sea level curve shows that levels at Liman Tepe during the Late Neolithic were up to 2-3 m lower than predicted by regional glacio-hydro-isostatic models, indicating the importance of local tectonic effects (i.e. basin subsidence) in the Bay of Izmir.

## **OVERVIEW OF 2008-2010 EXPLORATION PROGRAM MOUNT PLEASANT PROPERTY, SOUTHWESTERN NEW BRUNSWICK: GEOCHEMISTRY, MINERALOGY, AND DEPOSIT MODELING OF Sn-In-Zn-Cu AND WO<sub>3</sub>- MoS<sub>2</sub>-Bi ZONES**

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During 2008-2010, the Mount Pleasant Mine Property owned by Adex Mining Inc. underwent a series of exploration and deposit appraisal programs comprising extensive diamond drilling plus the additional re-sampling of material stored on-site from previous drill programs on the property. In addition, samples of the multi-metal porphyry mineralization from different zones on the property were chosen for quantitative mineralogical characterization.

The geochemical analyses generated from this program were compiled and incorporated into a computer database with the purpose of generating regulatory compliant physical deposit models and resource estimates of the mineralized bodies for both the Sn-In-Zn-Cu and WO<sub>3</sub>-MoS<sub>2</sub>-Bi zones on the property.

In this presentation, Adex Mining discusses the results of the program and its context with respect to better understanding and integrating the geochemical and mineralogical variations within and among the zones. The purpose is to update and improve the evolving economic geology model of the polymetallic mineralization hosted on the property.

## **U-Pb DETRITAL ZIRCON DATA FROM THE LATE PALAEOZOIC PULO DO LOBO AND SOUTH PORTUGUESE ZONES, SOUTHERN IBERIA: IMPLICATIONS ON THE EVOLUTION OF THE NORTHERN APPALACHIANS**

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The Devonian Pulo do Lobo Zone (PDLZ), which outcrops immediately north of the allochthonous South Portuguese Zone (SPZ) in Southern Iberia, is classically interpreted as a polydeformed accretionary complex developed along the southern margin of the Gondwanan para-autochthon (Ossa Morena Zone, OMZ), during the late Paleozoic closure of the Rheic Ocean. This closure was a major event during the development of the Variscan orogen and the amalgamation of Pangea. U/Pb laser ablation inductively coupled mass spectrometry (LA-ICPMS) analysis of detrital zircons from Late Paleozoic Devonian-Carboniferous clastic units in the SPZ and PDLZ yield contrasting populations and attest to the exotic nature of both zones.

A sample from the middle late Devonian continental clastic strata of the SPZ yields detrital zircon ages dominated by Neoproterozoic and Paleoproterozoic zircons. These data together with other geological data are consistent with late Paleozoic detrital zircon populations derived from the peri-Gondwanan Meguma terrane, which lay along the southern flank of Laurussia at that time. In contrast, olistostromal quartzite clasts and matrix from the polydeformed PDLZ both have an abundance of Mesoproterozoic zircons. PDLZ polydeformed samples also lack the Neoproterozoic and Paleoproterozoic zircons that are typical of late Paleozoic sedimentary rocks derived from either Gondwana (OMZ), peri-Gondwanan terranes (e.g. Meguma terrane).

The polydeformed PDLZ metasediments are consistent with derivation from Baltica, Laurentia or recycled early Silurian deposits along the Laurentian margin which themselves were derived from either a Baltica or Laurentia source. An example of one such deposit that could yield the appropriate zircon populations is the Southern Uplands terrane (SUT) of the British Caledonides. This terrane is an early Silurian accretionary complex developed along the Laurentian margin during the closure of the Iapetus Ocean and

was located well inboard of the Rheic Ocean suture at the time of Laurussia-Gondwana collision. Taken together, our data can be reconciled by a model involving tectonic transport of a crustal fragment that was laterally equivalent to the SUT between the allochthonous SPZ and the Gondwana paraautochthon as a result of an early Devonian collision between an Iberian indenter (Gondwana) with Laurussia.

## **FERRIC IRON CONTROL ON THE PARTITIONING OF Ru, Rh, Ir, Pt AND Pd BETWEEN CHROMITE AND SILICATE MELT**

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Partitioning experiments were done to assess the role of chromium-rich spinel in controlling the behaviour of the platinum group elements (PGEs) during igneous differentiation. Spinel were equilibrated with natural and synthetic iron-bearing basalt at 1 bar and 2 GPa at 1400-1900°C over an  $f_{O_2}$  range of IW+1.6 to IW+7.

Results from relatively reduced, graphite-encapsulated experiments done at 2 GPa indicate that Ru is compatible in Cr-spinel (mineral/melt partition coefficient,  $D$ , of approx. 4), followed by Rh and Ir, which are moderately incompatible ( $D$  range of 0.03 to 1), with Pt and Pd the most incompatible ( $D < 0.03$ ). Partition coefficients for Ir, Ru and Rh measured at more oxidizing conditions in this and previous studies are 10 to 1000 times higher than results from experiments using graphite capsules.

We account for the variation in spinel-melt partitioning with a model which considers both the affinity of the PGE cation for a particular spinel lattice site, and the change in site occupancy accompanying the increase in ferric iron component with  $f_{O_2}$ . Assuming that Ir and Rh are present as divalent species, with a strong affinity for VI-fold coordination,  $D_{Ir}$  and  $D_{Rh}$  are predicted to rise rapidly with the ferric iron component, explaining the large  $D$ -values for magnetite-rich spinels. Model results indicate that  $D_{Ir} < 20$  and  $D_{Rh}$  are  $< 100$  for ferric-iron poor, Cr-rich compositions, as would crystallize in komatiites, some layered intrusions, and ophiolites. The overall compatibility of Ru for chromite is consistent with the predominance of  $Ru^{3+}$  at experiment conditions and the similarity in the size of  $Ru^{3+}$  to  $Cr^{3+}$  and  $Fe^{3+}$ . The increase in  $D$  for Ru with the ferric iron content of the spinel likely involves a strong effect of mineral composition superimposed on a change in melt speciation ( $Ru^{3+}$  to  $Ru^{2+}$ ) with  $f_{O_2}$ . The effect of mineral composition is a consequence of the difference in octahedral site preference energy (OSPE) between  $Ru^{3+}$ ,  $Fe^{2+}$  and  $Cr^{3+}$ , with partitioning larger into  $Fe^{3+}$ -rich compositions because of the enhanced reduction in energy gained by the  $Ru^{3+}$  substitution. Ru partition coefficients for ferric-iron poor spinel are expected to be approx. 30, which is somewhat lower ( $3\times$ ) than values estimated from in situ analyses of natural chromites.

The ferric iron content of chromite exerts a strong control on the partitioning of some PGEs which should be taken into account in both future experimental work and in models of igneous differentiation.



## **CHARACTERIZING THE QUATERNARY HYDROSTRATIGRAPHY OF BURIED VALLEYS USING MULTI-PARAMETER BOREHOLE GEOPHYSICS, GEORGETOWN, ONTARIO**

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Thick Quaternary deposits are exploited widely in southern Ontario for groundwater but their stratigraphic complexity can present a challenge for groundwater exploration. In 2009, Halton Region and McMaster University initiated a regional investigation of the geology and hydrostratigraphy of Quaternary sediments near Georgetown, Ontario to assist the search for new high yield aquifers. The project involved drilling of new continuously cored boreholes (> 40) and surface and downhole geophysical investigations to characterize the infill stratigraphy of the Middle Sixteen Mile Creek (MSMC) and Cedarvale (CV) buried valley systems. Multi-parameter log suites (natural gamma, EM conductivity, resistivity, magnetic susceptibility, full-waveform sonic, caliper) were acquired in 30 new and 8 existing test wells (16 m to 55 m depth) to assist in subsurface correlation and the identification of potential aquifer and aquitard units. Characteristic log responses (electrofacies) were identified by cross-plotting of log parameters and correlated with core lithofacies.

In the MSCM buried valley 7 distinctive lithostratigraphic units were identified within a thick (>55 m) interbedded sequence of diamict (aquitards), laminated silts and coarse-grained glaciofluvial deposits (aquifers) overlying shale bedrock. Gamma, magnetic susceptibility, resistivity and conductivity logs were most useful for lithologic typing. Downhole changes in p-wave velocity and resistivity were also important for discriminating and correlating more compact diamict units. In a number of locations the lowermost diamict unit was thinned or erosionally truncated, allowing direct communication of the upper and lower aquifers. The infill stratigraphy of the CV valley comprised a complex succession of glaciofluvial sand and gravel up to 45 m thick. The CV sediments truncate the older MSCM stratigraphy across a well-defined erosional unconformity and were deposited in a sediment-hosted valley.

The results demonstrate that the Quaternary sediments below Georgetown are complex and characterized by significant lateral and vertical sedimentary variability. The geophysical log responses of a number of hydrostratigraphic units were distinctive and provided useful subsurface marker horizons for correlation of the Quaternary deposits in areas where core data are unavailable. Electrofacies in the MSCM buried bedrock valley were generally predictable, whereas the sediment-hosted CV valley was more complex and variable. The differences in the two valley systems can be attributed to their contrasting depositional environments.

## **CHARACTERIZATION OF THE ONAPING INTRUSION IN THE VICINITY OF JOE LAKE, SUDBURY, ONTARIO**

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The Onaping Formation is 1.4-1.6 km thick and lies stratigraphically above the Sudbury Igneous Complex (SIC). It is composed of a complex series of breccias (the Garson, Sandcherry and Dowl- ing members) and more minor igneous-textured rocks (the Onaping Intrusion). First investigations of the Onaping Formation led to interpretations as to it being a pyroclastic accumulation. Subsequently, the discovery of shock metamorphic effects in basement lithic inclusions within the Onaping Formation led to its interpretation as an impact-generated fallback breccia. More recently, it

has been suggested that the Onaping Formation originated not only via impact, but also involved the interaction of seawater with the underlying impact melt. Recent petrographic work has identified partially annealed, decorated planar deformation features (PDFs) within individual quartz in mineral and lithic clasts in both the Sandcherry and the Onaping Intrusion.

The Onaping Intrusion occupies approximately 50% of the contact between the Onaping Formation and the underlying Sudbury Igneous Complex (SIC) and also occurs as discordant intrusive bodies within the Onaping Formation. Field sampling and subsequent analyses, including; optical microscopy, scanning electron microscopy and geochemistry have been aimed at characterizing the Onaping Intrusion in the vicinity of Joe Lake in the North Range of the SIC. The matrix of samples from the Onaping Intrusion demonstrate an evident igneous texture. Mineral grain size of the matrix increases from the top of the Onaping Intrusion down towards the upper contact of the Granophyre of the SIC. The opposite trend is seen for clast content, which decreases from the top of the Onaping Intrusion to the upper contact of the SIC. Quartz clasts in the Onaping Intrusion typically have reaction rims, heavily concentrated in pyroxene, epidote and chlorite. Reaction rims may be indicative of partial assimilation by the matrix of the Onaping Intrusion.

By definition, an impact melt rock demonstrates an igneous texture and contains clasts of target rock, some of which have evidence of shock metamorphism. Thus far, the presence of an igneous texture, decorated PDFs in quartz grains and variable clast content provide evidence that the Onaping Intrusion is, in fact, an impact melt rock, by definition. Studies are continuing to characterize the Onaping Intrusion and determine its possible genetic relationship to the main coherent impact melt sheet (the SIC) at Sudbury.

## **THE CHRONOLOGY OF PREHISTORIC EARTH FLOWS WITHIN BRECKENRIDGE VALLEY, QUEBEC: A CONTRIBUTION TO ASSESSING HAZARDS IN THE OTTAWA VALLEY**

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Breckenridge Creek is a small tributary of the Ottawa River that drains about 66 km<sup>2</sup> and is located approximately 14 km northwest of Aylmer, Gatineau, Quebec. Twenty-six prehistoric earth flow scars are clustered along the creek and its tributaries within an area of about 11 km<sup>2</sup>. This portion of the stream network is incised up to 30 m within a quasi-flat plain composed of fine-grained Champlain Sea sediments. The scars are up to 252 000 m<sup>2</sup> in surface area, exhibit retrogression distances of up to 920 m, and are the product of either spreading or flowing. The local Champlain Sea sediments are 'quick' with local sensitivities reported to be in excess of 100. Geophysical data reveal that the landslide scars are situated over top of a buried bedrock valley filled with up to 90 m of soft sediment. The ages of the failures were determined using organic materials collected from spoil exposed in the scarps of modern failures and slumps, as well as along stream courses. At scars where spoil was not exposed or exposure(s) were barren of buried organic materials, wetlands situated between micro-ridges on the scar surfaces, and assumed to have formed on the post-earth flow topography, were cored to obtain minimum age(s) for these failures. Datable materials were collected from 11 of the 18 scars investigated. Radiocarbon analyses reveal that the ages of the failures span the past about 7000 yr BP (7800-7900 cal BP). Spoil from one event, aged about 1100 yr BP (1000-1100 cal BP), flowed down Breckenridge Creek valley, probably reaching the

Ottawa River. The ages of the Breckenridge earth flows are compared to those of landslides and disturbed terrain associated with paleoseismic events in the Bourget-Lefavre area, about 60 km east of Ottawa.

#### **GEOCHEMICALLY REQUIRED CORRECTIONS OF THE BASIN-SCALE GENETIC MODEL FOR LOW-TEMPERATURE SEDIMENT-HOSTED STRATIFORM COPPER DEPOSITS**

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Since the initial definition of the modern genetic model for low-temperature sediment-hosted stratiform copper (SSC) mineralization about 4 decades ago, it has been assumed, largely from sulfide replacement textures and the zoning of sulphides, that copper entered the host greybeds from underlying intracontinental rift redbeds and that the hematitic nature of the footwall redbeds assured that Eh conditions within the pore solution of the coarse-grained redbed aquifer were sufficiently oxidizing in a low-temperature brine at near neutral pHs (approx.  $+0.1 \pm 0.1$  v) for the transport of copper as chloride complexes into the basal graybeds. However, the hematitic pigment of typical rift redbeds is itself a product of diagenetic ore-stage oxidation and would not have been previously present in the footwall to have provided the oxidizing conditions necessary for a significant copper solubility. Furthermore, buffering by the abundant ferrous mineral constituents of the footwall aquifer would establish reducing Eh levels in the pore solution equivalent to the stability boundaries between ferrous silicates and hematite (approx.  $-0.2$  v), at which level copper is not significantly soluble.

The only plausible means of mobilizing copper in a low-temperature brine requires a long-term influx of initially oxygen-rich water (e.g. downward circulating meteoric water) which becomes progressively depleted in oxygen by oxidation of ferrous minerals within its aquifer, the coarse-grained footwall sediment in the case of the SSC model. That oxidation process produces the hematitic pigment of the redbeds, and trace amounts of copper are simultaneously released by progressive diagenetic alteration of common labile mineral constituents of the aquifer. If the meteoric pore water had previously assimilated evaporitic salts, the evolved water should be capable of taking up and transporting those trace amounts of copper at moderately oxidizing Ehs attained by progressive oxygen depletion. It is significant that, even upon circulating into redbeds, any other deep basin brine which had previously equilibrated with surrounding ferrous minerals should not attain Eh levels above the fields of ever-present ferrous silicate or oxides in the footwall sediment and would therefore remain too reduced to carry significant amounts of copper.

#### **STRATIGRAPHY, MINERALOGY, AND GEOCHEMISTRY OF THE 1806 ZONE, RAMBLER, BAIE VERTE PENINSULA, NW NEWFOUNDLAND, CANADA**

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The early Ordovician Ming Mine within the Rambler Mining Camp is hosted within the Notre Dame Subzone of the Dunnage Zone in the Newfoundland Appalachians. The bimodal-mafic Ming Cu-Au-(Zn-Ag) volcanogenic massive sulfide (VMS) deposit consists of numerous different zones, including the precious metal-enriched 1806 zone ( $\sim 487,000$  t @  $0.64\%$  Cu,  $1.01\%$  Zn,  $3.40$  g/t Au, and  $22.31$  g/t Ag). Field studies of the 1806 zone illustrate that it is hosted primarily by a footwall of variably altered

ryholitic flows, tuff, and volcanoclastic rocks, and a hanging wall consisting of turbiditic rocks of mixed provenance, all of which are cut by numerous generations of mafic dykes. The footwall rocks contain variable sericite-quartz-green mica alteration, often with intense silicification occurring near the sulfide-hanging wall contact. The mineralization is hosted within the felsic volcanic rocks and consists of sulfide stringer, semi-massive and massive sulfide lenses. The sulfides are dominated by pyrite, chalcopyrite, sphalerite and metamorphic pyrrhotite, with lesser galena, arsenopyrite, tetrahedrite, and gold. Ore microscopy and scanning electron microscopy (SEM) reveal a complex sulfide mineralogy including argentotetrahedrite, tennantite, acanthite, tetradymite, boulangerite, stannite, cassiterite, electrum, and unidentified phases containing Ag, Hg, In, Ni, and Sb. Electrum has variable grain size ranging from mm to sub- $\mu$ m and occurs (1) with chalcopyrite, on pyrite margins; (2) along pyrite or arsenopyrite grain boundaries; (3) along veinlets in pyrite and arsenopyrite; (4) as inclusions in pyrite and arsenopyrite; (5) with chalcopyrite – arsenopyrite – sphalerite  $\pm$  galena in tetrahedrite as sub- $\mu$ m grains; and (6) in quartz with or without chalcopyrite, arsenopyrite, tetrahedrite and pyrrhotite. The strong association of Au with a complex sulfide mineral assemblage of sulfosalts, arsenides, and tellurides, and with Ag-Hg-As-Sb-Sn-In elemental associations strongly favors a synvolcanic origin with a magmatic contribution to the hydrothermal ore fluid for the Au in the 1806 Zone and Ming VMS deposit. Following VMS formation, gold was remobilized and upgraded during later deformation and greenschist grade metamorphism.

#### **EXPLORING FOR DEEP BEDROCK GROUNDWATERS ALONG THE NIAGARA ESCARPMENT CUESTA OF SOUTHERN ONTARIO**

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Results presented are part of a five-year study to map the Early Silurian sequence stratigraphy and bedrock aquifers of Niagara Escarpment region of southern Ontario. Hundreds of deep boreholes, including more than 60 PQ- and HQ-cored holes, and numerous key outcrops have been examined, spanning the upper Cabot Head Formation to base of Salina Group. The time duration of rock strata spans the late Llandovery through Wenlock with many discrete time breaks represented within a predictable sequence stratigraphic framework.

This project is the first attempt by the OGS to systematically delineate discrete bedrock aquifers and aquitards within Silurian carbonate strata along the Niagara Escarpment cuesta of southern Ontario (Niagara Falls to Manitoulin and Cockburn islands). The foundation of such studies is the development of a robust and testable sequence stratigraphic and structural framework that integrates vertical and lateral changes in the physical and hydraulic character of the sedimentary rocks. Detailed chemostratigraphic and lithogeochemical analyses of the strata (carbon, oxygen and selective strontium isotopes, whole-rock and trace-element geochemistry on a 30 cm to metre scale) is being integrated with the hydrochemistry of water-bearing rock units in order to define discrete hydrogeologic units (HGUs) and make inferences regarding local and subregional aquitards. Several methods of discrete, single-hole hydraulic testing have also been conducted at key locations across the study area to estimate local physical hydraulic properties and further characterize HGUs. Multi-level monitoring well installations have been completed across the study area and

seasonal discrete hydrochemistry data and hydraulic head profiles will be integrated into the bedrock aquifer mapping process.

The field-based methodologies developed during this five-year project will be applied to other regions of Ontario in order to develop regional bedrock aquifer maps for all Paleozoic sedimentary strata. These maps, coupled with an improved regional-scale bedrock aquifer characterization, will allow for improved management of groundwater resources throughout southern Ontario.

This work is a collaborative effort between the Ontario Geological Survey (OGS), and staff at The City of Guelph, Regional Municipality of Waterloo, Halton Region, City of Hamilton, Town of Shelburne, Parks Canada, the Grand River Conservation Authority, University of Guelph, University of Ottawa, University of Western Ontario, University of Cincinnati, The Ohio State University, Wisconsin Geological Survey, various consulting firms (e.g. Golder Associates Ltd., Lotowater Technical Services Inc., Flexible Liner Underground Technologies, Ltd. Co. FLUTE™, Stantec Inc. and S.S. Papadopoulos & Associates), and with co-operation of private landowners and quarry operators.

#### **DIAGENESIS OF ZEOLITE-CEMENTED SANDS IN THE FRIO FORMATION, PERDIDO FOLD BELT, WESTERN GOM**

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Oligocene-age Frio sands represent a significant HC resource in the western GOM Perdido Fold Belt. Oil-bearing reservoirs include volcanic ash-rich sands that contain significant amounts of pumice and glass-rich material in which shards are still preserved. These sands are characterized by high macro porosity and good permeabilities. By contrast, zeolite-cemented sands tend to be micro porous and are characterized by significant loss of permeability, attributable to the diagenetic reaction of volcanic ash to clinoptilolite, a common zeolite mineral.

All of the ash-rich sands were originally deposited as mass flow deposits in seawater. Detailed petrologic study of cuttings and sidewall cores from several Frio sands shows that the presence of ash and zeolite are almost mutually exclusive. The presence of stacked ash-rich and zeolite-rich sands presents a technical challenge in risking the presence of hydrocarbons and predicting reservoir quality. It also debunks the hypothesis that the ash to zeolite transition is primarily a function of temperature (depth).

Based on our geochemical, petrological and detailed petrographic study of Frio sands, we have established a thermodynamic model for the ash to zeolite transformation that is consistent with brine and clinoptilolite compositions. Results of our study show that in every instance, clinoptilolite is more sodic than its precursor ash and that there is a regional increase from Na-poor and K-rich ash in the south, to almost a completely Na-bearing clinoptilolite in the North. This regional increase in the Na content of clinoptilolite is mimicked by the composition of coexisting brines.

We conclude that the most likely cause for the selective transformation of ash-rich sands is due to progressive infiltration of brine that is more concentrated than present day seawater (Ionic Strength up to  $2\times$  SW), along certain ash-rich horizons. The infiltration of the concentrated brine is mediated by favorable fault transmissibility both on a regional and local scale. Alteration along a particular horizon apparently terminates when the ash is completely altered to zeolite, resulting in an effective decrease in brine permeability, inhibiting any further infiltration of brine

#### **U-Pb GEOCHRONOLOGY AND MAGNETIC OVERPRINTING OF LATE NEOPROTEROZOIC DYKE SWARMS ASSOCIATED WITH OTTAWA-BONNECHERE AND TIMISKAMING GRABENS AND SW FAULTS OF THE UPPER ST. LAWRENCE RIVER**

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West-trending Grenville, NW-trending Lac Pommeroy, and SW-trending Rideau and Brockville diabase dykes parallel the Ottawa-Bonnechere graben, Timiskaming graben and faults along the St. Lawrence River, respectively. Together they converge to a focus east of Montreal, the locus of a postulated mantle plume associated with the opening of the Iapetus Ocean. Grenville, Rideau and Lac Pommeroy dykes are geochemically similar. Published ages for Grenville dykes range from 592-585 Ma, although new and revised U-Pb analyses suggest that emplacement mostly occurred during a brief pulse from ca. 589-584 Ma. A U-Pb baddeleyite age for a Rideau dyke of  $584 \pm 1$  Ma and a preliminary age for a Lac Pommeroy dyke of ca. 590-580 Ma are also reported herein, indicating that Grenville, Rideau and Lac Pommeroy dykes belong to a single magmatic event. Undated Brockville dykes may have a different age; they are amygdaloidal, suggesting emplacement at a high crustal level, and differ geochemically from the three other swarms. Previous paleomagnetic studies of Grenville dykes reported distinct remanence directions from different sites, scattered from steep down NW to shallow up SE or SSE (with some sites magnetically reversed), leading to debate concerning a high or low paleolatitude for Laurentia at 0.59 Ga, multiple ages of dyke emplacement, rapid apparent polar wander (APW), true polar wander (TPW), aberrant geomagnetic fields, magnetic overprinting, etc. In this study, Rideau dykes also carry steep to shallow SSE directions. Sites with steep and shallow remanences are shown here and in previous studies to be coeval, indicating that the directional data are not readily explained by multiple emplacement ages, rapid APW or TPW. We demonstrate that magnetic overprinting is extensive and complex at many Grenville and Rideau dyke sites. Multiple directional components, smeared distributions and reversals are commonly observed in detailed AF-TH demagnetization experiments. Overlapping blocking temperature spectra are common. Given significant chemical overprinting, it is difficult to assess whether components are primary or secondary, except potentially through baked contact tests or comparison of multiple sites along individual dykes. Both steep and shallow remanences have been interpreted as primary, which could indicate anomalous geomagnetic field behaviour during dyke emplacement. However, the prevalence of complex overprinting at many sites suggests, pending further study, that caution should be exercised when interpreting the age of the various components.

#### **MAFIC DYKE SWARMS OF CANADA'S NORTH: A 1:500K SCALE DIGITAL MAP FOR YUKON, NORTHWEST TERRITORIES AND NUNAVUT**

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We present a new digital mafic dyke swarm map of Canada north of 60°N latitude. The map forms a component of the 1:500K scale Tri-Territorial Bedrock Geological Synthesis being prepared under the direction of the Geological Survey of Canada ([http://gsc.nrcan.gc.ca/gem/min/tri-bed\\_e.php](http://gsc.nrcan.gc.ca/gem/min/tri-bed_e.php)). The dykes are mapped (using ArcGIS 9.3) from both aeromagnetic and geological sources, and grouped into swarms based on their distribution,

trend, geochronology, paleomagnetism and geochemistry. This work builds on previous maps of dyke swarms and related magmatic units at a variety of scales, most recently for Canada at a scale of 1:5M by Buchan and Ernst (2004), Slave craton at various scales up to 1:30K by Stubley (2005), Nares Strait region at a scale of 1:2.25M by Harrison et al. (2006), and Slave craton and Wopmay orogen at a scale of 1:2M by Buchan et al. (2010). It complements mapping of dyke swarms (and related units) elsewhere in the North Circumpolar Region (e.g. in Russia; <http://www.largeigneousprovinces.org/projects.html>). Our goals in this mapping project are to: 1) provide dyke swarm distributions across the three territories at a more detailed scale (1:500K) than previously available for most of the region; 2) extend coverage to areas that have not been mapped previously (e.g. beneath Phanerozoic cover rocks); 3) clarify the extent of swarms and their geometry (e.g. radiating or linear); 4) identify the focal points of radiating swarms and infer links with mantle plumes and potential breakup margins; 5) integrate recent U-Pb geochronology to identify new swarms and recognize links between coeval but spatially separated swarms; 6) recognize truncated swarms which locate the boundaries of crustal blocks and major transcurrent faults; 7) identify swarms that become offset or deformed along strike, reflecting younger tectonics or orogenesis; 8) use swarms as monitors of regional intraplate stress variations; and 9) identify other magmatic units (e.g. sills, volcanic rocks, layered intrusions) which can be linked with regional dyke swarms as part of Large Igneous Provinces (LIPs).

#### **YOUNGEST HILLS IN AXEL HEIBERG ISLAND, CANADIAN ARCTIC ARCHIPELAGO: ARE THE SALT DOMES RISING?**

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Since the 1960s, geologists have wondered whether some of the 46 exposed evaporite diapirs in Axel Heiberg Island (composed of allochthonous Carboniferous Otto Fiord Fm) have grown in the Holocene. These domal or narrow ridge structures form flat-topped hills less than one to several kilometres in horizontal diameter that rise hundreds of metres above the bottom of U-shaped glacial valleys. Their steep and freshly gullied flanks give them an alien appearance of “warts” in the landscape. Because they are composed of the relatively soft and soluble minerals gypsum, anhydrite and halite, they are unlikely candidates to have posed much resistance to glacial erosion; in some localities they are topographically higher, yet down-ice from very hard igneous bedrock that displays striations and roches moutonnées. Present day glaciers (e.g. Thompson Glacier) have no difficulty slicing through diapirs. In some localities diapirs appear to intrude young sediments and they disrupt the course of glacial streams. The fact that mountain building processes ceased after the Eurekan Orogeny in the Eocene, makes the case for actively growing salt domes hard to defend. Part of the surface swelling of the evaporite outcrops is caused by expansion during hydration of anhydrite, but the large topographic bulges formed by the diapirs still pose a problem. The best evidence for present-day growth is in the Stolz Diapir near Whitsunday Bay in SE Axel Heiberg Island. The Stolz Diapir has a diameter of 1.2 km and its irregular surface is pitted with solution sinkholes. Dissolution is caused by a seasonal stream which, obstructed by the diapir wall, penetrates into it and reappears down valley. House-size blocks of banded halite stumble down the steep

flanks, and despite this obvious disintegration, the diapir towers over a hundred metres above the valley.

In order to test the hypothesis that some diapirs are actively rising, an early attempt using RADARSAT-1 data from the Stolz Diapir indicated successive images are completely decorrelated, which we interpret to indicate the structure is moving, although the displacement cannot be quantified. In order to detect possible neotectonic movements, we placed radar corner reflectors on selected exposures of evaporite and “stable” bedrock reference areas near by in the region of Expedition Fiord. Data acquisition of RADARSAT-2 at 24 day intervals along the same orbit has been commissioned to accumulate data for a few years to build a suitable time series for more robust analysis.

#### **MULTIPLE SULFUR ISOTOPES INDICATE A SULFURETUM IN MARINE SEDIMENTS ABOVE GAS HYDRATES**

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The flux of methane from gas hydrate-bearing seeps in the marine environment is partially mitigated by the coupled microbial processes of anaerobic oxidation of methane and sulfate reduction. Sedimentary porewater sulfate profiles above gas hydrate deposits are frequently used to estimate the efficacy of this important microbial biofilter. However, to differentiate how other microbial processes (e.g. sulfate reduction coupled to organic matter oxidation, sulfide re-oxidation and sulfur disproportionation) affect sulfate profiles, a complete accounting of these processes in the sulfur cycle is necessary. Characteristic minor isotopic fractionations, even when major isotopic fractionations are similar in magnitude, help to quantify the contributions of different microbial processes to the overall sulfur cycling in the system. To this end, we investigated minor sulfur isotopic ratios (<sup>33</sup>S/<sup>32</sup>S, <sup>36</sup>S/<sup>32</sup>S), in conjunction with the commonly measured <sup>34</sup>S-<sup>32</sup>S ratio, from porewater sulfate above gas hydrate-bearing seeps from the Cascadia margin, Canada.

Down to sediment depths of 1.5 to 4 metres, the  $\delta^{34}\text{S}$  values of porewater sulfate generally increases in association with a decrease in sulfate concentrations. While this is a natural consequence of bacterial sulfate reduction, the linear variation of sulfate concentration profiles with depth suggests sulfate reduction is coupled to anaerobic oxidation of methane at a localized sink rather than to continuous organic matter oxidation with depth. Supporting this interpretation, the sulfate concentration and  $\delta^{34}\text{S}$  profiles can be reproduced by a minimal S cycle model that has been developed based on the assumptions of (1) steady-state S cycling; (2) diffusion-dominated sulfate transport; (3) sulfate consumption by anaerobic oxidation of methane at a localized sink; and (4) S isotope fractionation associated only with anaerobic oxidation of methane.

Consideration of minor isotope fractionations in this model, however, reveals that two of three sulfate isotopic profiles exhibit correlated <sup>33</sup>S/<sup>32</sup>S and <sup>34</sup>S/<sup>32</sup>S variations that are nearly orthogonal to what would be expected from sulfate consumption by anaerobic methane oxidation alone. The implication of the linear sulfate profiles and isotopic covariation, therefore, is that sulfate reduction and regeneration (though sulfide oxidation and S disproportionation) must be occurring. We hypothesize that sulfide re-oxidation is coupled to the reduction of Fe(III) and Mn(IV)

species which are abundant in the local system and that the regenerated sulfate may be available for additional methane oxidation. Recognizing that sulfate reduction is only one of several microbial processes controlling sulfate profiles challenges current paradigms for our understanding of methane oxidation at gas hydrate-bearing seeps.

#### **FACIES DISTRIBUTION AND SEDIMENTARY ENVIRONMENTS FOR THE ROCKY BROOK FORMATION, WESTERN NEWFOUNDLAND: EXPLORING THE CASE FOR TRANSTENSIONAL TECTONISM IN A MISSISSIPPIAN LACUSTRINE SETTING**

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With published reports showing TOC values as high as 15% and thermal maturity indicators between  $R_o \sim 0.4$  to  $\sim 0.7$ , the late Mississippian Rocky Brook Formation of the Deer Lake Basin is considered to be one of the better petroleum source rocks in western Newfoundland. To date, exploration has simply identified several significant gas shows. In order to better assess hydrocarbon source rock distribution and to learn more about the basin origin and evolution, both old and new exploration data are examined and summarized for stratigraphy, sedimentology and structures.

Rocky Brook strata are formally divided into the Squires Park Member, a predominantly greenish grey and dark grey siltstone and shale and the underlying Spillway Member, a mix of greenish grey and dark grey siltstone and shale with thick bands of brownish red siltstone and thin bedded sandstone. However, and in subtle contrast, drilling reports from earlier mineral exploration programmes show five informal members, the upper grey beds (equivalent to the Squires Park Member), and the underlying brown beds, lower grey beds, mottled beds, and red beds (all equivalent to the Spillway Member). All beds are thought to be lacustrine or paralic in origin.

In our work, and when strata are correlated on the Squires Park-Spillway contact, the formation apparently shows three discrete cycles each up to 150 m thick. Internally, cycles consist of dark, organically enriched strata separated by layers of light, somewhat oxidized and silty strata. So too, within these thick cycles, there are thinner and similarly constructed cycles, each generally less than 10 m thick.

Conceptually, it is tempting to ascribe this pattern of sedimentation to worldwide orbitally forced glacial events, but neither the age nor the timing for local faulting and folding are sufficiently resolved. One can however use inference and comparison with other studies to suggest that thin cycles of alternating source rocks and lean rocks correspond with half precession cycles approximately 10 ka duration. In modern settings, these cycles mark changes in monsoon activity in equatorial regions. Collected, the three thick cycles may be recording a tropical lacustrine record for Mississippian glacial-interglacial events. Strata appear to represent fluctuating profundal environments in a lake where for a brief time there was a balance between sediment and water input and tectonic subsidence.

#### **HOW THE OTTAWA-BONNECHERE GRABEN CONTINUES TO CONTRIBUTE TO THE UNDERSTANDING OF THE ROLE OF INTRA-CONTINENTAL RIFTS IN THE GEODYNAMIC HISTORY OF THE EARTH**

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The Ottawa-Bonnechere (O-B) graben was among the earliest recognized of ancient intra-continental rifts (Kay, 1942) and has con-

tinued to yield information that improves the understanding of intra-continental rifts and of their role in the Wilson cycle of ocean basin opening and closing. That is perhaps as it should be because Tuzo Wilson was born in the graben in Ottawa in 1908. Kumarepeli identified what is now recognized to have been the rifted margin of Laurentia that formed in the latest Precambrian times and work by Doig soon dated alkaline igneous rocks erupted in association with that rifting (i) in the O-B graben itself, (ii) on the rifted continental margin and (iii) in contemporary rifts that strike at high angles from the then continental margin into the interior of Laurentia. Rocks of populations (ii) and (iii) are now recognized farther afield, for example on the shores of the Labrador Sea, in Assynt in Scotland, in Kangerdluqsuaq fjord in east Greenland and in the Tromso nappe in Norway. In the three last-named localities the alkaline rocks are gneissic having become deformed during continental collision. The importance of dike intrusion in rift development is seen in the Grenville dike swarm of 594 Ma (Kamo et al., 1995) associated with the O-B rift and is being demonstrated in active rifts, for example in Ethiopia and in Tanzania (Ebinger et al., Calais et al.). An early idea (e.g. Siedlecka, 1972; Burke and Dewey, 1973) was that rifted margins consisted of linked rifts of 3-armed systems that had formed over swells related to plume eruption but evidence of "upside-down drainage" into rifts (Sleep) such as that shown by the eruption of the Deccan plume at 65 Ma into a Permian (ca. 300 Ma) rift indicates that this is likely to be less common than was formerly thought. A current need is for more high-resolution age determinations of igneous rocks to clarify O-B rift and other rift histories.

#### **FLUID-MEDIATED ALTERATION AND RARE-ELEMENT MINERALIZATION IN THE LITTLE NAHANNI LCT-TYPE PEGMATITES, NWT, CANADA: A TEXTURAL AND FLUID INCLUSION APPROACH**

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The Cretaceous (82 Ma) Little Nahanni Pegmatite Group (LNPG), which straddles the Yukon-NWT border in the Mackenzie Mountains, is a subvertically dipping, centimeter to meter scale, swarm of several hundred LCT-type pegmatites that outcrop over a 15 km strike length. The dikes intrude Precambrian to Lower Cambrian host rocks of the Yusezyu and Narchilla formations that consist of siliciclastic and carbonate rocks formed in a passive margin setting. The dikes are spectacularly exposed in cirques which allow 3D viewing of exposures and internal textural features. Field work (i.e. channel and chip sampling) and detailed petrological study indicates varying degrees of albitization and phyllic alteration accompanied ore-grade enrichment of Ta-Nb-W-Sn in the pegmatites, which are dominated by a primary Qtz-Spd-Kfs-Ms assemblage lacking graphic intergrowth, but characterized by comb-textured Spd-Kf oriented perpendicular to pegmatite contacts. The role of a fluid phase accompanying melt injection, crystallization and subsequent alteration remains an important question in rare element pegmatites and has been investigated using fluid inclusions. Detailed petrographic study integrated with SEM/EDS, microthermometry and laser Raman have been used to characterize the mineralogical evolution of the pegmatite phases, fluid: mineral interaction and the fluid chemistry. Initial studies indicate that fluid infiltration post-dated pegmatite solidification and accompanied alteration-mineralization with two different types observed: (1) a low-salinity (2 wt. % equiv. NaCl) aqueous fluid, and (2) an aqueous-carbonic fluid with varying  $X_{CO_2}$  (0.4 to 0.07 mol%  $CO_2$ ) and variable purity of  $CO_2$  ( $T_m(CO_2) = -57^\circ C$  to  $-61^\circ C$ ). Importantly, the more abundant type 2 fluids, present as secondaries in

Qtz, Spd, Kfs, Ab and Cassit, appear to post date type 1. Furthermore, the two fluids cannot be related via a fluid unmixing process and, thus must reflect different reservoirs. However, even though one or both of the fluids appear to be implicated in the rare-element mineralization, their source still remains poorly constrained. Further complicating the nature and origin of the fluids and relationship to pegmatite evolution is the presence of a later 65-70 Ma thermal disturbance, as revealed by Ar-Ar and Rb-Sr dating. Thus, although we note similarities of the LNPG fluid inclusions to those reported in other studies of rare element mineralization, we are cautious about making inferences about their ultimate source and role in the rare element mineralization.

### 3D RECONSTRUCTION OF BASE METAL ZONING IN THE FLIN FLON-CALLINAN-777 VOLCANOGENIC MASSIVE SULFIDE DEPOSITS, MANITOBA

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The study addresses the spatial distribution of Cu- versus Zn-rich lenses in the Flin Flon, Callinan and 777 volcanogenic massive sulphide deposits of the Paleoproterozoic Flin Flon Belt, Manitoba. The relative distribution of these elements can be used to locate hydrothermal vent sites in VMS ore systems that contain multiple sulphide lenses or deposits. Using historical and modern assay datasets, a 3D Gocad model characterising the spatial relationships between copper and zinc concentrations was constructed. The model shows that the Cu-rich zones decrease in size from the base to the top of the Flin Flon and 777 deposits, which is consistent with upward and outward zone-refining of the sulphide lenses. The Cu-rich zones are typically elongate parallel to the elongation of the sulphide lenses, which are shaped as elongate flattened ellipsoids that plunge parallel to a pronounced regional stretching lineation. A second, less distinct trend is oriented oblique to the stretching lineation, in both the Flin Flon and 777 deposits. The Flin Flon and 777 deposits have at least three and two distinct Cu-rich zones, respectively, suggesting the presence of separate hydrothermal vents. The Callinan deposit does not contain a Cu-rich zone, but is slightly more Cu-rich towards its south end. The deposit shows an overall decrease in Cu/Zn ratios from south to north as well as a localized decrease northerly around the interpreted vent. The Callinan ore lenses are interpreted as a clastic sulfide deposit fringing the Zn-rich shell of the 777 deposit possibly derived by mass wasting of sulfide mounds and mass flow transport of sulfide clasts during periods of tectonic instability. A lateral Zn variation is also present and suggests input of additional metals from one or more separate vents located north of the Callinan deposit.

### EPD AS A TOOL FOR UNDERSTANDING BREAKAGE AND LIBERATION CHARACTERISTICS: A CASE STUDY FROM THE BUSHVELD UG-2 CHROMITITE REEF

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The UG-2 chromitite Reef in the Bushveld Complex (South Africa) is a major repository of PGE-Ni-Cu, noted for high PGE-to-sulphide ratios and a high proportion of Rh in the Pt-element suite (Pt, Pd, Rh). In contrast to the Merensky Reef, where Rh is dominantly held in solid solution in pentlandite, discrete Rh PGMs in the UG-2 have implications for relatively better recovery, provided effective liberation is achieved. In the UG-2, preferential,

grain boundary breakage of chromite is a well-known phenomenon, meaning that effective release of interstitial base metal sulphide (BMS) and PGM occurs at the liberation size of the chromite.

In this study, a novel technology, Electric Pulse Disaggregation (EPD) was applied to a UG-2 sample and the resulting products were analysed both chemically and by Mineral Liberation Analyzer (MLA) to determine the deportment of PGM and sulphides resulting from EPD treatment. Results demonstrate that breakage to a particle size of D80 of 850 µm effectively transfers as much as 26% of BMS and 53% of Pd and 58 % of Rh to the passing 75 µm size fractions at less than 10% of mass transfer to this size fraction. Liberation data reconciled by assays were used to demonstrate relative partitioning of Pd, Pt and Rh as a function of size and mineral assemblage/association. The implications for early release of values are discussed with regard to staged grinding strategies and the effectiveness of EPD to study fundamental natural breakage characteristics. During milling, by contrast, significant fines production and particle re-breakage occurs which may mask these effects. Quantitative deportment data for PGE and sulphides also have implications on characterization of PGE deposits and their genesis.

### EXPERIMENTAL EVIDENCE FOR Au AND Pd TRANSPORT BY Te UNDER ANHYDROUS CONDITIONS

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Tellurides are common platinum group minerals (PGM) in magmatic-hydrothermal ore deposits but little is known about how they form. It is unclear, for example, to what extent they result from hydrothermal activity or from exsolution from cooling sulfide melts. To understand the role of Te in the transport of platinum group elements (PGE) a series of experiments were conducted in nominally anhydrous systems. The experiments were conducted in piston-cylinder presses at temperatures ranging from 500 to 1150°C, at a pressure of 0.5 GPa and for durations ranging from 3 hours to 15 days. The starting materials consisted of a mixture of Fe-Ni-Cu sulfides and a mixture of PGE (Ru, Rh, Pd, Os, Ir, Pt) mixed in a mass proportion of 10:1 (total sulfides to total PGE). Two sets of experiments were prepared: Te-bearing runs and Te-free (reference) experiments. Elemental Te was added in the first set in a mass proportion of 1:5 (Te to PGE mixture). The mixed starting materials were placed inside graphite capsules and sealed inside Au<sub>80</sub>Pd<sub>20</sub> capsules (a common procedure that typically isolates sulfide-bearing starting material from enclosing precious metals capsules). Experimental products were characterized with SEM using an Energy Dispersive Spectrometer. In Te-free experiments all run products were contained inside the graphite capsules. In Te-bearing experiments at or above 600°C, Pd tellurides (ranging in size from sub-micrometer to a few micrometers) were found among the grains that compose the graphite capsule walls, distributed in a halo around the main charge. The telluride halo sometimes extended all the way to the outer Au-Pd capsule, in which case Au tellurides were also found (Au was not part of the starting materials). The rest of the PGE (Ru, Rh, Os, Ir, and Pt) were contained within the main charge along with the sulfides. The presence of these tellurides indicate that a Te-bearing phase (likely a Te-bearing gas) is capable of mobilizing Au and Pd across a medium (graphite in this case) that is a barrier to sulfide melts.

## **BASEMENT-COVER RELATIONSHIPS IN THE PALEOPROTEROZOIC AMER GROUP, NUNAVUT**

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The uranium-hosting Paleoproterozoic Amer Group, some 150 km north of Baker Lake, NU, comprises four sequences (Ps1 through Ps4) unconformably overlying Archean basement of the Rae sub-province. Basement of the study area around South Amer Lake is quartzo-feldspathic gneiss with subordinate metabasalt, intruded by agmatitic diorite. Ps1 in the Amer Group is the Ayagaq quartzite formed in a stable cratonic and/or marine setting. Ps2 is a sharply transgressive sequence of Resort Lake graphitic siltstone shallowing up to Aluminium River dolomite and intercalated overlying Five Mile Lake porphyritic basalt. Ps3 comprises three units recording an overall coarsening- then shallowing-upward sequence involving siltstone to feldspathic arenite: Three Lakes, Oora Lake and Showing Lake formations. The latter hosts sandstone uranium deposits. Above a profound post-D<sub>1</sub> unconformity, Ps4 Itza Lake arkose is preserved in a small area of outcrop in the study area.

The structural history of the Amer basin is spatially and temporally variable. The regional map pattern is defined by shallowly doubly plunging synclinoria (D<sub>2</sub>) affected by later open D<sub>3</sub> folds. Detailed field mapping has documented at least three preceding deformation generations, grouped as D<sub>1</sub>. The basement-cover contact varies throughout the study area; the nature of this first-order lithotectonic boundary is central to elucidating the structural history of the area. The basal unconformity of the Ayagaq quartzite is commonly marked by a distinctive polymictic conglomerate with a schistose matrix; elsewhere it is a schistose layer, or a sharp discontinuity.

Immediately adjacent to the basement-cover contact, D<sub>1</sub> deformation in the basal quartzite includes bedding parallel displacements and meso- to macroscopic isoclinal folds (locally two generations); hence, the layered quartzite sequence lying on the basement is defined by fold limbs. Proximal Archean gneiss foliations are sub-parallel to axial planes of the quartzite isoclinal folds. Gneiss and quartzite were first folded together during latest D<sub>1</sub> consistent with a significant decoupling of basement and cover during much of the pre-D<sub>2</sub> deformation. Folding of the basin during D<sub>2</sub> created steep axial planar cleavage. The two-stage development of the tectonic architecture is seen in the post-fabric folding of the basal schist, a presumed detachment, with the basement during D<sub>2</sub>. A primary conclusion is that large tracts of Paleoproterozoic units may be para-autochthonous to allochthonous with respect to the underlying Archean basement and that preservation of the basal conglomerate in some places may depend on the specific location of pre-D<sub>2</sub> detachment surfaces, although primary sedimentation also varied.

## **GLACIAL DISPERSAL PATTERNS FROM THE MOUNT FRONSAC NORTH Zn-Pb-Cu-Ag MASSIVE SULFIDE DEPOSIT, NEW BRUNSWICK, CANADA**

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Assessment of local scale geochemical patterns in glacial till over mineralized bedrock is difficult as the concentration of elements is dependent on several factors including; bedrock genesis, sub-

sequent alteration, remobilization or tectonic deformation, topographic relief and attitude of mineralized zones, glacier flow direction and dynamics, thickness and type of till, and pre- and post-glacial weathering. Varied dispersal patterns arising from these factors are examined in order to understand mineralized concentrations in till from Mount Fronsac North.

Two hundred thirty six samples were collected and analyzed from thin (<2 m) deformation and lodgement till overlying the Mount Fronsac North volcanogenic sediment hosted massive sulfide deposit in northern New Brunswick. Till samples were subjected to aqua regia digestion/ICP-MS/ES and CVAFS analysis. Mount Fronsac drill core and gossan samples from Mount Fronsac were examined.

Element concentrations in Mount Fronsac till show three distinct geochemical dispersal patterns: 1) a well defined fan shaped pattern (Pb, Ag, Cu), 2) a distinct ribbon pattern trending west to east (Ni, Co, Cr) and 3) an arcuate pattern (Hg, Cd).

Comparisons between geochemical distribution and concentrations in Mount Fronsac till, bedrock and weathered sulfides (gossan) indicate that surface till geochemical patterns are the result of bedrock mineralization and hydrothermal alteration, pre-glacial weathering, glaciation (erosion, entrainment, comminution and deposition down-ice) and post-glacial weathering. Amalgamation of bedrock, gossan and till data from Mount Fronsac North yields a model relating till geochemical signatures to bedrock geochemical sources.

## **BIOSTRATIGRAPHIC ANALYSIS OF CRETACEOUS (ALBIAN TO CENOMANIAN) STRATA ON EAGLE PLAIN, YUKON TERRITORY**

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Cretaceous strata exposed in outcrop in the Eagle Plain region, Yukon Territory, document the depositional history of the northern Western Interior Sea close to its opening to the Boreal Sea. To date, the region's stratigraphic framework carries many uncertainties, due mainly to the lack of fossil evidence. This study offers new insights based on microfossil (foraminifera) evidence supported by macrofossil occurrences. The Whitestone River Formation, composed predominantly of silty shale, yielded various foraminifera and radiolarian species, which support the previous assignment of an Albian age. Further south, in northern Alberta, radiolarian-rich zones have also been recognized within the interior sea and they are assigned to the lower Albian. Both regions have the radiolarian genus *Cyrtocapsa* in common. The dominantly shaly Parkin Formation overlies the Whitestone River Formation and has been previously assigned a Cenomanian age. However, macrofossils discovered in basal sandstone intervals suggest a mid-Albian age, contradicting previously established frameworks. The Parkin Formation appears nearly barren of micro- and macrofossils. However, benthic foraminifera reappear towards its boundary with the overlying sandstone-rich Fishing Branch Formation. Foraminifera are relatively rare but the assemblage composition including *Verneuilinoides tailleuri* suggests a continued Albian age. *V. tailleuri* has previously been identified in strata from neighbouring regions (the North Slope of Alaska, eastern Sverdrup Basin, and northeastern British Columbia) carrying a last appearance between the middle and late Albian. Overlying strata of Burnthill Creek and Cody Creek formations become increasingly non-marine, losing marine fossils. However, previously identified plant fossils and bivalves of Cody Creek strata were dated Cenomanian in age, lending support to our newly pro-



posed Albian age to the underlying Parkin Formation. Our findings from outcrop sections will ultimately be correlated with subsurface core strata leading to revised subsurface log correlations. Moving the extensive marine shale sections in the Eagle Plain region down into the Albian opens an interesting question concerning the extent of the Albian/Cenomanian unconformity that is widespread in northwestern Canada.

#### **BULK COMPOSITION OF JUVENILE UPPER CONTINENTAL CRUST DERIVED FROM GLACIAL TILL IN THE NORTH AMERICAN CORDILLERA**

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We use a compilation of bulk chemical analyses for 2645 bulk rocks and 3487 till samples (silt+clay fraction) from British Columbia, Canada to construct an estimate of juvenile upper crust composition in the North American Cordillera for comparison with upper crust estimates for older continental crust. Principle component analyses demonstrate that glacial tills are a robust natural average of their surface rock provenance. The tills underwent little or no chemical weathering during their generation and deposition, but preserve the chemical weathering history of their source regions. Our results show upper continental crust of the Cordillera is broadly similar to other estimates in terms of the abundance of Si, Al, Mg, Ca, Na, Zr, Y, Sr, Ba, Th and U. The till-based upper crustal estimate, however, shows consistent and marked enrichment in Fe, Ti, Mn, P and HREE and depletion in LREE and K. These attributes are not obviously attributed to any analytical or sampling bias; surface rock averages and modern river sediments from British Columbia show the same patterns of enrichment and depletion as the tills. We attribute the unique character of our Cordilleran juvenile crust estimate to a significant component of basaltic soils in till generation, as compared to upper crustal estimates from more mature denuded terrains. Nonetheless, our crustal estimate remains overall 'andesitic', similar to those from Precambrian shields, supporting the notion that reworking of old crust is volumetrically far more important than production of juvenile crust, even in a juvenile orogen of the North American continent.

#### **A LOOK AT THE SNOWBIRD TECTONIC ZONE AND ITS URANIUM POTENTIAL IN SASKATCHEWAN: A HEAVILY REWORKED FAULT (AND POSSIBLE PALEOPROTEROZOIC SUTURE?) ZONE THAT LAID THE GROUNDWORK FOR A FERTILE MINERAL SYSTEM**

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The Snowbird tectonic zone remains one of the most enigmatic features of the western Canadian Shield. Most recent work on this structure focussed on high-pressure granulites in the structure's hanging-wall north of the Athabasca Basin; however, it is also part of a fertile mineral system that spawned the Centennial uranium deposit beneath the Athabasca Basin and it continues to be the focus of exploration. Evaluating the mineral potential of this structure requires a good understanding of its history and that of the terranes it juxtaposes.

South of the Athabasca Basin, the Snowbird tectonic zone is referred to as the Virgin River shear zone; however, rather than a discrete shear zone, it is better described as a corridor of heterogeneous high strain. Three widely spaced bedrock mapping tran-

sects across this corridor indicate that the northwest-dipping, highly strained rocks within it are situated at an obvious lithologic transition. The hanging-wall is dominated by granulite-facies, 1.985-1.975 Ga intermediate plutonic rocks of the Taltson magmatic zone, whereas the footwall is dominated by upper amphibolite to granulite-facies Archean orthogneiss of the Hearne province. The <2.3 Ga Virgin schist group, a ~3 km thick supracrustal succession between the two, is dominated by lower-grade, graphitic pelitic rocks and subordinate volcanic rocks.

A regional set of steeply dipping, doubly plunging, northeast-striking buckle folds tightens with proximity to the Virgin River corridor indicating a genetic linkage. These folds imply a considerable pure shear component in the Virgin River high-strain corridor at the time of its formation. Strain was focussed along the limbs of the tight to isoclinal folds, resulting in transposition, strain localisation and mylonitisation. Thrust tectonics are inferred to have been dominant, attested to by abundant reverse (thrust)-sense kinematic indicators. Locally, dextral shear-sense indicators are common within superimposed zones, representing reactivation of these older structures before deposition of the Athabasca Basin. Further, syn-Athabasca Group, brittle reactivation localised in part within the lithologically weaker Virgin schist group (e.g. Dufferin Lake fault/Centennial deposit) played a fundamental role in uranium deposition.

The Virgin River corridor is focussed on a distinct lithologic transition and contains abundant evidence of fold-and-thrust tectonics. Therefore, a suture is a viable model for its formation. Copious evidence for strike-slip displacement represents an initial stage of reworking in the corridor. Although these displacements predate the Athabasca Basin, they set the stage for later, brittle reactivation that helped to focus uranium precipitation.

#### **AN EXPERIMENTAL MAGNETIC SURVEY IN THE GRENVILLE PROVINCE USING A SIMULATED UNMANNED AIRCRAFT SYSTEM**

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Carleton University and Sander Geophysics are developing an unmanned aircraft system (UAS) for aeromagnetic surveying. Aeromagnetic surveys for natural resource exploration are mostly done at a regional scale using manned aircraft and followed-up by ground surveys in regions of interest. UAS are a new technology that has the potential to bridge the two approaches with the benefits of reduced cost and increased safety. As UAS have the ability to fly at low altitudes and to follow terrain closely with no risk to personnel, the Earth's magnetic field will be recorded at a resolution which allows the delineation of finer geological details.

As an early test of the expected performance of the UAS being designed, a simulated UAS (sUAS) was built. The sUAS is a T-shaped structure configured as a horizontal gradiometer with two cesium magnetometers spaced 4.9 m apart replicating the wing span of the UAS. The sUAS is suspended beneath a helicopter and records the Earth's magnetic field at the same resolution and altitude that the UAS is designed to achieve based on the topography of the area being surveyed.

In February 2010, an 8.5 km<sup>2</sup> area in the Central Metasedimentary Belt of the Grenville Province, near Plevna, Ontario, was surveyed with the sUAS suspended 50 m above ground. The survey area was chosen on the basis of its geological structure. It features a vertical similar fold composed of strongly magnetic metasedimentary rocks interbedded with magnetite bearing metavolcanic rocks, folded with weakly magnetic carbonate metasedimentary rocks. The same area was resurveyed by a ground crew in February and November 2010 using a GSM-19 Overhauser magnetometer. The aeromagnetic data recorded by the

sUAS, and the ground magnetic data are compared to each other and to data acquired using a fixed-wing aircraft during a survey conducted in 1983 over the same area. Comparing how the fold structure has been delineated in the three data sets demonstrate the superior ability of the sUAS to define detailed geological trends.

### **BEDROCK AQUIFERS OF SOUTHERN ONTARIO: THE LUCAS “SULPHUR WATER” AQUIFER**

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Southern Ontario is underlain by a succession of undeformed, shallowly dipping marine sedimentary rocks up to 1400 metres in preserved thickness, varying from Cambrian to Mississippian/late Devonian in age. In Ontario, the Middle Devonian Lucas Formation is comprised of limestone, dolostone, anhydrite and sandy dolostone with a maximum thickness of 96 metres in the Sarnia area, thinning southeasterly to zero at its pinch-out edge beneath Lake Erie and the westernmost part of the Niagara peninsula. It underlies an area of over 33,000 km<sup>2</sup>, ranging in depth from outcrop to 350 metres below the surface. The Lucas was deposited in a restricted marine depositional environment centered in the Michigan Basin where it is dominated by evaporites, including thick beds of halite.

The Lucas Formation is a major regional water-bearing interval in the subsurface of southern Ontario. Where the Lucas Formation is confined by younger bedrock strata or impermeable drift, this water is salty and sulphurous and forms part of a major regional sulphur water aquifer together with the overlying Dundee Formation (where fractured) and parts of the underlying Amherstburg and Onondaga formations. Sulphur water from this aquifer flows at surface in topographic lows along the north shore of Lake Erie and streams flowing into the lake. Massive loss of circulation may be encountered when drilling through this aquifer and the sulphur water corrodes unprotected steel casings in petroleum wells which intersect it. Where the Lucas Formation outcrops or subcrops beneath glacial drift and where the overlying Dundee Formation is penetrated by karst-widened joints, fresh water may be encountered up to several tens of metres below the bedrock surface, especially along the shore of Lake Huron.

The Lucas Formation is also a major oil-producing interval in the subsurface of southern Ontario, hosting both the Oil Springs and Petrolia oil fields, discovered in 1858 and 1862 respectively.

Recent improvements to the petroleum well database maintained by the Ministry of Natural Resources and its Oil, Gas and Salt Resources Library have made it possible to map the distribution of water by type and construct regional static level maps for deep bedrock aquifers. As expected, the maps confirm regional down-dip flow within the Lucas. An unexpected result are 100+ metre depressions in the static level surface, especially in areas underlain by salt dissolution features in the Salina Group evaporites, suggesting downward, cross-formational flow.

### **REGIONAL BEDROCK AQUIFERS AND A CONCEPTUAL GROUNDWATER FLOW MODEL FOR SOUTHERN ONTARIO**

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At a regional scale aquifer systems in southwestern Ontario can be divided into; 1) a shallow, complex fresh water system of local to intermediate scale in unconsolidated glacial drift and more recent sediments, overlying; 2) consolidated Paleozoic bedrock containing several deep confined saline aquifers of regional extent.

The glacial sediments form a relatively thin veneer averaging a few tens of metres and ranging up to a maximum of 200 metres

in thickness. The drift aquifers are the source of most of the potable groundwater in southwestern Ontario and are recharged from surface and meteoric water with the exception of some local occurrences of glacial waters. The uppermost few metres of underlying bedrock are often porous and permeable due to fracturing, weathering and/or karstic dissolution. This porous bedrock is in hydraulic continuity with the drift and forms a regional fresh water “contact aquifer” with flow directions controlled by bedrock topography and local concentration of flow in buried gorges and valleys eroded into the bedrock surface.

Bedrock in southwestern Ontario is comprised of stratified marine sedimentary rocks of Paleozoic age with a maximum preserved thickness of up to 1400 metres. Within the bedrock regional aquitards are formed by shale strata, most notably the Upper Ordovician Queenston, Georgian Bay and Blue Mountain formations which exceed 300 m. in combined thickness, and by thick evaporites of the Salina Group. Carbonate rocks also generally form aquitards except where they have been fractured or exposed to near-surface karstic dissolution.

Within the bedrock regional aquifers of salty and locally sulphurous water occur within the Middle Devonian Lucas and Dundee Formation, the Upper Silurian Bass Islands Formation, within reefal portions of the middle Silurian Guelph and underlying Amabel and Lockport groups of formations, within linear fault-related hydrothermal dolomite zones in the Upper Ordovician limestones of the Trenton and Black River groups and in Cambrian sandstones. These aquifers are recharged by fresh water at their outcrop and subcrop edges with down-dip flow directions within the bedrock strata. Buoyancy effects of the deep subsurface brines are also inferred to produce shallow topography-driven lateral flow of fresh water along the strike of the bedrock units.

Subsurface bedrock aquifer data is derived from petroleum well records collected and maintained by the Ontario Ministry of Natural Resources at its Oil, Gas and Salt Resources Library.

### **IS THE OCEAN A VERY, VERY LARGE VMS DISTRICT?**

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The physical and chemical processes that operate at mid-ocean ridges today and accumulate base metal sulfides are similar enough to those which operated in the arc and back-arc settings which produced the VMS deposits on land that the oceans could be a giant VMS district with base metal resources hundreds of times those on land (and hundreds of times the estimates that have been made so far from direct seafloor observations). If processes on the seafloor that accumulate base metals are not be substantially different, and there is no reason to believe they are, the ocean resource can be estimated from the amount of hydrothermal circulation that discharges at ridge axes and an accumulation factor. The mass of ~350°C metal-enriched seawater that is circulated for each m<sup>2</sup> of new ocean crust formed by seafloor spreading is known quite accurately (~1.5×10<sup>7</sup> kg/m<sup>2</sup>). If 3% of the 10 µM Cu and 40 µM Zn that is venting in metal-poor black smokers accumulates within minable depths on the seafloor, the ocean resource would be 100 Gt of Cu and 425 Gt of Zn metal, the average metal surface density would be 1500 t Cu+Zn/km<sup>2</sup>, and the Cu+Zn resource of the 3.6×10<sup>8</sup> km<sup>2</sup> ocean would be 530 Gt. Sangster (1980) estimated the average surface metal density for seven land-based VMS districts is 6800 t Zn+Cu+Pb/km<sup>2</sup>, so the ocean VMS resource seems reasonable. I propose that we define 530 Gt base metal as one Scott, and debate how many milli-Scotts (mS) might be a reasonable consensus estimate for the ocean resource. I will argue that 321 to 4530 mS is a reasonable range.

## HUMANITY'S GREATEST RISK IS RISK AVOIDANCE

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As economic geologists, our challenge is to provide the ultimate world population of 10.5 billion with the energy and materials needed to sustain a European standard of living indefinitely. Any other goal has almost unthinkable negative implications. Can we do it? Of course! Considering the oceans, the world is a planet awash in energy with ample material resources. Raising energy consumption to the current European level of 7 kW/p would require tripling total energy production (15 TW to 45 TW). Accommodating 1.5 billion 100 years from now will require 72 TWe. Growing from 15 to 72 TW over 100 years represents a modest compound growth rate of 1.6%/yr. With breeder technology, the  $4.6 \times 10^9$  tonnes of U dissolved in the oceans (not to mention Th which is a better nuclear fuel) can sustain a 72 TW production for 78 centuries. My estimated seafloor Cu and Zn resources can sustain humanity for 50 and 140 centuries, respectively. Less than 3% of the Li in the oceans would allow 10.5 billion to share  $\frac{1}{4}$  of a hybrid car. The deep oceans contain enough phosphate for 33 centuries of agricultural production. So if we tap the oceans, humanity will have the resources needed for a sustainable future. There is of course some risk, but humans are tremendously good at solving problems once they have been identified, and this means to me that we will be able to recover resources from the oceans with minimal and ever-diminishing risk, as we are currently doing. The greatest risk seems to be the timidity bred of specialization (no one being sure what someone else is doing). Rather than fearing what our neighbor is doing, we should have confidence that our neighbors can fix whatever goes wrong. We should engage the next generations by moving forward with a positive, world-inclusive agenda and impressing them, not with the immensity of future pain, but by the immensity of future gain (everyone indefinitely at a European standard and huge opportunities to increase scientific understanding of how natural, including resource, systems work). If we do this, the future of our profession and humanity will be very bright indeed.

## FORMATION OF POIKILITIC ANORTHOSITE TEXTURE IN THE BUSHVELD COMPLEX, SOUTH AFRICA

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Poikilitic anorthosite (also called mottled anorthosite) consisting of large, scattered oikocrysts of orthopyroxene up to 4 cm in size enclosing euhedral plagioclase grains, interspersed with volumes containing only plagioclase are common in the Bushveld Complex. We have undertaken both textural and chemical investigations. In terms of chemical analyses, we took four different portions of each of twelve samples having different proportions, sizes and densities of oikocrysts, namely: oikocrysts only, pure anorthosite, edges of oikocrysts and whole rock. Pyroxene comprises up to 15% of the oikocrysts, whereas the pure anorthosite contains less than 2% pyroxene. Incompatible trace elements, P, Ti, K and Zr are present in exactly the same concentrations in all four aliquots.

The model for formation of the texture involves two stages. First, accumulation of plagioclase grains occurred, possibly with some compaction until the proportion reached about 85%. At that stage the liquid became effectively trapped on a scale of several cm. Second, in the proto-anorthosite volume, crystallization of plagioclase continued. In the proto-oikocryst volume a single nucleus of pyroxene formed and grew. As a result, chemical gradients were set up between the proto-anorthosite and proto-oikocryst,

such that Mg and Fe diffused through the liquid from the anorthosite to the oikocryst, with a reverse flow of Ca and Al. Thus, crystallization of a single phase continued in the two respective volumes. Importantly, the four trace elements mentioned above did not move, but retained the same concentration in all aliquots of the rock. There was no mass movement of liquid (e.g. being squeezed out by crystal growth), nor normal crystal-liquid fractionation trends on a large scale, only chemical diffusion. This interdiffusion between Mg + Fe and Ca + Al occurred over distances of up to 3.5 cm.

A CSD (crystal size distribution) study reveals the differences in shapes and sizes between plagioclase grains which have frozen in their primocryst shape within the oikocrysts and those grains that have been subject to further post-primary crystallization and re-equilibration.

## EXTENT OF CONTINENTAL CRUSTAL COMPONENT IN THE PARENTAL MAGMAS TO THE BUSHVELD COMPLEX, SOUTH AFRICA

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The Bushveld Magmatic Province comprises three units, a volcanic succession, the Rooiberg Group, the layered mafic suite, and the Lebowa Granite. All were emplaced at 2060 my. Each has been considered to contain a large proportion of melted continental crust, totaling possibly 7 km, based on high initial Sr and oxygen, and low initial Nd isotope ratios. However, the granite shows high incompatible trace-element abundances, comparable to those in the first phase, the Rooiberg lavas. Also the density of the underlying lower crust and its total thickness are no different from typical Kaapvaal craton crust, and hence show no evidence of having been so extensively melted. Further, a comparison of the trends of An in plagioclase versus mg# in mafic minerals in the mafic Bushveld Complex with oceanic gabbros shows that the Bushveld trend has a higher An content at any given mg#, the exact reverse of that expected if continental crustal contamination had occurred.

An alternative model is based on derivation from a plume emanating possibly from the core-mantle boundary that contains a major component of recycled oceanic crust. Sea-floor alteration could have caused an increase in oxygen isotope ratios. Subduction and prolonged incubation of oceanic crust with a higher Rb/Sr ratio than typical mantle could have produced high initial Sr ratios. The time scale for subduction to the core-mantle boundary and heating may be in the order of 1 by. The Bushveld is 2060 Ma old, and so may have been derived from subducted Archaean ocean crust, which contained a significant proportion of komatiite with a higher SiO<sub>2</sub> content at a specific MgO content than typical basic liquids. Partial melting of such rocks, together with mantle could have produced the distinctive geochemistry of parental magmas to the first phase of Bushveld Complex without extensive crustal contributions. We reject arguments that suggest that the Bushveld magma is derived from the lithosphere because the necessary high temperatures would have destroyed the diamonds and the distinctive high-pressure, low-temperature mineralogy and chemistry in kimberlitic lithospheric nodules emplaced through the Bushveld Complex.

We do not disallow any crustal component in these magmas, but suggest that the proportion proposed in previous models has been greatly overestimated.

## QUANTITATIVE CHARACTERIZATION OF IMPACT BRECCIAS USING DIGITAL IMAGE ANALYSIS

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Impact cratering is, arguably, one of the most important geological processes involved in planetary evolution and resurfacing. It is a high energy, low frequency geological event, with this contrast increasing relative to the size of the projectile. Due to the low frequency of occurrence the process cannot be studied by direct observation. Impact cratering results in a number of geomorphologically and petrologically distinct products. With the actual crater cavity being the prevailing morphology, impact cratering also produces a series of rocks with unique characteristics that reflect their impact origin and the dynamics of this process. These impact produced lithologies are generally called “impactites”.

Several brecciated impactites are observed within an impact structure. One of the most interesting, common and debated types are so-called “suevites”, which are described as fragmental melt-bearing lithic impact breccias that can vary greatly in appearance, composition and mode of occurrence in the field. Melt-bearing lithic breccias can be found below the impact melt sheet, above the impact melt sheet, and even in dykes, within or outside the rim of an impact crater. The high diversity and poor understanding of the depositional mechanism contributes to the difficulty in the systematic description of ‘suevites’. The aim of this study is apply digital image analysis to record a large number of physical characteristics and construct a database of ‘suevite’ samples from various impact craters.

Here we present the preliminary results of the detail quantitative digital image analysis performed on a set of samples from various impact structures. The National Institute of Health (NIH) ImageJ software was used for the image analysis. The physical parameters measured include modal abundances of mineral fragments and melt particles, clast shapes and sizes, and fractal dimensions. ‘Suevite’ samples were scanned and the images were then imported to ImageJ. Image processing, segmentation and analysis were all performed in ImageJ. This semi-automated method of analysis allows for a large number of samples in a relatively short time.

Petrologic and textural characteristics between samples are compared and contrasted with other crater and field parameters, including target lithology and field occurrence. Grain size frequency distributions, possible preferred orientations of the clastic content and other attributes are examined. In addition parameters like mineral-fragment included in melt particles and vesicle content are also mapped and analyzed.

The goal of this research is that the systematic petrologic and textural comparison of suevites will increase our understanding of the origin and depositional mechanism(s) and inform our knowledge on impact cratering dynamics.

## ZIRCON $Ce^{4+}/Ce^{3+}$ RATIO DETERMINATION BY LA-ICP-MS MICROANALYSIS AS A PROSPECTING TOOL IN PORPHYRY Cu EXPLORATION: CASE STUDIES FROM THE SOUTHERN YUKON

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Numerous studies suggest that a genetic link exists between oxidized magmas and porphyry-style Cu ( $\pm$  Au  $\pm$  Mo) mineralization.

It is therefore both commercially and scientifically important to determine whether this association is robust and, if so, whether it can be used as a reliable indicator of the prospectivity of intrusive igneous bodies. However, traditional indicators of magmatic redox state – such as whole-rock  $Fe^{3+}/Fe^{2+}$  ratio and oxide mineralogy – can be reset during both hydrothermal alteration and surficial weathering.

Zircon ( $ZrSiO_4$ ) is an abundant accessory mineral in granitoid igneous intrusive rocks, and is both refractory and resistant to alteration. As such, it preserves its primary crystallization chemical composition even where the parent rock has been hydrothermally altered, or subjected to intense physical and/or chemical weathering. Trivalent heavy rare earth elements readily substitute for Zr within the zircon crystal lattice, but the degree of substitution decreases markedly with increasing ionic radius. Hence, the light rare earth elements are relatively excluded, with distribution coefficients readily predictable by calculation from a standard lattice-strain model. Both Ce and Eu show significant deviations from this model behaviour, however, due to their additional stable +4 and +2 oxidation states, respectively. Zircon commonly displays a significant positive Ce anomaly, as  $Ce^{4+}$  is preferentially incorporated into the zircon lattice over  $Ce^{3+}$  due to its identical charge to  $Zr^{4+}$ . The magnitude of this anomaly correlates directly with the  $Ce^{4+}/Ce^{3+}$  ratio in the parent magma, and as such can be used as a qualitative proxy for oxidation state.

In this study, we used laser-ablation inductively-coupled plasma mass spectrometry (LA-ICP-MS) microanalysis to determine zircon  $Ce^{4+}/Ce^{3+}$  ratios and U-Pb ages for a complex suite of granitoid intrusions from southern and western Yukon. Much of the Yukon remained ice-free during the last glacial maximum, in contrast to the majority of the rest of Canada, and as a consequence the depth and degree of surficial weathering is commonly greater than is present elsewhere. Sampling was conducted at a number of scales, from detailed investigation of individual phases within a single intrusive stock, to regionally extensive reconnaissance sampling of pluton and batholith complexes across the territory. Initial results show that LA-ICP-MS microanalysis allows deconvolution of complex magmatic redox evolution within a long-lived igneous system, and can fingerprint phases associated with economically significant base metal mineralization.

## ASSESSMENT OF THE BIOGEOCHEMICAL ALTERATION OF OIL SANDS PROCESSED MATERIAL (OSPM) USING IN SITU CHEMICAL MICRO-SENSORS

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Processing oil sands for extracting bitumen produces a significant volume of mine waste. The current practice is gravity settling and subsequent storage in large basins. The denser material, mature fine tailings (MFT), is then transferred into end-pit lakes (EPLs). An ongoing sustainable strategy is creating a containment region by combining the mined-out pits, (e.g. West In Pit) into a series of end pit lakes. One key factor to the implementation of successful end pit lake design is how the underlying sediment will develop over time. Sediment Oxygen Demand (SOD) is a major contributor to oxygen depletion. Biochemical processes occurring at the sediment-water interface can influence lake dynamics and sustainability. The biogeochemical reactions associated with the evolution of natural sediment can be altered by the presence of Oil Sands Processed Material (OSPM). Establishing the biotic and abiotic controls of SOD is imperative in assessing and developing current end pit lake remediation prediction models. Laboratory microcosm experiments are used to investigate the effects of the established microbiology on the REDOX chemistry associated

with the MFT/water interface. Changes in the physico-chemical properties of the MFT are being assessed in both aerobic and anaerobic environments. In this study we apply novel microelectrodes to assess the diffusion rates of sulfur and oxygen during the onset of deposition. The information collected from these experiments will be used to develop SOD prediction models for large end pit lake systems.

#### GEONEUTRINOS AND THE SNO+ PROJECT

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The successor experiment to the Sudbury Neutrino Observatory is called SNO+ and consists of the same detector from the original experiment only to be filled now with liquid scintillator. This will enable, as one of several science goals, the detection of geoneutrinos—the antineutrinos emitted by natural radioactivity in the Earth's crust and mantle. Neutrino physicists and geoscientists are starting to explore what can be learned from their detection. By detecting geoneutrinos SNO+ plans to measure the amount of uranium and thorium in the crust as well as deeper inside the Earth. SNO+ is located in a thick and relatively uniform region of continental crust which has been exquisitely characterized (because of mineral exploration, seismic studies, heat flow measurements, deep bore holes and airborne radiation surveys). It is thus an ideal place to measure geoneutrino fluxes since local contributions can be well calculated and removed from the expected signal (permitting a measure of the deep Earth component). SNO+ is currently under construction and an overview of this project and of geoneutrinos will be presented.

#### PRELIMINARY LA-ICP-MS TRACE ELEMENT AND ISOTOPIC CHARACTERIZATION, AND U-Pb DATING OF CARBONATE AND APATITE FROM THE OKA CARBONATITE COMPLEX, QUÉBEC (CANADA)

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The Oka carbonatite complex is one of the most westerly intrusions of the Monteregean Igneous Province (MIP). The exact origin of the MIP alkaline intrusions still remains unknown and has been attributed to either melting of lithospheric mantle, a mantle plume origin, or linked to magmatism associated with the Vermont White Mountains and the New England seamounts. Moreover, there remains much debate as to the exact origin of parental melts to carbonatites; i.e., derivation from lithosphere, a mixture between lithosphere and asthenosphere, or an asthenospheric origin. However, deciphering mantle sources and melt crystallization histories based on whole rock isotopic data is rendered difficult since previous studies of carbonatite-bearing, alkaline complexes indicate isotopic disequilibrium amongst co-existing minerals and/or with their corresponding host rock.

Consequently, a multi-faceted study was initiated involving in-situ chemical (major and trace element) and isotopic (C, O, Sr, U-Pb) characterization of the dominant minerals (e.g. apatite, calcite) at the micron scale in the carbonatites and associated alkaline Si-undersaturated rocks (e.g. okaite) from Oka. Preliminary major and trace element analyses (laser ablation-ICP-MS) and in-situ Sr isotope analyses (laser ablation-MC-ICP-MS) of mainly carbonates were obtained for several carbonatites and a melilite-bearing okaite. Major element analyses reveal that carbonates are calcite and apatite is REE-enriched (total REEs >4 wt%). In-situ trace element analyses of calcite within 5 distinct areas from a carbonatite indicate similar REE abundances, and corresponding in-situ  $^{87}\text{Sr}/^{86}\text{Sr}$  isotope values are extremely uniform (0.70322–0.70339; given uncertainties). Contrarily, in-situ trace element analyses of calcite from the okaite show variable REE

abundances that correlate positively with their  $^{87}\text{Sr}/^{86}\text{Sr}$  values (0.70270–0.70303). The first U-Pb dates obtained by LA-ICP-MS on individual apatites from a carbonatite define a range of between ca. 100 and ca. 137 Ma, and these correlate negatively with U and Th contents; grains yielding the oldest dates define a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $124 \pm 4.7$  Ma ( $2\sigma$ ). The negative correlation between U (and Th) contents and Pb/U ages is attributed to recent Pb loss. Apatites displaying uniform trace element compositions from the okaite yield a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $111 \pm 3$  Ma ( $2\sigma$ ). These U-Pb ages overlap the range previously reported for the Oka complex (between  $109 \pm 2$  and  $131 \pm 7$  Ma).

The chemical and Sr isotope data and U-Pb dates obtained thus far for calcites and apatites cannot be explained by closed system magmatic processes, or partial melting from the same (unique) mantle source.

#### TIME PERIOD OF PHASE B OF THE YANSHANIAN OROGENY IN THE EAST OF NORTH CHINA CRATON REFINED FROM DATING OF A DUCTILE SHEAR ZONE IN THE YANSHAN BELT NORTHEAST OF BEIJING

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The Yanshan orogenic belt is an important Mesozoic tectonic feature in the north of the North China Craton (NCC). It was formed by the “Yanshanian orogeny” (Wong, 1927, Bulletin of Geological Society of China). The Yanshanian orogeny has two phases (A and B) reflected by two regional angular unconformities. Both phases are characterized by crustal shortening. Phase A is marked by the unconformity beneath the andesite volcanic rocks of the Tiaojishan formation and Phase B by the unconformity beneath volcanic rocks of the Zhangjiakou formation. The end of Phase B represents the transformation of the east part of the NCC from crustal shortening to crustal extension. Although the time gap represented by the angular unconformity marking Yanshanian Phase B has constrained isotopically to be between 145 and 126 Ma, the precise time duration for Phase B remains to be further refined.

Within the central segment of the Yanshan orogenic belt, the Sihetang ductile shear zone is identified as having developed during Phase B of the Yanshanian Orogeny. We have dated the deformation of this shear zone and our work has bearings on the timing of Phase B of the Yanshanian orogeny. The Sihetang shear zone is located to the north of the Early Cretaceous Yunnengshan pluton. Shear sense indicators suggest top-to-the-SSW thrusting. The metamorphic basement, Meso- and Neo-proterozoic cover layers, and Late Jurassic to Early Cretaceous plutons are involved in the ductile shear zone deformation. Many syntectonic dykes are present in the Sihetang shear zone, and their order of emplacement during shearing is established by structural analysis. Dykes are divided into early, intermediate, and late stages, based on their geometries within the shear zone. Zircons from dykes of each stage are selected for dating. LA-ICP-MS zircon U-Pb ages for the three stages are respectively  $143.0 \pm 2.1$  Ma,  $140.8 \pm 1.4$  Ma, and  $137.5 \pm 2.4$  Ma, consistent with dyke emplacement order constrained from structural analysis. We suggest that 143–138 Ma should be the time period for the Sihetang ductile shear zone deformation. Considering the ages of deformed and un-deformed plutons associated with the shear zone, we suggest that the shear zone deformation represent the entire duration of Phase B. Therefore, the time period of Phase B of the Yanshanian Orogeny is 143–138 Ma. After 138 Ma, the east of the NCC entered a regime of crustal extension.

## RECONSTRUCTION AND ANALYSIS OF MORPHOLOGICALLY COMPLEX PRIMARY VOIDS IN THE NEOPROTEROZOIC LITTLE DAL REEFS, NWT, CANADA

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Most work directed toward determining the timing and nature of the origin of metazoans focusses on biomarker evidence, but controversial morphological evidence has also been put forward. Previous work on polymuds and stromatolite voids in Paleozoic and Neoproterozoic rocks indicates that the former presence of metazoan-grade tissue can be inferred from distinctive microstructures in carbonate rock, such as polymuds and stromatolite voids. It is also possible that unmineralised, simple biological entities embedded in firm carbonate sediment decayed after death leaving behind voids that represent the moulds of their bodies.

Complex millimetre-scale voids are moulded in calcimicrobial lithofacies of reef rock from the Basinal assemblage of the Neoproterozoic Little Dal Group, NWT (<1083 Ma; >779 Ma). The voids were studied with a combination of optical petrography and serial grinding at 200  $\mu\text{m}$  intervals followed by 3-D reconstruction. The voids form irregular, interconnected networks of globular, tubular and laminoid volumes, each enclosed by numerous increments of microbial lamination. In many cases, microbial laminae are deflected in the vicinity of voids, suggesting that they interacted spatially with a mass embedded in the microbial mat. Voids are lined with thick isopachous rinds of marine cement, indicating that they formed extremely early.

The Little Dal reef voids are in a laminar microbialite and do not resemble the framework voids that are common among digitate calcimicrobial stromatolites elsewhere in the reefs. They do not conform to existing descriptions of other well-known void types such as fenestral fabric, stromatolite or molar-tooth structure. Existing descriptions of voids formed by gas bubbles trapped in tufa, travertine, speleothems and microbialites indicate fairly simple sphaeroidal to lenticular shapes, to which the Little Dal voids do not compare favourably. It is possible that the complex early voids in Little Dal calcimicrobialite represent moulds of macroscopic eukaryotes, but the data obtained in this study do not permit their identification, and other analytical work will be required.

## THE ROLE OF IRON OXIDES AND COPPER IN AEROBIC BIOLOGICAL METHANE CYCLING

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Copper co-precipitation and adsorption on poorly crystalline Fe oxides such as ferrihydrite, formed at the oxic-anoxic redox boundaries in many environments, may exert a dominant control on biological Cu utilization. We show that the concentration of Cu substituted in ferrihydrite controls the activity of organisms involved in aerobic biological methane oxidation. Ferrihydrite-rich minerals with relatively low Cu/Fe molar ratios (~0.1) appear to promote growth for both type I and type II methanotrophs, resulting in elevated  $\text{CH}_4$  oxidation rates. By contrast, at higher Cu/Fe molar ratios where ferric nitrate was a significant component of the ferrihydrite, enhanced dissolution of Cu from the minerals reduced  $\text{CH}_4$  oxidation rates by up to 90%. Furthermore, growth of aerobic methane oxidisers in the presence of these minerals results in significant Cu isotope fractionation, with lighter  $\delta^{65}\text{Cu}$  signatures associated with biomass. The magnitude of isotopic fraction-

ation is related to both growth and  $\text{CH}_4$  oxidation rates, confirming Cu utilization from minerals for growth and activity. These results provide a likely explanation for the widespread association of these organisms with naturally occurring ferrihydrite-rich deposits.

## MICROSTRUCTURAL AND FLUID INCLUSION STUDIES OF OROGENIC GOLD DEPOSITS FROM THE RED LAKE AND ABITIBI GREENSTONE BELTS, CANADA: IMPLICATIONS FOR HYDRODYNAMICS AND FLUID-STRUCTURAL RELATIONSHIPS

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Large fluid pressure fluctuations have been commonly documented in shear zone-related orogenic gold deposits, and interpreted to be largely responsible for opening and closing of fractures and associated fluid flow at a given stress condition, as outlined in the fault-valve model. However, combined microthermometric and microstructural studies of fluid inclusion planes (FIPs) from several localities in the Archean Red Lake greenstone belt and the Donalda gold deposit in the Abitibi greenstone belt appear to indicate that the local principal stresses may have flipped episodically during the formation of the auriferous quartz-carbonate veins.

In the world-class Campbell-Red Lake gold deposit and smaller-scale deposits in the eastern Red Lake greenstone belt, a large number of carbonate  $\pm$  quartz veins are developed along SE-trending subvertical deformation zones and are commonly parallel or subparallel to the foliation. Fluid inclusions in the pre-ore and syn-ore carbonate and quartz are dominantly carbonic, contrasting aqueous and aqueous-carbonic inclusions in post-ore minerals. Large fluid pressure ranges were estimated for the pre-ore (0.7–3.5 Kb) and syn-ore (0.9–5.4 Kb) stages. Most of the FIPs are parallel or subparallel to the foliation. Although a reduced tensile strength along the foliation coupled with supralithostatic fluid pressure may explain the formation of the foliation-parallel veins with the  $\sigma_1$  being perpendicular to foliation and  $\sigma_3$  being subvertical, the orientation of the FIPs requires  $\sigma_3$  being subhorizontal, suggesting that  $\sigma_3$  may have flipped episodically during the incremental history of the veins.

In the Donalda gold deposit in the southern Abitibi greenstone belt, two subhorizontal auriferous quartz veins are developed and slightly displaced by unmineralized subvertical shear zones. Fluid inclusions occurring in a randomly distributed mode and as intracrystal FIPs comprise aqueous and aqueous-carbonic types, whereas those in intercrystal FIPs representing post-ore fluids are mostly aqueous. FIPs and veinlets cutting primary vein minerals are mostly subvertical, indicating subhorizontal  $\sigma_3$ . This local stress orientation is different from the regional stress field in which  $\sigma_3$  is subvertical, suggesting that the local stress field may have periodically changed in orientation during the growth of the vein.

The episodic flipping of local principal stresses in shear zone-related gold deposits, also reported elsewhere in the literature, may be related to episodic upwelling of deeply derived fluids and/or the bridging effect due to uneven mineral growth in fractures. Both factors are inherently associated the development of shear zone-vein systems.

## THE PISECO LAKE SHEAR ZONE: A SHAWINIGAN SUTURE?

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The Piseco Lake Shear Zone (PLSZ) spans the Adirondack Dome for over 100 km from west to east and is a crustal-scale boundary separating ca. 1.35-1.25 Ga arc rocks of the southern Adirondacks from younger rocks of the Trans-Adirondack Back-arc Basin (TABB) to the north. The PLSZ is over 30 km wide, and characterized by a pervasive, shallowly plunging E-W lineation, vertical zones of well-developed L- and L-S tectonite, and megacrystic granitic mylonites of calc-alkaline chemistry; in contrast with the adjacent AMCG pluton-dominated (ca. 1.65-1.55 Ga) central Adirondacks. Analysis by LA-MC-ICP-MS indicates that rocks from the PLSZ contain zircon with ca. 1.20 Ga cores and 1.16 Ga rims, with little, if any zircon younger than 1.10 Ga. Nearby anatectic melts of the pelitic mylonites of Sacandaga Formation contain ca. 1.18-1.16 Ga metamorphic zircons. The lack of ca. 1.06-1.04 Ga "Ottawan" zircon within the PLSZ and surrounding pelitic mylonite suggests that this part of the Adirondacks was assembled and experienced the bulk of its deformation just after or during the later stages of the Shawinigan Orogeny. It is proposed that PLSZ is a cryptic suture of Shawinigan age which accommodated displacement between, and welded, the Dysart-Mt. Holly arc to the Laurentian margin during collapse of the TABB. Voluminous calc-alkaline granitic gneisses, with depleted mantle Nd model ages of 1.37-1.54 Ga and radiogenic  $\epsilon_{\text{Nd}}$  values of 1.97-3.66, were intruded along this suture and were derived from the reworking and melting of a source region dominated by ca. 1.35-1.30 Ga tonalitic and associated cover rocks during subduction and collision. Left-lateral kinematic indicators, strain markers and the width of the shear zone require considerable displacement, making the origin geospatial configuration of key components across the PLSZ unknown. A Shawinigan age for deformation associated with the PLSZ further establishes the importance of this event throughout the region, requires a suture and associated subduction zone, and explains the associated lack of Ottawan zircon in pelitic anatectites. Key questions remain concerning the eastern exposure of the PLSZ where it has a southerly trace, and may be the intersection transition with dextral shear zones (1.08-0.88 Ga) that trace NE out of Hudson Highlands. Late muscovite and chlorite growth indicate a low-grade history whose timing remains unresolved, but is likely late to post-Ottawan.

## MAGNETOTELLURIC PROSPECTING IN THE MATAGAMI MINING CAMP

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The Perseverance mine is the only productive mine in the Matagami mining camp and has a 2-3 more years of life expectancy. Bracemac-McLeod is the only mine under development and should start production in year 2013 for duration of 4+ years.

In order to explore for new orebodies and help understanding the subsurface structure between two known zones of ore deposits, a magnetotelluric survey was carried out in 2007. The data were collected by Quantec Geoscience using their Titan24 system, at 1297 sounding sites along 22 MT profiles in the frequency range (10<sup>-1</sup>-10<sup>4</sup> Hz).

Data analysis shows that the subsurface is in general bi-dimensional with a few sites being tri-dimensional. The regional geoelectrical strike was found to be N40°W for the 2D sites. TM inversions with static shift corrections and various controlling parameters were achieved for profiles aligned along the survey profiles. 2D inversion along cross lines was also carried out to level all survey profile models.

Resulting 2D MT inversion models along survey lines were interpolated into 3D models. MT responses were computed from those 3D models and compared with the survey data. A good fit was generally found. 3D MT inversions were also performed in order to validate the main structures found in the 2D inversion models. Some strong correlations were found between the resistivity distribution from the 3D models and IP, gravity and magnetic anomalies observed in the region. Shallow structures of high resistivity were found in the N-W area of the MT survey. The shallow structures correlate with higher topographic relief and thin overburden and where the IP anomalies were detected.

A gravity survey done in the same region as the MT survey shows a gravity low anomaly corresponding to a low resistivity region. This region is located where thicker overburden with the presence of clay is interpreted. The anomaly also correlates with the DC resistivity and the magnetic survey. Deep vertical structures showing lower resistivities with strike oriented at N440E were observed at depths below 1.5 km; these structures could be related to the Proterozoic dikes found in the region and mapped by the magnetic survey. Also the 3D models show an increase of resistivity at a depth of about 1.5 km over the whole survey area. A contact between mafic rocks (basalts) above and more felsic rocks (rhyolite or intrusive granitoid rocks) below can be inferred. Joint interpretation of MT with gravity and magnetic data, constrained by geological data, needs to be done to increase confidence in the findings which are of importance to the exploration program in the region.

## THE NIOBIUM-TANTALUM MINERALIZATION OF THE UPPER FIR CARBONATITE, EAST-CENTRAL BRITISH COLUMBIA, CANADA: PRELIMINARY RESULTS

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This presentation focuses on the niobium and tantalum mineralization in the Upper Fir carbonatite which is the largest system within a group of carbonatite-alkaline-ultramafic rocks in the Monashee Mountains of British Columbia. These complexes together with the regional miogeoclinal strata have been multiply deformed and metamorphosed to upper amphibolite facies. It is proposed that during such events Nb, Ta and the REE have been locally re-mobilized.

The carbonatites form sill-like bodies of variable thickness that show textural evidence of intense recrystallization and strong deformation. Despite the metamorphic overprint that led to the development of such fabric types as granoblastic, gneissic, and porphyritic, different types of carbonatite can be distinguished. The two most widespread carbonatite types are magnesio- and calcio-carbonatites with the former prevailing. The magnesiocarbonatite consists mostly of ferroan-dolomite, fluorapatite, amphibole-group minerals and minor amounts of monazite, zircon, iron oxides and sulfides, and the Nb-Ta minerals pyrochlore and ferrocolumbite. Calciocarbonatites occur only within the magnesiocarbonatites and are similarly enriched in pyrochlore, but lack ferrocolumbite. Both pyrochlore- and columbite-tantalite group minerals can be found in a large number of assemblages and carbonatite sub-units allowing a comparison of the compositional variations in these



phases with their geostructural-morphological position in the complex.

The pyrochlore group minerals show a continuous change in composition, basically following trends which are also known from other carbonatites world wide. Some grains, however, show compositions that reach into the microlite field of the pyrochlore classification diagram. These are areas within typical pyrochlore grains that show evidence for metasomatism and remobilization of Nb and Ta. The composition of ferrocolumbite is controlled to some degree by the composition of the associated pyrochlore which is replaced by the former. It shows micro-textural and compositional evidence for dissolution-precipitation processes resulting from intense metasomatism. Such a metasomatic event could be related to the late stages of the magmatic evolution or, given the circumstances, related to high-grade metamorphism and accompanying fluid flow.

These preliminary results show that parts of the magmatic record of carbonatites can be preserved despite intense metamorphism and tectonic reworking. Magmatic textures and lithological relations are partly preserved, but localized mechanical remobilization caused a redistribution of many phases including the Nb-Ta minerals. Additionally, evidence are provided that Nb and Ta have been remobilized either during late-stage magmatic processes or during metamorphism.

#### **EVIDENCE OF MIXING BETWEEN MICHIGAN BASIN BRINE AND GLACIAL MELTWATER IN DEVONIAN & SILURIAN FORMATIONS, BRUCE NUCLEAR SITE, BRUCE COUNTY, ONTARIO**

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Multi-disciplinary geoscientific studies were conducted at the Bruce nuclear site to confirm the suitability of the site to host a proposed Deep Geologic Repository (DGR) for the long-term management of low and intermediate level radioactive waste (L&ILW). The Bruce nuclear site, situated 225 km northwest of Toronto, on the eastern shore of Lake Huron, is underlain by an 850 m thick sedimentary sequence of Cambrian to Devonian age near-horizontally bedded shales, carbonates and evaporites of the Michigan Basin. The proposed DGR would be excavated within the low permeability argillaceous limestone of the Middle Ordovician Cobourg Formation at a depth of 680 m, which is overlain by 200 m of Upper Ordovician shales.

A 4-year geoscientific investigation of the Bruce nuclear site, including a deep drilling and data collection program, coupled with regionally based hydrogeologic studies, has provided a basis to examine fluid and solute migration within the sedimentary sequence (Intera 2011; NWMO 2011). A key element in this assessment was the analysis of groundwater and pore fluids to determine the spatial distribution of natural tracers within the entire 850 m sequence. The natural tracers included  $^{18}\text{O}$ , D, major ions,  $^{87}\text{Sr}/^{86}\text{Sr}$ ,  $\text{CH}_4$  ( $^{13}\text{C}_{\text{CH}_4}$  and  $\text{D}_{\text{CH}_4}$ ),  $\text{CO}_2$  ( $^{13}\text{C}_{\text{CO}_2}$ ), and He ( $^3\text{He}/^4\text{He}$ ). The results provide evidence of a predictable geosphere with distinct shallow (0-170 mbgs), intermediate (170-447 mbgs) and deep (447-860 mbgs) hydrological systems.

The environmental tracers reveal a history of mixing between meteoric waters and basin brines, with a transition from fresh water (TDS  $\sim 0.5$  g/L) in the shallow system to brine (TDS  $> 350$  g/L) in the underlying intermediate system. The  $\delta^{18}\text{O}$  and  $\delta\text{D}$  profiles suggest that the Devonian waters of the shallow domain, and the groundwater and pore fluids within the Silurian intermediate system, have mixed to varying degrees with glacial melt water(s)

and/or meteoric water. The saline groundwater (30 g/L) from the confined Salina A1 Unit carbonate aquifer ( $\sim 325$ - $328$  mbgs) has a depleted stable isotopic fingerprint,  $^{18}\text{O}$  ( $< -14.3\text{‰}$ ) and D ( $< -102.6\text{‰}$ ), relative to the overlying units of the Salina Formation and the underlying Lower Silurian carbonates, and represents the maximum depth of glacial melt water infiltration at the Bruce nuclear site. Below the Salina A1 Unit carbonate, porewater salinities increase sharply to  $\sim 370$  g/L in the Guelph Formation groundwater ( $\sim 375$ - $379$  mbgs), and  $^{18}\text{O}$  and D values increase to  $\sim 2.5\text{‰}$  and  $\sim 49\text{‰}$ , respectively. The observed depth of penetration by glacial waters is consistent with paleohydrogeologic simulations of the regional groundwater system in response to Pleistocene glaciation (Peltier, 2011; Sykes et al., 2011).

#### **A NEW FACILITY FOR AMS, STABLE ISOTOPE AND GEOCHEMICAL RESEARCH IN THE EARTH AND ENVIRONMENTAL SCIENCES AT THE UNIVERSITY OF OTTAWA**

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The University of Ottawa is establishing a new facility dedicated to isotope and geochemical research in the earth and environmental sciences which will be located in a new research building being constructed by the Faculty of Science. A central feature of this facility, supported by the Canada Foundation for Innovation, is a 3 MV multi-element AMS system manufactured by High Voltage Engineering Europa B.V. in The Netherlands. The system is equipped for routine analysis of tritium,  $^{10}\text{Be}$ ,  $^{14}\text{C}$ ,  $^{26}\text{Al}$ ,  $^{36}\text{Cl}$  and  $^{129}\text{I}$  but features injection and analyzing magnets for the analysis of masses up to and beyond plutonium. Multiple ion source configurations include a 200-sample SO110 sputter ion source with a high-resolution injection magnet with fast and slow isotope selection electronics, a novel  $\text{CO}_2$  gas ionization source and the new isobar separator developed at IsoTrace that eliminates  $^{36}\text{S}$  and other confounding isobars. Given the growing demand in Canada for  $^{14}\text{C}$  by AMS, three new state-of-the-art,  $\text{CO}_2$  preparation and graphitization laboratories are being built at the University of Ottawa, Centre d'études nordiques, Université Laval, and GEOTOP, UQAM, for collaboration on  $^{14}\text{C}$  target preparation for the new AMS system. A radio-halide preparation laboratory is featured in the new building at uOttawa, and cosmogenic nuclide samples for the AMS will be prepared in fully-renovated facilities at the Dalhousie Geochronology Centre, including a new low background stainless steel vacuum system for in situ cosmogenic  $^{14}\text{C}$ .

The AMS is supported by a broad range of new, CFI-supported instrumentation, including a JEOL JXA-8230 electron microprobe with 3 wavelength dispersive spectrometers and an energy dispersive spectrometer, a JEO JSM-6610LV scanning electron microscope with EDS, an Element XR high resolution sector ICP-MS with ultra short pulse Excimer laser ablation system, a Helix Split Flight Tube noble gas mass spectrometer for primarily helium isotopes and a Helix Multicollector noble gas mass spectrometer for isotopes of He through Xe, a ThermoFisher Delta V with IsoLink interface for stable isotopes in organics, as well as two laser cavity ring-down stable isotope analyzers for  $^{18}\text{O}$  and D in water. The new isotope and geochemical instrumentation will be installed in the new building, to which the existing G.G. Hatch isotope and geochemical laboratories at the University of Ottawa will be moved. The new facilities feature an open concept to enhance collaboration between the laboratories, based on physical connectivity and adjacency. The HQP training experience for

visiting students and researchers will be promoted in the new AMS and associated labs, facilitated by a wing of offices and desks for temporary assignment. Construction is anticipated to be completed in late 2012. In the interim period, temporary laboratory space is now accommodating the construction of sample preparation systems for  $^{14}\text{C}$  and radiohalides as well as the major, non-AMS instruments, and the University of Ottawa is continuing to operate the existing IsoTrace facility at the University of Toronto for radiohalide and actinide analyses and further AMS research.

#### **GEOPHYSICAL PILOT STUDY OF A SMALL AQUIFER NEAR DEEP RIVER, ONTARIO**

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A group of undergraduate students performed a geophysical pilot study in October 2010 at a small aquifer just South of the Ottawa River. The site has been the focus of hydrological research for over a decade, and has seen the installation and monitoring of over 30 research wells and extensive auguring. The aquifer consists of sand from an old meander of the Ottawa River bounded by glacial till. The group acquired ground-penetrating radar (GPR), magnetometry, and resistivity data along a 100 m SE-NW trending transect. All three methods show very clear variations which compare well with the augur results at the edges of the aquifer. The GPR data beautifully delineates the bottom of the aquifer and shows an interesting feature near a well that has a unique geochemical signature. An expansion of our initial survey is being planned.

#### **A SEDIMENTOLOGICAL AND STRATIGRAPHIC STUDY OF THE COAL-BEARING LENTON DEPOSIT, BOWEN BASIN, CENTRAL QUEENSLAND, AUSTRALIA**

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The Bowen Basin is one of the most intensely explored sedimentary basins in Australia and hosts one of the world's largest coking coal deposits. This study focuses on the Lenton Coal deposit that occurs in the central part of the Bowen Basin and targets the Rangel Coal Measures, which is the youngest (245 Ma), most extensive and least structurally deformed of the three groups of Permian coals currently being targeted for coking coal resources in the Bowen Basin.

Six lithofacies have been identified from detailed bed-by-bed logging of two cores (229.5 and 454.5 m, respectively) in the Lenton deposit and include (A) medium- to coarse-grained sandstone, (B) interbedded siltstone and mudstone, (C) interlaminated siltstone and sandstone, (D) carbonaceous siltstone and mudstone, (E) coal and (F) volcanic ash, which then make up two facies associations. The first consists of a 50 m thick interval consisting of Facies (D), (E), and (F). It, in turn, is unconformably overlain by Facies Association 2, which comprises two parts; a 100-150 m thick basal unit of Facies (D), (A) and (C) gradationally overlain by a 200 m thick unit of interbedded Facies (A), (B) and (C), which collectively indicates a temporal change from permanently waterlogged (E) to seasonally waterlogged (B) soil conditions. The boundary between facies associations 1 and 2, on the other hand, is sharp marked by an abrupt change in colour (from grey to green strata), a sharp increase in grain size (fine-medium to medium-coarse sand) and an overall decrease in organic carbon content. This boundary coincides also with the Permian-Triassic boundary and the mass extinction of 95% of the Earth's peat forming plants. The change from grey (clay-carbonate minerals) to

green (chlorite-zeolite minerals) coloured strata suggests a significant reduction in the amount of available organic material, a consequence of the disappearance of widespread peat-forming swamps.

#### **DOLOMITIZATION OF THE LOWER ORDOVICIAN CATOCHE FORMATION: IMPLICATIONS FOR HYDROCARBON EXPLORATION IN WESTERN NEWFOUNDLAND**

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The lower Ordovician St. George Group in Western Newfoundland consists of a sequence of subtidal and peritidal carbonates, which are extensively dolomitized. The current study investigates the diagenetic evolution of the Catoche Formation from the major exposed reservoir on the Port aux Choix Peninsula and the proven hydrothermal dolomite reservoir on the Port au Port Peninsula in order to study the controls on reservoir quality in western Newfoundland.

Three phases of dolomite have affected the formation. Early and pervasive replacement dolomicrite ( $D_1$ ) are fine grained and indicate that dolomitization began during early stages of diagenesis at almost near-surface conditions. Stable isotope and trace element data indicate significant variations between  $D_1$  dolomite on the Port aux Choix and Port au Port peninsulas. The Port aux Choix Peninsula is interpreted as a structural high and was exposed soon after deposition of the Catoche carbonates. The  $\delta^{18}\text{O}$  signature of  $D_1$  dolomite fluids ( $-8.8 \pm 1.3\text{‰ VPBD}$ ), along with trace element contents, support a mixing zone model for  $D_1$  dolomitization. In contrast the Port au Port Peninsula was located in a shallow restricted basin and  $D_1$  is more pervasive and  $\delta^{18}\text{O}$  and trace element data indicate that it was associated with mixing of possibly post evaporitic brines (sourced in the overlying restricted basins) with meteoric waters (from the structural highs), similar to strand-zone dolomitization in modern environments.

Later replacement dolomites ( $D_2$ ) formed due to the influx of warm ( $>100^\circ\text{C}$ ), saline ( $>15$  eq. wt% NaCl) waters. Comparisons between fluid inclusions homogenization temperatures,  $\delta^{18}\text{O}$  values and maximum burial temperatures indicate that  $D_2$  dolomitization was hydrothermal on the Port au Port Peninsula but likely geothermal on the Port aux Choix Peninsula. Intercrystalline porosity in  $D_2$  dolomites formed due to the dolomitization of precursor calcite, due to the lower molar volume of dolomite compared to calcite. Therefore porosity development is lower on the Port au Port Peninsula, with no significant volume change during the recrystallization of the pervasive early ( $D_1$ ) dolomicrite. Similarly, extensive porous horizons on the Port aux Choix Peninsula are related to the limited extent of early  $D_1$  dolomitization. This suggests that the quality of a potential dolomite reservoir is strongly controlled by tectonic and diagenetic history of host carbonates and future hydrocarbon exploration in western Newfoundland should focus on structural highs, which have the best chance of preserving significant porosity.

#### **THE KIPAWA ALKALINE SYENITE COMPLEX AND ITS RARE EARTH ELEMENT DEPOSIT**

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The 1033  $\pm$  2 Ma syenite Kipawa complex is a folded sheet-like body ( $<300$  m-thick) located north of the allochthon boundary thrust, and which has been traced along-strike for about 100 km (vanBreemen and Curry, 2004). Peralkaline lithologies hosting the REE mineralization are mostly amphibole syenite, nepheline syen-

ite, quartz syenite, and peralkaline granite. Marble and various calc-silicates are located along the contact between the Kipawa complex and the 2.7 Ga Kikwissi (granodiorite and tonalite). As compiled from the literature and our results, the identified rare minerals from the Kipawa region include: alkali and/or calcic zirconosilicates (eudialyte, vlasovite, mosandrite, gittinsite, hiortdahlite, allanite), fluorocarbonate (britholite, fluorite, bastnaesite), phosphate (monazite, xenotime), oxide and other silicates (agrellite, miserite, pectolite, zircon, thorite). Four main REE-Y-Zr zones are known at the main deposit (Sheffield): eudialyte, mosandrite, britholite, vlasovite.

Syenites and alkali granites from the Sheffield deposit have similar chondrite-normalized REE profiles characterized by pronounced negative Eu anomalies ( $\text{Eu}/\text{Eu}^*=0.4$ ). Ratio of  $\text{Eu}/\text{Eu}^*$  remains constant with the increase in  $\text{SiO}_2$  or  $\text{Al}_2\text{O}_3$  and the decrease of CaO suggesting that the fractionation of plagioclase was not significant. Bird-wing patterns with relatively high normalized values for the lightest and heaviest elements (La, Yb-Lu) also occur. Primitive mantle normalized profiles show systematic prominent negative K, P, Ti, Eu anomalies and positive Zr anomalies. A strong positive correlation between whole rock content of fluoride and REE suggest that the involvement of metasomatic fluids combined with the high degree of fractionation of the syenite magma were key aspects in the transport and concentration processes for this REE system.

Wu et al. (2010) reported laser ICP-MS analyses of eudialyte from the Sheffield deposit which provided a U-Pb age of  $1012 \pm 16$  Ma, similar within error to TIMS results for zircon from the peralkaline skarn ( $994 \pm 2$  Ma; vanBreemen and Curry 2004). This eudialyte with an isotope composition of  $\epsilon_{\text{Nd}(t)} = -10.64$ , indicate a geochemical signature akin to partial melting of an enriched mantle source and/or mixing with fluids derived from melting of the over-thickened lower continental crust during the Grenvillian orogeny.

#### **<sup>40</sup>Ar/<sup>39</sup>Ar INVESTIGATION OF THE OTTER LAKE REGION, QC, CENTRAL METASEDIMENTARY BELT, GRENVILLE PROVINCE**

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Convergence during the Grenville orogeny led to crustal thickening and juxtaposition of the currently shallow southeast-dipping imbricated terranes of the Central Metasedimentary Belt (CMB). Subsequent crustal thinning during post-orogenic collapse was likely accommodated along shear zones that were reactivated during extension. The Mont Laurier terrane of the CMB in Quebec contains intercalated Paleoproterozoic gneiss, marble, amphibolite, and quartzite units that originate from upper amphibolite to granulite facies metamorphism of a back-arc sequence. In the Otter Lake region, the terrane is divided into the Marble (west) and Quartzite (east) Domains, separated by southeast dipping Heney deformation zone (HDZ). We performed <sup>40</sup>Ar/<sup>39</sup>Ar thermochronology on a suite of samples, which were collected on a broad transect across the HDZ. Similar thermochronologic investigations conducted in the southern CMB (of Ontario) record cooling ages which young to the east across domains, with marked increases in cooling ages immediate east of shear zones separating the domains. From the Otter Lake region, mineral separates were obtained from garnet-biotite, biotite-plagioclase, and potassium feldspar gneisses, amphibolites and metagabbros, and a marble containing subvertical relict sedimentary bedding. Most samples are pervasively deformed, with fine- to medium-grained biotite defining the foliation fabric; amphiboles exhibit little to no alignment, and are relatively inclusion-free. In the samples from which

mineral separates were taken, deformational features include some sutured and bulging quartz grains, subgrain development, and the brittle deformation of garnet in one sample. Preliminary <sup>40</sup>Ar/<sup>39</sup>Ar analyses yield generally well-behaved age spectra with antithetic Ca/K spectra exhibiting full or near plateaux. East of the HDZ, hornblende ages are ca. 1145 Ma and (euhedral) phlogopite ages are ca. 1120 Ma, whereas west of the shear zone hornblende ages are markedly younger (ca. 890-930 Ma) and similar to biotite ages from this region (ca. 885-905 Ma). Initial interpretation of the <sup>40</sup>Ar/<sup>39</sup>Ar mineral ages considers early exhumation of the Quartzite Domain during collision resulting from thrusting along the HDZ, and younger mineral ages from the Marble Domain as subsequent (dynamically recrystallized) resetting or later exhumation during extensional reactivation of the HDZ.

#### **THE DEVELOPMENT OF THE NORTH MARGIN OF THE NORTH CARIBOU TERRANE THROUGH THE NEOARCHEAN, BUILDING THE FOUNDATION FOR LODE GOLD MINERALIZATION**

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Fault bounded crustal blocks record a complex history of geologic development for the northern margin of the North Caribou Terrane in Manitoba and Northwestern Ontario. Bedrock mapping and structural, geochemical, geochronological and isotopic research in the northwestern Superior Province of Manitoba reveal a complex geologic history of the margin of small continental landmass between ca. 3.0 and 2.7 Ga. Cyclical periods of rifting and the formation of back arc basins, alternating with basin closure and suturing, have been documented. The basin closure was followed by post collisional crustal adjustment concomitant with periods of metamorphism on the craton. These events produced a fertile structural and lithological framework for formation of lode gold mineralization. Subsequent collision with the 3.6 Ga. Hudson Bay Terrane at circa 2.7 Ga left the remnants of a juvenile oceanic basin, the Oxford Stull Domain along the north margin of the North Caribou Terrane. The pre-existing sutures in the North Caribou Terrane and newly formed sutures formed in the collision with the Hudson Bay Terrane provided the framework for an extensive anastomosing set of transpressional shear zones that are now the locus of numerous gold occurrences. These sutures formed crustal scale zones of weakness that provided pathways for mineralizing fluids to migrate upward to pressure temperature regimes conducive to gold deposition. The regionally extensive anastomosing network of transpressive shear zones thus provided the physical traps for an extensive region of lode gold mineralization. It is entirely possible that more than one mineralizing event occurred in the North Caribou Terrane, however, geological evidence indicates post 2.7 Ga mineralization occurred in the juvenile Oxford Stull Domain along the Stull-Wunnummin transpression zones.

#### **MINAS DE CAMAQUÃ (RIO GRANDE DO SUL, BRAZIL): ALSO AN IOCG-TYPE DEPOSIT?**

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After the formation of the Gondwana Supercontinent, rift-type basins associated with ENE-NNE-trending faults were installed in the central-southern region of the State of Rio Grande do Sul (Brazil). The Camaquã Basin, cropping out in an area of more than 3200 km<sup>2</sup> in the Riograndense Shield, is the most conspicuous and is composed of a large variety of continental and coastal sediments

and volcanic rocks associated with A-type granites. Minas do Camaquã, located in the central part of the Camaquã Basin, has the best expositions of the Santa Bárbara Group, which represents the Ediacaran sedimentation of the Camaquã Supergroup, according to the most recent stratigraphic evaluation.

Minas do Camaquã host major base-metal deposits, which are in direct association with a major fault system that crosscut the sedimentary bedding. The ores occur as massive veins, stockworks, and disseminated ores. Exploited for more than 100 years, Minas do Camaquã stopped operating in 1996. Before exhaustion, the ore reserves were 30.8 million tonnes, averaging 1.06% Cu, with Au and Ag as the main byproducts.

Recent lithological-structural mapping of three open pits (namely Uruguai, Piritas and Intermediária) showed that the ores are preferably concentrated in NW-trending, SW-dipping faults and fractures, which are variably mineralized in Au-bearing platy hematite (specularite intergrown with quartz), Cu sulfides and barite. Previous underground works carried out in the neighboring São Luiz mine indicated that the NW-trending faults are perpendicular to oblique in relation to the N30-40E-trending faults of the Irapuá System. Mineralization was also stratigraphically controlled, as it is hosted by the Seival and Rincão dos Mouras Formations, composed of shoreface sandstones and siltites, and fluvial/alluvial sandstones and conglomerates, respectively.

The ore mineral assemblages include chalcopyrite, pyrite, bornite, chalcocite, gold, silver, and hematite. Preliminary MEV-EDS analyses revealed the presence of Bi-Cu-(Ag) sulfides associated with chalcopyrite. Gangue minerals, such as chlorite, K-feldspar, sericite, quartz, carbonate and barite, characterize hydrothermal alteration haloes, which are more intense in the vicinities of the faults and fractures.

A magmatic hydrothermal origin for the Camaquã deposit has been proposed by previous works. Because of the similarity of style of mineralization and hydrothermal alteration with the some deposits of the Proterozoic Tennant Creek district of the Northern Territory (Australia), we propose that at least part of the mineralization (characterized by hematite, chalcopyrite, gold, Bi-Cu-(Ag) sulfides and associated with chlorite, sericite, quartz, carbonate and barite) is of the IOCG-type.

## **PRECAMBRIAN GEOLOGY OF MELVILLE PENINSULA, NUNAVUT: A WINDOW ON THE EVOLUTION OF THE WESTERN CHURCHILL PROVINCE**

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The Western Churchill Province (WCP) forms a collage of Archean crustal blocks with Proterozoic supracrustal sequences, mafic dykes and plutonic suites that were variably reworked in the interval ca. 1.90-1.80 Ga, during the final assembly of the Supercontinent Nuna. Melville Peninsula provides a well-exposed section through the central-eastern Rae Craton, one of the largest pieces of the WCP mosaic. The section exposes from north to south i) a Mesoproterozoic continental rift sequence (Fury and Hecla Formation) and associated E-W brittle normal faults, ii) a granulite facies terrane dominated by metaplutonic rocks of yet unknown –but likely NeoArchean– age, iii) Meso- to Neo-Archean age, *de facto* Rae crust, iv) two Paleoproterozoic supracrustal sequences (Penrhyn Group and Folster Lake Formation), v) a zone of localized ductile transpression with a dextral slip component (Lyon Inlet Boundary Zone), and vi) presumably Archean-age orthogneiss with an anhydrous, orthopyroxene-bearing plutonic suite and a granulite facies cover sequence of marble and metapelite, of likely Proterozoic age (Repulse Bay Block).

The Rae crust consists of isolated strands of upper-greenschist to middle-amphibolite facies Archean volcano-sedimentary belts intruded by, and separated by, ca. 2.76 to 2.60 Ga plutonic rocks of predominantly monzogranitic composition. The Archean supracrustal belts, collectively referred to in the literature as the Prince Albert Group, appear to form remnants of volcanic, volcanoclastic and associated sedimentary rocks, with internal unconformities suggesting complex histories. Preliminary U-Pb age determinations on zircon suggest that two of the largest greenstone belts, the Prince Albert Belt (new name) to the west and Roche Bay Belt (new name) to the east, are separated in age by about 200 m.y. However, similar Nd model ages of about 2.9 to 3.2 Ga on plutonic components of both belts suggest a common source and potential affinities with the Mesoproterozoic Mary River Group on Baffin Island. These ages also suggest a separate evolution from the younger (ca. 2.73-2.71 Ga), Meadowbank and Committee Bay belts that occur further to the southwest. The Paleoproterozoic Penrhyn Group hosts sedimentary strata that appear to indicate an evolution from intracratonic platform to continental margin anoxic or restricted circulation basins that are overlain by thick greywacke-turbidites. North of the Penrhyn Group, the subgreenschist facies Folster Lake Formation may represent remnants of a foreland flysch or molasse basin deposited during the peak of Trans-Hudson Orogeny. Its relatively low grade metamorphic overprint and moderate deformation may provide a northwestern limit for Hudsonian tectonothermal overprint.

## **THE IOCG ALTERATION TO BRECCIATION AND MINERALIZATION ZONING MODEL – A VECTOR TO MINERALIZATION TESTED IN THE GREAT BEAR MAGMATIC ZONE, NWT**

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A conceptual alteration to brecciation and mineralization zoning model that frames the development of iron oxide-apatite, magnetite- and hematite-group iron oxide copper-gold (IOCG) and associated skarn deposits is proving to be a powerful predictive tool for mineral exploration and regional mapping in under-explored and under-mapped terrains. Under the Geomapping for Energy and Minerals (GEM) program, the systematics of alteration and evolution of brecciation were used in the significantly under-explored Great Bear magmatic zone (NWT) to 1) recognize new IOCG systems, 2) validate the model and continuity with other deposit types at known showings and past-producing mines, 3) infer maturity and potential fertility of identified systems, and 4) vector towards mineralization.

One of the case studies centres on the 31 Mt Au-Co-Bi-Cu NICO deposit. Here, magnetite-group IOCG ore is associated with a cyclical build-up of high-temperature calcic-iron and potassic-iron (magnetite) alteration below an unconformity (stages 2 and 3 of the model). The extensive early sodic alteration that provides nutrients for IOCG systems (stage 1) and the low temperature potassic-iron (hematite) alteration, plus uranium/REE mineralization and silicification that should have formed through the cyclical outflow of remaining fluids and elements (stages 5 and 6) had not been observed. Systematic alteration mapping away from the deposit led to the discovery of a 2 by 0.5 km structural breccia corridor with syn- to post-tectonic hydrothermal iron oxide (magnetite to hematite) replacement-style alteration, breccias and veins, and U-Th-arsenopyrite+molybdenite anomalies within sodic-, potassic- or silica-altered metasedimentary rocks. This system records cyclical build up of alteration stages 5 and 6 within albite (stage 1). Strain partitioning between the overlying mas-

sive rhyolite and the steeply-dipping, stratified and more ductile metasedimentary rocks focuses much of the brittle-ductile deformation in the altered metasedimentary rocks. This led to preferential brecciation of the competent albite-altered units and focussed fluid flow upward towards the unconformity. The U-Th mineralizing event with arsenopyrite and traces of molybdenite occurs at ductile-to-brittle and magnetite-to-hematite transitions coevally with syn- to post-tectonic emplacement of porphyry dykes and brecciation. Late-tectonic magnetite veins and post-tectonic hematite veins record the shift to brittle conditions during which brecciation was mainly accomplished by hydraulic fracturing and accompanied by the emplacement of tourmaline breccias and porphyry dykes.

Syn- to post-tectonic development of hydrothermal alteration at the magnetite to hematite transition, structurally controlled (faults, breccias and/or unconformities) alteration and mineralization and regional-scale alteration are attributes of many other hydrothermal systems of the Great Bear magmatic zone.

#### **COMMEMORATING CANADA'S MINING HERITAGE: A LOOK AT NATIONAL HISTORIC SITES, PEOPLE, AND EVENTS**

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Created in 1919, the Historic Sites and Monuments Board of Canada (HSMBC) advises the Minister of the Environment on the commemoration of nationally significant aspects of Canada's history. Following a thorough evaluation process and recommendation by the Board, the Minister declares the site, event or person to be of national historic significance. National historic sites, people, and events are usually commemorated with a bilingual bronze plaque installed in a location that is closely related to the significance of the designated subject and accessible to the public. Parks Canada administers the National Commemoration Program and manages a nation-wide network of national historic sites that reflect the rich tapestry of Canada's cultural heritage.

This talk will first provide an overview of the National Commemoration Program and of the body of commemorations that relate to Canada's mining history. The HSMBC's perspective on Canada's geosciences and mining history has evolved through the decades to cover different aspects of the Canadian past. Considering that the nominated subjects must have an historical significance from a national perspective, beyond local or regional importance, which men and women have been designated for their contribution to the geosciences? Which events have been designated for having a significant impact on Canadian history?

The presentation will also provide an overview of the sites that have been commemorated for their associations with the history of mining. These include sites administered by Parks Canada—such as Dawson Historical Complex National Historic Site of Canada and its important collection of buildings from the Klondike Gold Rush—and a large number of sites owned by other level of governments or private interests across the country. The talk will conclude on a brief discussion of the values the HSMBC is looking for when considering the designation of a mining site for national significance as well as of the challenges encountered in the commemoration and preservation of Canada's mining heritage.

#### **SEAFLOOR GEOLOGY OF THE NORTHEAST PACIFIC OCEAN**

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Steve Scott may be best known for his research work on mineral

deposits, but Scott and colleagues have also collected an extensive set of seafloor lavas from mid-ocean ridges, near-ridge seamounts, and intraplate seamounts in the northeast Pacific. The outstanding characteristic of all seafloor rocks from the northeast Pacific is the intimate co-existence of depleted and enriched components in their upper mantle sources that produce a spectrum of lava compositions from N-type MORB to REE-enriched E-type MORB and alkaline basalts. The enriched component has slightly higher  $^{87}\text{Sr}/^{86}\text{Sr}$  and commonly higher  $^{206}\text{Pb}/^{204}\text{Pb}$ , but lower  $^{207}\text{Pb}/^{204}\text{Pb}$  at a given  $^{206}\text{Pb}/^{204}\text{Pb}$ , compared to the depleted component.  $^3\text{He}/^4\text{He}$  ratios are generally similar to normal MORB, but there is a general tendency for ratios to be lower in E-type lavas. La/Sm correlates positively with  $^{87}\text{Sr}/^{86}\text{Sr}$  and negatively with  $^{143}\text{Nd}/^{144}\text{Nd}$  in northeast Pacific mid-ocean ridge lavas. Garnet does not appear to be a residual phase in the enriched mantle source, but the high water content of northeast Pacific alkaline magmas suggests that the enriched mantle source includes a hydrous phase, possibly phlogopite or amphibole. Melts of amphibole peridotite mixing with melts of depleted upper mantle spinel lherzolite can reproduce the trace element-isotope mixing trends evident in northeast Pacific basalts. The ridge topography and highly heterogeneous nature of MORB along the northern Juan de Fuca ridge do not support a hotspot-type source for the enriched lavas, but the shallow depth of the Southern Explorer Ridge may be consistent with a mantle plume, as is a possible gradient from mixed E- and N-MORB mantle at the shallowest depths to primarily N-MORB mantle to the south. The Tuzo Wilson Volcanic Field, at the north end of the Juan de Fuca-Explorer spreading system, is a pull-apart basin that is tapping enriched mantle derived from the southern Pratt-Welker plume (Bowie Seamount). The Cobb Offset, a non-transform offset that bounds the south end of the Endeavour segment of the Juan de Fuca ridge, is a geochemical boundary that separates the primarily N-MORB Gorda and southern Juan de Fuca spreading segments from the highly heterogeneous N- to E-MORB northern Juan de Fuca, Explorer and TWVF oceanic rifts. Thus the Cobb Offset is the southern boundary of a distinct northern Pacific enriched mantle province.

#### **DOES pH AFFECT SULFUR ISOTOPIC FRACTIONATION DURING BACTERIAL SULFATE REDUCTION?**

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Bacterial sulfate reduction (BSR), which is thought to be one of the earliest bacterial metabolisms to appear on Earth, is a process by which some prokaryotes use sulfate as an electron acceptor to obtain energy for metabolic processes. It results in the reduction of sulfate to sulfide, with a concurrent depletion in the heavier isotope of sulfur,  $^{34}\text{S}$ , relative to the lighter isotope,  $^{32}\text{S}$ . Archaeal sulfide minerals typically present moderate isotopic depletions, in the order of -25‰ (per mil) or less, whereas modern marine deposits are depleted in  $^{34}\text{S}$  by up to 70‰. A variety of factors have been investigated under laboratory conditions as well as in natural settings to explain the isotopic fractionation of sulfur isotopes during BSR, including temperature, substrate type and availability, and sulfate reduction rate. However, because BSR is a proton-consuming reaction, acidophilic and acid-tolerant sulfate reducers possess an energetic advantage at low pH. We hypothesize that pH, which has so far not been investigated as a controlling factor, has the potential to affect fractionation, and that as pH moves away from optimal growth conditions, sulfur isotope fractionation will increase, due to the need for the cells to expend energy in order to maintain electron balance in the cytoplasm. To test this hypothesis,

we will present data from closed-system experiments using two pure strains of acid-tolerant sulfate-reducing bacteria (optimum pH 4 and 4.5).

#### **ca. 720 Ma VOLCANISM IN THE NORTHWESTERN CORDILLERA: A FAR-FLUNG COMPONENT OF THE FRANKLIN IGNEOUS EVENT?**

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Neoproterozoic continental flood basalts (CFB) are known from the North American Cordillera and are thought to be associated with the breakup of Rodinia. However, unlike the short eruptive timeframe of Phanerozoic flood basalt provinces, instances of Neoproterozoic CFB within the North American Cordillera are separated by the unusually long time interval of ca. 56 My (ca. 780 Ma Gunbarrel Event and the ca. 717 Ma Franklin Igneous Event), suggestive of episodic rifting and a long lived thermal anomaly and/or fertile mantle situated under Rodinia.

The Neoproterozoic Tatonduk Inlier, spanning the Alaskan-Yukon border, contains the Pleasant Creek Volcanics which are composed of mafic volcanics and a large arcuate dyke swarm. Previous K/Ar dates on the dikes range from  $532 \pm 11$  Ma to  $644 \pm 18$  Ma appear to be inconsistent with geological constraints and correlations between the Tatonduk strata and the Neoproterozoic sequence of the well-dated Coal Creek Inlier to the east. We present stratigraphic correlations, geochemical data and petrological modeling for the Pleasant Creek Volcanics and evaluate whether these volcanics represent a far-flung component of the Franklin Igneous Event.

#### **EARTH SCIENCE EDUCATION IN ONTARIO HIGH SCHOOLS**

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For most teenagers entering high school their first exposure to Earth Science is through the Astronomy unit in their Grade 9 Science course. They are then further exposed to Earth Science when they study Climate Change in Grade 10. Since the Science graduation requirements for an Ontario high school diploma are two Science credits only, these units may be a teen's only exposure to Earth Science during their entire four years of high school. In Ontario, a senior Earth Science course has been in existence as purely a Science course for only the last two iterations of the Provincial Science curriculum (1999-present), prior to that it was available as both Grade 11 Science (SGE 3A0) or Geography course (GGE 3A0). Currently it is taught as the Grade 12 Earth and Space Science (SES 4U0). However, unless a student is specifically interested in this course, most will not take it, opting instead for either the traditional Chemistry, Physics or Biology courses or finalising their Science education with Grade 10. For those who register for SES 4U0, their decision is based largely on their experience in Grade 9 or through the encouragement of a teacher. Climate Change (or Meteorology, in the old curriculum) in Grade 10 has very little impact on their choosing of this course.

On average classes of SES 4U0 run once per year or once every other year with class sizes varying between 19 and 25 students. Whether the course is offered or not is completely dependent on there being a teacher in the school who has an interest in the subject and can 'fire up' student interest. What is needed in the Ontario high school Science curriculum is a 'carrot' to encourage students to consider the SES 4U as an option for their science education. This incentive could take several possible forms. One pos-

sibility is a change to the graduation requirements. Mathematics requires students to graduate from high school with three math courses, one of which must be a senior math. Why not have the same requirements for Science? Are not both subjects complementary? Another incentive would be the development of a national programme in Canada equivalent to the Iris Consortium's 'Seismographs in Schools' program in the U.S., since this might not only increase interest amongst high school students, it would also serve to enlighten and educate the public on a very important part of Earth Science.

#### **CHEMICAL EXCHANGE BETWEEN HIGHLY CONTRACTING LITHOLOGIES: A STUDY OF ELEMENT AND FLUID MOBILITY BETWEEN AMPHIBOLITE AND MARBLE FROM THE GATINEAU REGION, QUEBEC**

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The geochemistry, mineralogy and D/H isotope variations between amphibolite and marble have been examined to assess the bulk-chemical exchange between these highly contrasting lithologies. The Gatineau Region, to the north of Ottawa, comprises a section of the Grenville Province which contains large volumes of marble-bearing lithological units. Previous studies suggest that the temperatures of metamorphism reached  $>700^{\circ}\text{C}$  and occurred during the Grenvillian orogeny, although the exact cycle(s) and timing(s) of the tectonic activity is still unconstrained. Within the marbles, amphibolite xenoliths ranging in size from a few centimetres to over one hundred metres can be found. These have been incorporated into the marble units during high-T metamorphism which resulted in plastic deformation and "flow" of the marble, breaking up the original amphibolites. This in turn created various volumes of mafic material which form reaction zones (essentially skarns) between the two lithologies. It is noteworthy that the smaller, cm-sized, xenoliths have either small or indeed no reaction zones present. This strongly suggests that the bulk-chemical exchange is controlled by element leaving the amphibolite which is also consistent with the relatively invariant compositions of the essentially mono-mineralic marble. In newly exposed road sections, along the Gatineau River, very large amphibolite units outcrop, and these are surrounded by large and complex reaction zones. The amphibolites are dominated by hornblende, biotite and plagioclase with minor quartz. Olivine is present near the margins of some amphibolites suggesting an overall Si-loss. Another striking feature is that many of the amphiboles show a distinct coarsening near the amphibolite margins. The reaction zones themselves form two basic types; (1) between the marble and amphibolite contacts, and (2) as veins between separate amphibolite blocks and not in direct contact with the marbles. Reaction zones of type (1) comprise mineral assemblages that include diopside, plagioclase, phlogopite, and minor amphibole either hornblende or tremolite. The type (2) reaction zones (essentially veins) contain rocks which are essentially mafic syenite in composition. Thus, the textures suggest that the process of chemical interaction between these highly contrasting lithologies were controlled by dehydration reactions and by volume exchange of elements from the amphibolite into the surrounding marble. The D/H isotope signatures and incompatible trace-element patterns will be presented to test and model this hypothesis.

## IMPROVING THE ASSESSMENT OF SEISMIC HAZARDS IN THE CITY OF OTTAWA

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A demonstration project by the Geological Survey of Canada and Carleton University recently published two microzonation maps of the City of Ottawa. One map depicts the 2005 National Building Code of Canada (NBCC) seismic site categories, based on an average stiffness (or shear wave velocity) of the upper 30m of the ground. The second shows the distribution of fundamental site periods across the city.

To compile the seismic site class map, shear wave measurements were made at over 700 locations. These geophysical data were used to develop representative velocity-depth functions for each of the three generalized material types found in the upper 30m of the ground surface: bedrock, glacial and glaciofluvial deposits, and Champlain Sea–post-glacial deposits. These relationships were applied to an existing database of 20,000 boreholes, which allowed for each stratigraphic record to be converted into a shear wave velocity profile, whereby the seismic site class could be determined for each site. Fundamental site periods were calculated using the 2005 NBCC equation of  $4h/V_s$ , where  $h$  is the depth to the main acoustic impedance layer, and  $V_s$  is the average shear wave velocity to this depth. GIS and geostatistical techniques were used to interpolate the complex regional datasets.

The seismic site class map revealed that all five seismic site classes (A through E) are present in the City of Ottawa. Abrupt changes in site class (and thus in expected shaking intensity) occur over distances as short as 100 m, reflecting variations in subsurface geology. Thick pockets of soft soil, corresponding to site category E, are present in downtown and suburban areas of the city, making them particularly vulnerable to amplified ground motions during significant earthquake events. The fundamental site period map indicates periods can be as high as 2.6 seconds, corresponding to 140m of soft soil over bedrock. The map has implications for urban environments, as structures with periods matching those of the subsurface are at risk of increased shaking.

The maps have been well received by the City of Ottawa and the geotechnical engineering community. They have had a major impact on the geotechnical reporting requirements for the issuing of building permits, and City officials are using the maps as a guide to make more informed decisions regarding land use and emergency response planning. The datasets are also being used in hazard and risk assessment studies by academic partners in the Canadian Seismic Research Network (CSRN).

## PETROLOGICAL AND GEOCHRONOLOGICAL CONSTRAINTS ON THE HIGH-TEMPERATURE EXHUMATION OF THE GRAND FORKS COMPLEX, SOUTHEASTERN BRITISH COLUMBIA

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Metasedimentary gneisses of the Proterozoic Grand Forks Group (GFC) experienced rapid high-temperature, ~2.5 kbar exhumation in the late Paleocene to early Eocene, coincident with orogenic collapse in the hinterland of the Canadian Cordillera. This exhumation postdates Late Cretaceous peak metamorphism at  $84 \pm 3$  Ma, yet predates greenschist facies extension on the overlying Eocene Kettle River detachment ( $49\text{--}47$  Ma). Peak metamorphism is characterized by upper amphibolite facies conditions, with subsequent high-T exhumation evidenced by the development of a number of independent decompression assemblages. In migmatitic  $\text{Sil}+\text{Kfs}$  paragneisses from the basal and intermediate pelite units,  $\text{Crd}+\text{Spl}+\text{Ilm}$  coronae form around sillimanite and biotite in mesosome layers. Bulk rock thermodynamic modeling fails to predict

this assemblage, suggesting a local Al-rich effective bulk composition centered on sillimanite. In  $\text{St}+\text{Bt} \pm \text{Grt}$  schists from the upper pelite units, decompression is evidenced by thin  $\text{Crd}$  coronae around staurolite. Along the eastern margin of the GFC,  $\text{Hbl}+\text{Grt}+\text{Cpx}+\text{Opx}$ -bearing, granulite facies amphibolites in the basal unit of the GFC display  $\text{Opx}+\text{Cpx}+\text{Pl}+\text{Ilm}$  symplectites after garnet. In comparison to the surrounding gneissic rock matrix, the symplectite assemblages are undeformed, suggesting that low-P recrystallization postdates high-T dome uplift. In metapelites, poorly oriented biotite in melanosomes that rim anatectic leucosomes also suggest back reaction and late recrystallization in a relatively static environment.

Thermobarometric estimates from the structurally lowest metapelites suggest peak P-T conditions of  $750 \pm 20^\circ\text{C}$ ,  $5.8 \pm 0.5$  kbars, with the decompression assemblage constrained to  $725 \pm 35^\circ\text{C}$ ,  $3.2 \pm 1.0$  kbar. A U-Pb zircon age on ductilely deformed anatectic pegmatite ( $51.2 \pm 0.6$  Ma) suggests the Grand Forks complex was still at high temperatures and undergoing exhumation in the early Eocene. Undeformed biotite leuco-granites, dated to  $50 \pm 0.85$  Ma, crosscut high-T deformation fabrics. Previous K-Ar dating of biotite in the GFC suggests passage through greenschist facies conditions at  $49.2 \pm 2.9$  Ma (weighted average), requiring rapid cooling following high-T exhumation but preceding low-T extension along the Kettle River detachment.

The near-isothermal decompression, undeformed high-T decompression assemblages, and evidence for early Eocene anatexis seen in the GFC, as well as the lack of strong mylonitic fabrics, are consistent with a rapid extension rate, as outlined in modeling by Rey et al. (Geology, 2009). Fast extension followed by rapid cooling is observed elsewhere in British Columbia, most notably in the Monashee Complex (e.g. Norlander et al., 2002; Lithos) and Valhalla Complex (e.g. Gordon et al., 2008; Tectonics). Forthcoming U-Pb monazite and Ar-Ar hornblende and biotite ages will help constrain the timing and duration of high-T exhumation and the rates of subsequent cooling.

## DISPERSAL TRAINS IN ESKERS

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Eskers are commonly sampled for indicator minerals during drift prospecting campaigns on the Precambrian Shield. Esker sampling is a proven method: it has led to the discovery of several kimberlites, including the Lac de Gras kimberlite field, home to Canada's first diamond mine. Although commonly associated with diamond exploration, it can be used to locate any mineral deposit type that yields a characteristic suite of indicator minerals (e.g. Ni-Cu-PGE deposits). However, a literature review reveals that indicator-mineral dispersal in esker sedimentary systems is a poorly understood phenomenon. Beyond basic concepts established almost a century ago—most eskers are derived from till and contain dispersal trains that extend roughly parallel to those in the till—exploration companies lacking their own proprietary knowledge are left with little basis for understanding how to sample eskers or interpret esker data. What parts of eskers should be targeted when sampling for indicator minerals? How long are indicator-mineral dispersal trains in eskers, typically? Tens of metres? Tens of kilometres? Hundreds of kilometres? What about pebble dispersal trains? Are they typically shorter? Based on the literature review and on recently collected data from the Keewatin, and drawing insights from a broader body of literature on modern glaciers, lab experiments, and gravel-bed streams, a preliminary conceptual framework for esker sedimentary systems is established to address these issues. A research strategy is then outlined, one whose objective



is to fill knowledge gaps and, in doing so, improve the effectiveness of mineral exploration in glaciated terrain.

#### **THE FINAL CHAPTER: QUATERNARY DEPOSITS IN THE OTTAWA-BONNECHERE GRABEN (CHAMPLAIN SEA BASIN) NEAR OTTAWA**

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The Champlain Sea was an inland arm of the Atlantic Ocean that invaded part of the Ottawa-Bonnechere graben following retreat of the Laurentide Ice Sheet. The sea lasted for about two thousand years around the start of the Holocene, its level falling continuously as the crust rebounded isostatically. Although both glacier and sea are now gone, the sediment they left behind preserves a detailed record of the deglacial event history, and remains integral to life in the Lowland. It is farmed extensively, mined for aggregate, and used as a substrate for waste disposal. Buried eskers host abundant supplies of potable groundwater and Champlain Sea mud is prone to slope failure.

The Geological Survey of Canada has worked in the Champlain Sea basin for over 100 years, accumulating an extensive body of data and knowledge in the process. Over the past 5 years, a large dataset of cores, outcrop data, and seismic transects has been collected to study mud-buried esker aquifers in the Champlain Sea basin near Ottawa, Canada. The dataset provides new insight into the late Quaternary history of the Ottawa-Bonnechere graben, and, in particular, the contribution of esker sedimentary systems to basin infilling. The objective of this talk is to provide a broad review of the historical development of facts and ideas regarding the Quaternary history of the Ottawa-Bonnechere graben (Champlain Sea basin), then show how the new data advance the existing conceptual framework. Links between graben geometry and Quaternary sedimentation will be discussed; new evidence for catastrophic, proglacial, early Holocene meltwater discharges down the Ottawa-St. Lawrence corridor into the Atlantic Ocean will be presented; and a sequence stratigraphic model tailored for glacial depositional systems will be proposed to explain and unify the litho-, bio-, chemo- and seismic stratigraphic patterns observed in the basin fill.

#### **EARLY ORDOVICIAN DEVELOPMENT OF THE ANNIEOPSQUOTCH ACCRETIONARY TRACT: INFERENCES FROM THE MORETON'S HARBOUR GROUP, NEWFOUNDLAND**

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The closure of the Taconic Humber Seaway and the resultant subduction flip lead to development of the Annieopsquotch Accretionary Tract (AAT), a collage of arc-backarc terranes that formed outboard of Dashwoods microcontinent. The oldest of these terranes, the c. 480 Ma supra-subduction zone Annieopsquotch Ophiolite Belt, records the initiation of subduction and the earliest stages AAT development. The understanding of the geometry of the early AAT requires documentation of lateral variability in the Annieopsquotch Ophiolite Belt, yet correlative terranes in the Notre Dame Bay have not been conclusively identified.

The Moreton's Harbour Group, exposed in Notre Dame Bay, comprises a fault-bounded ophiolitic sequence of layered gabbro, sheeted diabase, pillow basalt and felsic intrusive rocks. It is offset by high-angle shear zones that are associated with a  $477.4 \pm 0.4$  Ma syn-tectonic and syn-magmatic suite of trondhjemite and tonalite. Trace element data indicate formation in a supra-subduction zone setting. This age and chemistry clearly distinguish the

Moreton's Harbour Group from the adjacent Cambrian Lush's Bight oceanic tract. Hence, the Moreton's Harbour Group is interpreted to form the northernmost extent of the ca. 480 Ma Annieopsquotch Ophiolite Belt.

The isotopic data from the Moreton's Harbour Group felsic intrusive rocks ( $\epsilon\text{Nd}$  (3.45) to (-10.53), Td/m 1200-1800 Ma) indicate significant contamination by Mesoproterozoic or older continental crust. We present a model in which the Moreton's Harbour Group formed during propagation of the Annieopsquotch Ophiolite Belt spreading centre into Dashwoods microcontinent. This ridge propagation model supports the formation of the Annieopsquotch Ophiolite Belt immediately outboard of Dashwoods and provides a possible explanation for the occurrence of continental basement in outboard AAT terranes.

#### **RECONSTRUCTION OF SUBMERGED LATE BRONZE-AGE SHORELINES AND ANCHORAGE SITES AT KALAMIANOS (KORPHOS, GREECE)**

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Kalamianos is a recently discovered fortified Mycenaean (late Bronze Age) coastal settlement located on the Saronic Gulf, near the modern town of Korphos, Greece. The settlement's coastal context and site plan indicate its function as a port but the location of the harbour basin was unknown. The modern coastline provides few clues as to the harbour configuration as the site was partially submerged by >6 m of coastal tectonic subsidence since the site occupation. In 2009, a detailed marine geophysical survey and underwater diver search was conducted in the inshore waters to identify potential anchorage sites and to examine evidence for coastal subsidence. >400-line km of single-beam bathymetry and magnetic gradiometer data were acquired across a 10-km<sup>2</sup> area and integrated within a detailed digital bathymetric model (DBM). Underwater geological mapping and sampling of beachrock platforms was conducted by diver survey over a 2-km area.

The DBM revealed two submerged beachrock platforms (BR-1, BR-2) paralleling the modern shoreline and a submerged isthmus connecting the mainland with small island 200 m offshore. The BR-1 platform (3.5-3.7 m depth) consisted of a well-cemented calcarenite containing abundant Late Helladic (LH; 1400-1060 BC) pottery sherds (30-50%) and wood charcoal fragments. The pottery showed little evidence for reworking or bioencrustation, consistent with rapid burial in a low energy beach environment. <sup>14</sup>C dating of the extracted charcoal yielded an AMS <sup>14</sup>C age of  $3250 \pm 40$  BP consistent with the LH ceramics. The BR-2 platform (5.8-5.9 m depth) contained less pottery (<20%) and included well-preserved fragments of Early Helladic (EH) jars. The beachrock elevations and <sup>14</sup>C and pottery ages were used to reconstruct a sea level curve and a series of paleogeographic maps of the EH to LH shoreline. These maps show that during the initial EH phase of site occupation the mainland was connected to the island by a narrow isthmus with a well-sheltered harbour basin on its east side. During the subsequent Mycenaean phase, sea level had risen by about 1.5 m submerging the promontory. The presence of abundant pottery and wood charcoal in the BR-1 beachrock indicates that shipping activity during the LH was focused at the south end of the site in a western harbour basin. This is supported by the magnetic gradiometer results, which identified several magnetic anomalies in the western harbour basin. These

were investigated by diver search and found to be concentrations of ship ballast stones (mainly andesite) and clay pottery.

#### **THE ORIGIN OF PLATINUM-GROUP ELEMENTS IN ACCESSORY PYRITE FROM MAGMATIC SULFIDES FROM A SUDBURY Ni-Cu-PGE DEPOSIT**

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Magmatic platinum-group element (PGE) and Ni-Cu-PGE sulfide deposits consist of pyrrhotite, pentlandite, chalcopyrite  $\pm$  accessory pyrite. Laser ablation (LA) ICP-MS of these base-metal sulfide (BMS) phases is a useful tool to constrain the mineralogical sites of the PGE in these deposits which is important for the petrogenetic models of the ores and for the efficient extraction of the PGE. Previous work has shown that 1) pyrrhotite and pentlandite typically host much of the IPGE (Os, Ir, Ru, Rh), 2) pentlandite also hosts much of the Pd and Co, 3) chalcopyrite does not host PGE, 4) Pt is absent from the BMS and forms Pt minerals spatially associated with the sulfides and 5) the role of pyrite has not been closely investigated.

We have determined the trace element content of BMS from 5 massive sulfide samples from the McCreedy East deposit of Sudbury, using a 213 nm Nd:YAG UV laser and a Thermo X7 ICP-MS at UQAC. The samples are pyrrhotite-rich, with minor pentlandite, chalcopyrite  $\pm$  accessory pyrite (< 2 wt.%). Pyrite forms small, euhedral grains which are associated with pyrrhotite and pentlandite. A surprising result is that the PGE are hosted not only in pyrrhotite and pentlandite but also in pyrite. Relative to the co-existing pyrrhotite and pentlandite, pyrite is significantly enriched in IPGE (e.g. <130 ppm Rh), As (<30 ppm)  $\pm$  Pt (<0.15 ppm). Furthermore, the concentrations of these elements in pyrite, together with Co and Se, are oscillatory zoned and the PGE-As concentrations decrease from core to rim as the Co-Se concentrations increase.

The pyrrhotite-rich assemblage of McCreedy East represents a cumulate of Fe-rich monosulfide solid solution (MSS) which crystallized early from the sulfide melt (~1000°C). Experiments show that IPGE and Co preferentially partition into MSS whereas Pt, Pd and As remain in the fractionated liquid. Upon cooling of the MSS cumulate (<600°C), pyrrhotite, pentlandite  $\pm$  accessory pyrite exsolved and inherited the IPGE and Co. The enrichment of IPGE in pyrite indicates that 1) pyrite exsolved early from MSS and 2) the IPGE, and the small amount of Pt and As in MSS, both showed a preference for the pyrite structure over pyrrhotite or pentlandite. The oscillatory zonation of the PGE, As, Co and Se in pyrite resulted from a boundary layer effect during its complex growth from MSS.

#### **MAPPING GRABEN-FISSURE SYSTEMS IN THE VICINITY OF A PROMINENT VIRTIS VENUS EXPRESS EMISSIVITY ANOMALY, IDUNN MONS, IMDR REGIO**

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Detailed mapping of the Venusian surface in an area approximately 3.1 million km<sup>2</sup> of Imdr Regio (204–224°E and 35–55°S) has unveiled four interacting graben-fissure systems in the vicinity of Idunn Mons. Regional graben-fissure systems and lava flows were identified using Synthetic Aperture Radar (SAR) images from NASA's Magellan satellite mission and assessed by cross-cutting relationships. Idunn Mons is of current interest due to recent recognition of a high emissivity anomaly identified using the Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) of the Venus Express spacecraft. VIRTIS measures spectral emissivity, that is, the ratio of the radiance measured from the planet's

surface to the radiance emitted by a black body at the same temperature. Weathered material is characterized by lower emissivity values than unweathered material. Unweathered, high emissivity areas reflect younger lava flows which might have occurred as recently as 250 ka.

The graben-fissure systems we mapped, thought to represent the plumbing systems for volcano-plutonic systems, are labelled G1, G2, G3 and G4, in order of inferred younging age. Here, we compare the distribution of high emissivity regions with our relative chronology of volcanism of Idunn Mons and its surrounding area. The summit of Idunn Mons, which is included in the anomaly, is comprised of nested caldera (presumably overlying magma chambers) each with an average radius of 3 km. Trending away from the summit are three radiating graben-fissure systems (G1, G2 and G3). Older systems G1 and G2 are located on the flanks and their associated volcanic edifices are expected to have been overprinted by the later flows related to G3. The emplacement of G3 is linked with the caldera-forming pulses since it is focused on the summit of Idunn Mons. Distributed evenly around Idunn Mons are volcanic flows that occur in two phases; the first (associated with low emissivity) precedes the formation of G3 and the second pulse (associated with the high emissivity anomaly) occurs following the formation of G3. The G4 system is centred on a topographically positive feature 400 km east of Idunn Mons, in an area of low emissivity. Sparse crosscutting relationships insinuate G4 is either younger or coeval with G3. A lower proportion of lava flows in the region of G4, compared to Idunn Mons, justifies its low emissivity signature.

#### **VOLCANIC ARCHITECTURE AND PRECISE U-Pb GEOCHRONOLOGY OF THE MATAGAMI MINING CAMP, ABITIBI SUBPROVINCE, QUEBEC: IMPLICATIONS FOR VMS EXPLORATION**

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The Matagami mining camp is located in the northern part of the Archean Abitibi Subprovince in Quebec. Some 19 zinc-rich volcanogenic massive sulphide (VMS) deposits are currently known in the camp. Ten of them have been mined, including the large Matagami Lake deposit (25 Mt), to produce about 46 Mt of ore so far. Most of the VMS deposits occur along three felsic bands oriented NW-SE to WNW-ESE known as the South Flank, the North Flank, and the West Camp.

The geology of the Matagami region is mainly composed of a bimodal volcanic sequence. A number of mafic to intermediate dykes and sills cut the lava-dominated volcanic rocks. Historically, the stratigraphy of the South Flank was divided in two major groups: the Watson Group, including the Watson Dacite and the Watson Rhyolite; and the younger Wabasse Group, composed principally of mafic rocks, with some localized felsic units near the base. These units are separated by a marker horizon called the Key Tuffite, along which most of the VMS deposits have been found. The stratigraphy of the West Camp is less understood, mainly because of a higher grade of deformation, the abundance of intrusive rocks, fewer drill holes, and a lack of outcrop.

A PhD project on the reconstruction of the volcanic architecture of the camp is currently underway at INRS. Six new high-precision U-Pb zircon ages on felsic units from the South Flank and the West Camp have been obtained at the GSC. Geochronology can help clarify the relationship between the South Flank and the West Camp, and more specifically test if a time correlation between the two bands is plausible. Further, geochronology can help constrain the temporal evolution of the volcanic activity in the

camp. The data shows that the felsic volcanism of the South Flank lasted at most 2.5 m.y. around 2727–2724 Ma, and gives a chronology of emplacement of felsic units along the South Flank. Two varieties of Dumagami Rhyolite from the South Flank have slightly different ages, suggesting that they should perhaps be separated into distinct stratigraphic units. The Key Tuffite, representing a hiatus of volcanic activity, was probably deposited within 0.5 m.y., as shown by the ages of the bracketing rhyolites. Finally, the rhyolite from the footwall of the Caber VMS deposit in the West Camp has an identical age to that of the Watson Rhyolite on the South Flank.

#### TRACE ELEMENT CHARACTERIZATION OF Cr-SPINEL IN FOREARC MANTLE PERIDOTITES FROM THE MARIANAS AND HIMALAYAS

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Chromium-spinel (chromite) is a common accessory phase of mafic and ultramafic rocks. Since it is alteration resistant, it is useful in petrogenetic studies of host igneous rocks, but the major element composition of spinel is not sufficient to fingerprint different tectonic settings. Since there are very few data on the trace element composition of spinel, we examined the minor and trace element composition of spinel in forearc mantle peridotites from two well-known locations: Marianas and Himalayas. In the Marianas, partially to totally hydrated peridotites protrude as serpentinite diapirs from the base of the mantle wedge in the outer 100 km of the forearc. The origin of the Himalayan peridotites is similar to that of the Mariana samples. They were exhumed together with the Tso Morati ultrahigh pressure unit, once sedimentary rocks on the margin of the Indian continent prior to being subducted to a depth of ~ 120 km beneath Eurasia at ca. 55 Ma.

Bulk rock compositions, relict minerals and textures indicate that all samples are harzburgite. This is consistent with high Cr in spinel ( $Cr\# = Cr/[Cr+Al] = 0.60\text{--}0.76$  in the Marianas and  $0.68\text{--}0.73$  in the Himalayas). Cr-spinel is commonly rimmed by ferichromite and magnetite, but cores contain low  $YFe^{3+}$  ( $Fe^{3+}/[Fe^{3+}+Al+Cr] = 0.01\text{--}0.06$  in the Marianas and  $\sim 0.04$  in the Himalayas); these cores were analyzed for trace elements using a laser-assisted ICP-MS.

Spinel contains significant contents of Mn, Zn and V: 1160–4310 ppm Zn, 1610–2660 ppm Mn and 363–1900 ppm V in the Marianas, and 2365–4080 ppm Zn, 2430–5540 ppm Mn and 701–1020 ppm V in the Himalayas. All three elements are inversely correlated with Mg#. The contents of Ni and Co are similar in two locations, ranging from 276 to 700 ppm. Titanium contents of different spinel grains in individual samples are similar, but they vary from ~ 20 to 800 ppm among different samples. Gallium and Al show a strong positive correlation in both locations, with Ga/Al ratios of  $2.1\text{--}4.2 \times 10^{-4}$ . The values are comparable to primitive mantle values, suggesting the coherent behavior of Ga and Al. Elements that are known to have an affinity with oxides are all detected in these Cr-spinels, including Zr (<0.46 ppm), Y (<0.015 ppm), and Sc (<4.2 ppm). Surprisingly high Zr/Y (20–180) and Sc/Y (700–3900), in contrast to primitive mantle values (2.4 and 3.8, respectively) suggest that spinel contributes to the fractionation of high-field strength elements.

#### GRAIN-SIZE DETERMINATIONS BY SIEVING AND IMAGE ANALYSIS: ARE THEY EQUIVALENT?

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Grain-size analysis of volcanoclastic deposits and rocks provides important quantitative information that can help identify transport or fragmentation mechanisms, or even eruptive styles. Sieving is the traditional method of acquiring grain size information, but even in young volcanic fields many volcanoclastic deposits are consolidated or cemented. For examples, phreato-magmatic deposits can be at least weakly indurated due to palagonitization. Restricting grain-size determinations to the sievable samples would yield unrepresentative information. Can image analysis provide comparable results?

Image analysis is largely employed for textural studies of vesicles and crystal size distributions in volcanic and intrusive rocks, but only infrequently to volcanoclastic samples. All data obtained with image analysis are in two dimensions: the surface area of each particle is measured in a 2D image, and particles are assigned to size classes. This can be expressed as number densities per unit of surface. Stereology is a statistical technique which converts the data in three dimensions, for example number densities per volume.

In order to compare results from sieving and image analysis, we performed an experiment on an unconsolidated sample from the Quaternary Pali Aike volcanic field of Argentina. We first sieved this sample to obtain a reference grain-size distribution. Then we reconstituted the sample and extracted a representative subsample, which was impregnated with glue. Finally we cut thin sections vertically in this artificial “volcanoclastic rock”.

Obtaining a range of representative images of these thin sections involved scanning them and taking numerous photomicrographs at various magnifications ( $\times 25$ ,  $\times 50$ ). The magnification range was determined by the smallest and largest grains size that we could identify. The number of images per magnification is an important parameter because it is necessary to have a more or less constant number of grains per magnification.

Because natural volcanoclastic samples are complex, even in the experiment, each grain was drawn by hand before performing the analysis in ImageJ. The latter software gives the surface area of each grain, which is convertible into a diameter. We took into account that we had non-spherical grains and non-uniform clasts such as sedimentary rocks, free crystals, lava fragments and juvenile clasts which can be highly vesicular. A number of steps were required to merge all the datasets from various magnifications and obtain a 3D (volume or mass) grain-size distribution, which could finally be plotted on the same cumulative graph as the sieving results for direct comparison.

#### ORDOVICIAN-SILURIAN BOUNDARY INTERVAL IN THE WILLISTON AND HUDSON BAY BASINS, MANITOBA: ISOTOPIC CARBON EXCURSION AND CONODONT TURNOVER

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The Ordovician-Silurian boundary in carbonate successions of the Williston and Hudson Bay basins was previously set at an abrupt mass extinction in which diverse Late Ordovician conodonts were replaced by an impoverished Early Silurian fauna, including representatives of Ozarkodina. In the Williston Basin, this boundary had been located in the upper Stonewall Formation, near the t-

marker bed. In the Hudson Bay Basin, where the stratigraphic framework is not as well established, the boundary had been placed at or near the contact between a formation identified as either Port Nelson or Red Head Rapids, and the overlying Severn River Formation. It was thought that latest Ordovician and possibly earliest Silurian deposits were absent in both basins due to a major regression caused by glaciation in Gondwana. In some regions of North America, however, the Ozarkodina fauna appears within strata that record the Hirnantian isotopic carbon excursion (HICE) of latest Ordovician age. Are such deposits present in the Williston and Hudson Bay basins?

The present study is based on data from the only known exposures of the Ordovician-Silurian boundary interval in the Williston Basin (two sites) and Hudson Bay Basin (one site), as well as drill cores from near those three sites in Manitoba. In the Williston Basin, a positive  $\delta^{13}\text{C}_{\text{carb}}$  excursion begins at the base of the argillaceous t-marker bed, reaches a peak (maximum value +2‰) in the upper part of the bed or a short distance above it, and decreases in the uppermost Stonewall Formation. Similarly in the Hudson Bay Basin, a positive excursion reaches a peak (value +3‰) just above a clayey marker bed. At all three sites, the Ozarkodina fauna, including *O. hassi* and *O. oldhamensis*, appears at or near the peak of the excursion.

For comparison, on Anticosti Island, Quebec, the *O. hassi* Zone begins within the peak of the major HICE excursion (value +4‰). In Nevada, where the magnitude of the HICE peak is very high (value +8‰), and in northeastern Illinois, where the magnitude is relatively low (value +2.5‰), Ozarkodina appears in the upper part of the excursion where values are decreasing. In Manitoba, the coincidence of the isotopic excursion with the appearance of Ozarkodina suggests that this excursion may represent at least part of HICE. Latest Ordovician, Hirnantian deposits may therefore be present in the Williston and Hudson Bay basins, and the stratigraphic position of the Ordovician-Silurian boundary may be higher than previously thought.

#### **MAGNETOMETRY AND RESISTIVITY AT TELL TA'YINAT, SOUTHEASTERN TURKEY: A PRELIMINARY SURVEY DETECTING AREAS OF HIGH ARCHAEOLOGICAL POTENTIAL**

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We performed non-invasive geophysical surveys at the Ta'yinat Archaeological Project (TAP) in the Amuq Plain of southeastern Turkey. Tell Ta'yinat, a low lying mound, is also known as the ancient city of Kunulua which was the capital of the Neo-Hittite-Aramean Kingdom of Patina/Unqi, and a prominent economic and cultural centre. The site was occupied by various ethnic groups during the Early Bronze Age (ca. 3000-2000 BCE) and Iron Age (ca. 1200-550 BCE). The objective of our research was to pinpoint areas of archaeological interest for future excavation, using magnetic and resistivity methods. Magnetic surveys involved mapping a 400 by 600 m area, filtering of magnetic noise, and adjusting contrasts to identify (rectangular) features that most likely are human-made. 2D pseudo-sections of resistivity data were created using the RES2DINV algorithms. These inverted models were then examined for any apparent archaeological features. The results of our geophysical surveys revealed patterns which suggest the existence of buried structures. In particular, we were able to delineate the extent of the ancient city to the North and identified a possible cobblestone pathway in the East. A prominent magnetic anomaly on the NE corner of the hill may be a large building. We suggest that the TAP focus future excavations on these areas we

identified. Future analysis of our data will include shaded and first derivative plots of maps and cross-sections.

#### **SPHERULITE GROWTH IN OBSIDIAN DOME, LONG VALLEY, CALIFORNIA**

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Obsidian Dome is a member of the 10 km long Inyo Chain which consists of several rhyolitic lava domes, numerous phreatic craters, and pyroclastic deposits located in the north western portion of Long Valley, California. Obsidian Dome represents ~0.1 km<sup>3</sup> of extruded finely porphyritic rhyolitic lava erupted 650-550 years ago during the most recent volcanic episode in Long Valley. The obsidians are typically chaotically flow banded at the mm to cm scale and have domains of flow banded pumice.

Field observations of the surface of Obsidian Dome suggest spherulite occurrence is limited to its interior. A vertical rock face located along the north western edge of the rhyolite dome exposes the internal stratigraphy including obsidian with numerous lithophysae (spherulites and voids of former gas bubbles). Spherulite-bearing obsidian samples were collected from blocks in the talus slope. Spherulites occur as 1-15 mm diameter isolated and agglomerated bodies with spherical to ovoid morphologies consisting of conically radiating fine, acicular crystals. Those with oblate shapes are flattened perpendicular to flow banding, indicating deformation above the glass transition. Some spherulites within lithophysae are fractured possibly as a result of gas bubble expansion within the melt.

Petrographic investigation of samples demonstrates spherulites overprint both flow banding, and microlites and microphenocrysts aligned parallel to flow banding. However, weak deflections of flow banding can be observed around some spherulites. Deformation shows that some spherulite crystallization took place above the glass transition whereas undeformed spherulites may have formed below the glass transition. Overprinting demonstrates that growth took place later after the cessation of flow banding.

Spherulite growth requires crystallization of anhydrous minerals causing the expulsion of water into the surrounding matrix. Water diffuses outward from the advancing crystalline front generating a water-concentrated zone, the concentration of which decreases from the spherulite-glass interface. We propose a new model of the diffusive transport of water away from the spherulite growth front by numerically solving the diffusion equation with a moving boundary in spherical coordinates. The essential idea is that water is swept away by spherulite growth hence modelling water transport provides an estimate of spherulite growth parameters and cooling rate of the host material. The water concentration profiles of specimens from Obsidian Dome are currently being measured using synchrotron source Fourier transform infrared spectroscopy so that they can be compared to those generated by the model.

#### **ARSENIC IN ADIT DRAINAGE FROM AN OROGENIC LODE GOLD DEPOSIT, BRALORNE MINE, BRITISH COLUMBIA**

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The Bralorne Mine, once the largest gold producer in western Canada, ceased operations in 1971. The mine worked a large

Mesozoic orogenic lode deposit where gold is found in quartz-carbonate veins hosted by diorite stocks and greenstones. Wall-rock alteration is characterized by an assemblage of quartz (25%), ankerite (35%) and sericite (13%), with pyrite and arsenopyrite (5%). While efforts to re-develop the mine are underway, management of drainage from the historic workings is an environmental concern. This drainage, which discharges from the lowest adit level (800-Level), contains arsenic at concentrations that exceed regulatory limits. In order to better understand effluent geochemistry, including the mobilization and attenuation of arsenic, drainage at the 800-Level portal was sampled weekly over a fourteen-month period, while discharge rate was monitored continuously. A synoptic survey of drainage chemistry within the 800-Level workings was also carried out in order to identify the various sources of mine water discharged at the portal. Over the study period, average flow from the adit was 427 m<sup>3</sup>/d, peaking at 841 m<sup>3</sup>/d during the spring freshet. The pH of drainage ranged between 8.3 and 9.5 without any clear temporal pattern. Drainage waters exhibited a mixed cation and mixed anion (including Cl) composition with TDS concentrations averaging 1080 mg/L. Total concentrations of Fe and As in portal effluent averaged 1651 µg/L and 3034 µg/L, respectively, whereas their dissolved concentrations averaged 27 µg/L and 2444 µg/L, respectively. Sorbed As was found to be highly correlated with suspended particulate Fe and was also found to decrease with increasing pH. Synoptic survey results showed that 62% of portal effluent originated as decant from the flooded lower workings of the mine which extend 1600 m below the adit level. The temperature (22°C) and chloride content (62 mg/L) of this water suggest possible mixing with deep hydrothermal inflows. The decant waters were found to be anoxic with dissolved Fe and As concentrations of 3502 µg/L and 5603 µg/L, respectively. These concentrations likely resulted as the workings flooded, with the reductive dissolution of accumulated Fe-oxyhydroxides and the concomitant release of sorbed arsenic. Decant waters emerging on 800-Level were observed to re-precipitate Fe-oxyhydroxides with sorbed As along the drainage flow path, thereby sequestering a significant mass of As within the adit. Total net loading of arsenic in portal effluent averaged 1.34 kg/day of which 24% was in suspended particulate form.

#### **VOLCANISM, HYDROTHERMALISM AND TECTONICS OF THE WOODLARK BASIN**

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The Woodlark Basin east of Papua New Guinea represents one of the few places on Earth where a spreading axis propagates into continental crust. This special tectonic setting allows both insights into the evolution of magma composition as continental breakup progresses from extension to the formation of ocean crust and also provides the opportunity for the huge thermal effects of oceanic magmatism to impinge on "source rocks" with a continental crust affinity. During cruise 203 of the F.S. "Sonne" we surveyed and sampled the four segments nearest to the continent/ocean boundary, a total of ~350 km of ridge length including Franklin Seamount, an area formerly studied by Steve Scott.

Studies of the magmatic chemistry show only the spreading segment closest to Papua New Guinea (the one which also hosts Franklin) to have a continental contamination signature. High-resolution mapping with an autonomous underwater vehicle show the ridge-axis to contain many other Franklin-like edifices, although none were found that were hydrothermally active. Over 40 plume-hunting turbidity sensor deployments along the whole 350 km axis yielded evidence of only 1 other hydrothermal system-

less than the one per 100km of axial length which would be expected. We conclude that repeated plate boundary re-orientation in the Woodlark Basin, for which there is extensive geophysical evidence, hinders the establishment of major crustal magma chambers, resulting in the establishment of only ephemeral, eruption-associated hydrothermal systems.

#### **TECTONIC HISTORY OF THE NORTH AMERICAN SHIELD RECORDED IN URANIUM DEPOSITS IN THE BEAVERLODGE AREA, SASKATCHEWAN, CANADA**

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Geochronology of uraninite and structural relationships in uranium deposits in the Beaverlodge area, in Northwestern Saskatchewan, Canada, reveal multiple periods of uranium mineralization of various ages and types associated with multistage deformation and distinct periods of alteration and remobilization during the Proterozoic.

New geochronologic data on uranium mineralization and alteration events record 2.3 Ga protracted tectonic evolution of the North American Shield and reflect recent advances into the evolution and formation of supercontinents. An oldest <sup>207</sup>Pb/<sup>206</sup>Pb age of 2293±17 Ma dates the first uranium mineralization stage associated with cataclasite rocks and coincides with the Arrowsmith Orogen. Early quartz-calcite uraninite veins give two oldest <sup>207</sup>Pb/<sup>206</sup>Pb ages of 2289±20 and 2276±29 Ma, consistent with late stage of the Arrowsmith Orogen. Post-mineralization alterations associated with these two mineralizing events record three distinct intervals at 2.2-2.1, 2.1-2.0 and 2.0-1.9 Ga consistent with stages of widespread global magmatism and breakup of the Kenorland supercontinent and the beginning of assembly of the Laurentia and Columbia supercontinent. During the Late Paleoproterozoic, cooling during tectonic exhumation along major faults caused the deformation style to change from dominantly brittle-ductile to brittle at a higher structural level. Massive brecciation of pre-existing rocks is associated with the major and fourth uranium-mineralizing event around 1886±64 Ma coincident with late stage Snowbird Tectonic Zone and Early Trans-Hudson Orogen. Subsequently, deposition of sediments in the Martin Lake Basin is associated with emplacement of alkaline mafic dikes that are spatially associated with the fifth minor uranium-mineralizing event at 1823±23 Ma reflecting late stage Trans-Hudson Orogen and final assembly of the Columbia supercontinent. Late stage mineralized veins during the Mesoproterozoic crustal growth of the Columbia Supercontinent are associated with the sixth minor uranium-mineralizing event at 1620±4 Ma, coincident with the Mazatzal Orogen and the major unconformity-related uranium-mineralizing events in the Athabasca Basin.

Post-mineralization alteration events obtained in the <sup>207</sup>Pb/<sup>206</sup>Pb system include the Granite Plutons Event around 1.55-1.35 Ga that marks initial breakup of the Columbia, the 1.27 Ga Mackenzie and Sudbury mafic dike swarms coincident with final breakup of Columbia, the Grenville Orogen around 1.3-0.9 Ga reflecting the assembly of Rodinia, the breakup of Rodinia at 0.7-0.8 and 0.6-0.5 Ga and the Appalachian Orogen around 0.3-0.4 Ga coincident with the Pangea assembly. Lower intercept ages in the U/Pb concordia system record periods reflecting evolution of the North American Shield from the Mesozoic to the Cenozoic consistent with the Early-Middle Jurassic (202±110, 175±90 Ma) breakup of the Pangea supercontinent, Late Cretaceous Sevier Orogen (140-50 Ma) and Late Cretaceous-Eocene Laramide Orogen (70 to 40 Ma) that affected the western active margin of the North American Shield, and finally, record stresses-related to Pleistocene glaciations.

## **TECTONIC SETTING AND PALEOWEATHERING CONDITION OF NEOPROTEROZOIC GLACIGENIC DIAMICTITE IN AKSU, XINJIANG, NORTHWEST CHINA**

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Two distinct Neoproterozoic (Cryogenian) glacigenic diamictites are exposed in the Aksu region of Xinjiang, northwestern China, along the northwestern rim of Tarim Craton. The older Qiaoenbrak Formation and younger Yuermeinak Formation are thought to correspond to a pre-Sturtian glaciation and the Sturtian glaciation, respectively. With a thickness of ~2 km, the Qiaoenbrak Formation is divided into four members from bottom to top: (1) sandstone member, (2) glacigenic diamictite member, (3) calcareous sandstone member and (4) conglomerate-siltstone member. There are two discrete glacial cycles of glacigenic diamictite separated by interglacial siltstone. The Yuermeinak Formation is composed of glacigenic diamictite (lower part) and sandstone (upper part). The contact between the conglomerate-siltstone member of the upper Qiaoenbrak Formation and the lower Yuermeinak Formation diamictite is an angular unconformity. This unconformity suggests that the two glaciations were separated by a significant tectonic event. We present new geochemical data to help constrain the tectonic setting and paleoweathering conditions at the time these two diamictites were deposited. We used major elements and trace elements diagram to reconstruct the tectonic setting. Samples of Qiaoenbrak Formation plot in continental arc field and the samples of Yuermeinak Formation cluster in a passive margins field. This suggests a tectonic evolution from island arc to passive margin. Chondrite-normalized REE data show a high LREE/HREE and flat HREE pattern with sharp negative Eu anomaly, reflecting a dominant sediment source of predominantly felsic rocks of the old upper continental crust. The chemical index of alteration (CIA) shows a change between glacial and post-glacial time. The median CIA values of the Qiaoenbrak Formation from first glacigenic diamictite to follow are 45.8 (glacial), 55.1 (inter-glacial), 51.6 (glacial) and 54.2 (postglacial). The median CIA values of Yuermeinak Formation for different rocks are 54.1 (glacial) and 62.4 (post-glacial). It indicates that there is less chemical weathering during glacial times than inter-glacial and post-glacial times, and that the paleoenvironment was colder and drier during the older (Qiaoenbrak) glaciation than during the Yuermeinak glaciation.

## **STRUCTURAL TRANSFORMATION OF A LARGE SILICICLASTIC CHAZYAN ESTUARY INTO A RESTRICTED CARBONATE SEAWAY: OTTAWA EMBAYMENT, EASTERN LAURENTIA**

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The Middle Ordovician Chazy Group (<270 m) of the Champlain Valley defines a mostly marine reefal-bearing carbonate succession that is traced north into the Laval Fm of the Montreal region, then west into the interior of the Ottawa Embayment where the equivalent succession is thin, 60-70 m thick. Here, the equivalent stratigraphy consists of the siliciclastic Rockcliffe Formation abruptly overlain by poorly fossiliferous shale and carbonate of the Hog's Back Formation. West of Ottawa, the equivalent succession is mostly red and green sandstone. This lateral regional gradient was previously interpreted to document a large paleoestuary, positioned between Precambrian highlands in northern New York State and southwestern Quebec; an estuary of similar scale and shape as the Rio de la Plata, eastern South America. The siliciclastic-to-carbonate lithostratigraphic succession within the

western Ottawa Embayment was interpreted to document evidence of conformable retrogradation of the estuarine (siliciclastic) facies in response to differential subsidence along the platform margin and Middle Ordovician marine transgression. Outcrop and geophysical transects show that the abrupt lithic superposition of Hog's Back on Rockcliffe strata was contemporaneous with seismites, co-seismic faulting, and fault-margin sedimentation. Evidence of possible seismites of contemporary age in the Montreal region illustrates a potential regional influence of seismicity and tectonism. The new structural framework for the interior of the Ottawa Embayment suggests that the large siliciclastic paleoestuary was structurally transformed into a restricted marine carbonate seaway (Hog's Back Fm). An abrupt subsidence across the embayment of only a few meters would be sufficient for this to occur. Such events are documented from Quaternary coastal successions along active margins in response to large earthquakes. The proposed Ordovician structural history is part of an episodic structural continuum throughout the Ordovician linked to reactivation of inherited Precambrian structure that underlies Lower Paleozoic strata in the Ottawa Embayment in response to distal Taconic orogenesis. There is no obvious equivalent structural surface within the marine Chazy Group of eastern New York State or Vermont, but an increase in reefal diversity in the lower Chazy Group might form a contemporaneous biolithic response to the craton-interior subsidence event.

## **SYNSEDIMENTARY FAULTS AND LOCAL DIFFERENTIAL SUBSIDENCE AS SIGNIFICANT DRIVERS OF STRATIGRAPHIC ARCHITECTURE WITHIN AN ORDOVICIAN FORELAND BASIN: OTTAWA EMBAYMENT**

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A Middle to Upper Ordovician foreland basin succession in the Ottawa Embayment (eastern Ontario) records progressive western cratonic onlap by successive shallow shelf successions (Carillon, Rockcliffe, Hog's Back formations) leading to a regionally extensive Upper Ordovician carbonate platform (Ottawa Group). Regional platform foundering gave way to deep-water shales (Billings Formation), and progressive basin fill by orogen-derived siliciclastics (Carlsbad, Queenston formations). Previously, stratigraphic and facies architecture related to this history was interpreted in the context of long-term eustatic sea level rise and regional subsidence, the latter driven by Taconic orogenesis. Study of outcrop, drill core, and gamma-ray well logs indicates that higher-order local fault control was also of influence. Examples occur throughout the entire platform succession: (1) Block faulting was initiated within a peritidal schizohaline environment (Carillon Fm, upper Beekmantown Group) during onset of foreland basin development in the Middle Ordovician. Transformation into a siliciclastic estuary defined by a seaward flood of siliciclastics (Rockcliffe Fm) was possibly related to embayment-margin uplift. (3) An abrupt change into a marginal-marine carbonate embayment (Hog's Back Fm) coincides with local faulting, fault margin sedimentation, and seismites. (4) For the lower Ottawa Group, there was a turning on, then off of local subsidence: the lowermost Pamela Fm (lowermost Ottawa Group) records a local thickening within the central embayment compared to the Ottawa and Montreal regions; in contrast, there is minimal variation (+ <0.5 m) in thickness of the overlying Lowville Fm along the same axis; but, the overlying Chaumont or Watertown formation then thickens (>4 m to 12+ m) dramatically eastward along the same axis. Differential thickening in early Pamela and Chaumont times are centered over a geophysically defined Precambrian (crustal) block

along the NE-SW-oriented contact between underlying Precambrian allochthons (Morin-Adirondack Highlands, Frontenac-Adirondack Lowlands). Contemporaneous local thinning of the Chaumont succession in the upper Ottawa Valley region can be explained by local block faulting. (5) Within the younger Verulam Formation, an anomalous shale-rich carbonate interval thickens appreciably toward a step-backed paleomargin in southern Québec. Short-term tilting of the regional platform coincides with evidence for tectonomagmatic modification of the more distal continental margin. And, (6) Local small-scale grabens and horsts were developed within the basin soon after burial of the Upper Ordovician carbonate platform by deep-water shale. The higher-order structural control is interpreted to reflect reactivation of an inherited basement structure associated with the shallowly-buried Late Precambrian failed rift system, ancestral to the Ottawa-Bonnechère Graben.

### 3-D LASER-IMAGING OF CORE FOR FRACTURE MAPPING

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As underground mines reach greater depth, where stresses are high, the stability of excavations becomes a critical component of the design process. The strength of the rock mass is strongly affected by the presence of fractures. The rock quality designation (RQD) – the percentage of unbroken core fragments longer than 10 cm over the total length of a core run – is a key indicator used in the strength assessment process.

It is challenging to distinguish natural fractures that are the result of geologic processes from mechanical breaks in the core. The type and quantity of fractures in core is often estimated by quick visual inspection. We show how the introduction of innovative 3-D imaging procedures and software can provide fast and accurate observations of fractures in core.

The 3-D images for this analysis were obtained with a Konica Minolta VIVID 9i laser digitizer at a camera target distance of approximately 1 m. The image files contain coordinates in x, y and z space. The x and y coordinates were used to spatially reference fractures in core (x is parallel to the core axis and y is perpendicular). The z coordinate was used to determine changes in the core surface. For example, if the core was intact, then the z values in the x direction were constant. Where the core was fractured, the z values increased. Changes in z values provided a simple parameter for preliminary identification fractures in core. The high accuracy of the laser camera allows subtle fractures with sub-millimetre spacing to be captured.

The next step is to characterize fractures with image processing techniques, such as edge detection. The use of statistical methods to analyze the similarity between z values will also be explored.

The 3-D imaging of core is a new use of this technology – a research frontier on the interface of mining geology, computer vision and engineering. Its application to routine geotechnical tasks typically carried out manually, such as RQD, will lead to significant improvements in both quantity and quality of data available for the mine design process.

### VOLCANISM AND VMS TYPE DEPOSITS IN SANJIANG OROGENIC BELT, EASTERN TETHYS

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Sanjiang Orogenic Belt of Eastern Tethys is tectonically the junction between the Himalaya-Tethyan tectonic domain and the Yangzi Platform. Volcanism as geological records plays an important role in understanding tectonic evolution and corresponding deep processes of the Sanjiang area. The belt is also considered as one of three important VMS-metallogenic provinces of China with many VMS type deposits. Therefore it is one of the key areas to understand the Tethyan evolution, and the related VMS deposits.

Various volcanic rocks of Proterozoic to Cenozoic age are widely distributed in the belt. The majority of volcanic rocks related to MVS type deposits were formed during the Tethyan and post-Tethyan stages, i.e., from Carboniferous to Triassic. Five types of volcanic petrotectonic assemblages in the Sanjiang Belt have been recognized as follows: Oceanic assemblages including MORB/Para-MORB assemblage and OIB assemblage, island arc and continental marginal arc assemblage, collision-related assemblage, post-collisional assemblage and intracontinental assemblage, which presented the characteristics of paleo-tectonic setting of the area. The VMS deposits are associated with submarine volcanic rocks in a wide range of depositional environments, including of island-arcs, rifts and ocean ridge, which are mainly formed late Permian and Triassic volcanic sequences with variable magmatic affinities. Among these, the rift and back-arc environments are the most important. The oceanic ridge and hot-spot systems are common and contain a few Zn-Pb(-Cu) type VMS deposits. Generally, three distinct VMS type deposits have been distinguished, including of Pb-Zn (-Cu), Cu (or Cu-Zn), and Zn-Pb (-Cu), distributing in three dominant belts. The Pb-Zn (-Cu) deposits were hosted by Triassic calc-alkaline felsic rocks in bimodal basalt-rhyolite sequences in the Yidun arc. The Cu or Cu-Zn types of deposits are closely associated with Permian to Triassic calc-alkaline, medium quartz andesite near boundary of Simao basin, while the Zn-Pb (-Cu) are restricted to the Permian mafic and ultramafic volcanic sequences along Lancang river.

In addition, it has been proved that the volcanic rocks have usually been deformed and the VMS deposits been overprinted by later mineralization stages in Sanjiang of eastern Tethys, resulting in mineral elements segregation variation or mineral distribution changes. The formation of the deposits is controlled by key factors, such as tectonic setting, volcanic petrotectonic assemblages, and volcanic lithology and so on.

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### DIEL VARIABILITY IN THE MICROBIAL AND GEOCHEMICAL COMPOSITION OF THE LACUSTRINE AIR-WATER INTERFACE

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Owing to its unique physical properties, the air-water interface of aquatic systems is a site of accumulation of chemicals and microorganisms. Understanding the composition and dynamics of the interface is critical because of the various biogeochemical processes it can regulate, including the exchange of gases and trace elements between the atmosphere and hydrosphere. In addition, as the initial aquatic compartment receiving atmospheric deposits, the air-water interface may serve as an indicator of atmospheric transport of trace elements and micro-organisms. Evidence regarding differences in the geochemical and microbial



composition of the lacustrine air-water interface relative to the underlying water column is mixed, particularly with respect to the enrichment of nutrients, trace elements, and prokaryotic cells at the interface. Temporal variability in the structure and composition of the air-water interface is poorly understood, which may help to explain these results. The objective of this study was to examine the structural characteristics and determine the geochemical and microbial composition of the lacustrine air-water interface and underlying water column (0.5 m depth) in two contrasting freshwater environments (Sunnyside Beach, Lake Ontario, a littoral hard water environment heavily impacted by anthropogenic inputs; Coldspring Lake, a limnetic and relatively pristine soft water environment) over a diel timeframe during the summer of 2010. The structure and composition of the air-water interface differed depending on the time of day in both environments. The interface was enriched in prokaryotic cells and trace elements relative to the underlying water in the early morning during calm weather conditions, with these enrichments abolished by midday and into the afternoon. Aggregates of inorganic and organic materials and prokaryotic cells at the interface were substantially larger and more abundant in the early morning as compared to midday and the late afternoon. Collectively, these results demonstrate that the microbial and geochemical composition and structural characteristics of the air-water interface can vary appreciably over the course of a day and that this may in part reflect changing weather conditions including wind speeds. Further, the potential for microbial transformation of trace elements is likely greatest overnight and in the early morning during calm conditions. Time of day should be accounted for when investigating this aquatic compartment.

#### **MICROBIAL ECOLOGY AND ARSENIC TRANSFORMATIONS IN A MICROCOSM EXPERIMENT USING SEDIMENT FROM AN ARSENIC-CONTAMINATED WETLAND**

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Terra Mine is an abandoned copper and silver mine in the Northwest Territories, Canada, at which mine tailings were disposed of into an existing lake adjacent to the mine's processing plant. The mine tailings contain elevated levels of arsenic (As) resulting in As levels exceeding Canadian sediment and water quality guidelines. High levels of As are found in Ho-Hum lake, as well as in the downstream wetland water and sediments. The microbial ecology as well as the reduction and oxidation of As, iron (Fe) and sulphur (S) in the wetland water and sediments downstream of Ho-Hum lake are the subject of a field and laboratory study. This wetland has been proposed as a passive remediation system for the removal and storage of As.

Microcosm experiments were performed over a 42-day period, comparing three locations (upper, middle and lower sites) within the wetland to assess the overall stability of As-bearing minerals. The formation of dissolved methylated-As and thioarsenic species was tracked over time as these species in dissolved form may be an important consideration in determining the toxicity of As. The reduction of As(V) to the more mobile and potentially harmful dissolved As(III) was also investigated, as it can be catalyzed by As-utilizing bacteria. The microcosms compared fresh sediments and sediments amended with a 10 mM acetate solution; however, no significant difference was found between the acetate-amended and non-amended microcosms. The dissolved methylated and thiomethylated As species increased over time at

all three locations from 3% or less of the total As on day 1 to 8%, 25% and 35% of the total As in the upper, middle and lower sites, respectively. Sediment samples taken at the beginning and end of the experiment were analyzed by X-ray absorption spectroscopy to identify changes in the As oxidation state over the course of the experiment. Results indicate that there was an average 18% increase in the proportion of As(V) in sediments over the course of the experiment. DNA sequencing of bacteria in pre- and post-microcosm sediments identified Fe- and S-transforming bacteria which may also utilize As in place of one or either Fe or S. While showing similar trends, abiotic control microcosms did not show as significant increases in dissolved As, Fe or S. Abiotic controls also showed less methylated and thio As species formation, indicating that microbial activity is an important contributor to arsenic mobilization and transformations in the wetland.

#### **THE WORLD-CLASS ROBERTO GOLD DEPOSIT, ÉLÉONORE PROPERTY, JAMES BAY AREA, SUPERIOR PROVINCE, QUEBEC: INSIGHTS FROM GEOLOGY AND GEOCHRONOLOGY**

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The world-class Goldcorp Roberto gold deposit (9 Moz) is one of the most significant discoveries made in the last 10 years in Canada and is a new illustration of the diversity of styles and settings of major gold deposits in the Superior Province. Located in the relatively underexplored northern part of the Superior Province, it is a lower amphibolite sediment-hosted Au-As-Sb-B deposit mainly hosted by post-2675 Ma Timiskaming age turbiditic wackes but with ore also present within >2675 Ma paragneiss, local high-grade quartz veins and ca. 2620-2600 Ma LCT pegmatites. The deposit straddles the contact between the La Grande (Uchi) volcano-plutonic and the highly metamorphosed Opinaca (English River) metasedimentary subprovinces. It is located within a window of lower metamorphosed but polydeformed La Grande sedimentary rocks within a km-scale fold hinge that affects amphibolite-facies turbiditic metagreywacke and paragneiss. Gold mineralization is primarily confined to sub-parallel decameter-wide mineralized zones and is associated with calcium-bearing veins, potassic alteration, and Mg-tourmaline (dravite). The principal mineralized zone (Roberto) consists of a stockwork of quartz ± actinolite ± diopside ± biotite-arsenopyrite-pyrrhotite veins and quartz-dravite-arsenopyrite veinlets, contained within microcline, phlogopite, dravite and arsenopyrite-pyrrhotite replacement zones. The alteration and mineralized zones are metamorphosed and deformed by structures attributed to D<sub>2</sub>, although some ore zones appear to be controlled by D<sub>2</sub> structures. Timing of gold mineralization is interpreted as being pre- or early-D<sub>2</sub>. Chronology between deformation, stockwork-replacement, disseminations and high-grade vein-type mineralization, with dated pegmatites, and ages of monazite, titanite and arsenopyrite indicate that: 1- gold mineralization is younger than ca. 2675 Ma; 2- the main stage of deformation (D<sub>2</sub>) was still active by ca. 2616 Ma but is older than ca. 2603 Ma; 3- major metamorphic and deformation event(s) occurred between ca. 2621-2606 Ma; 4- part of the mineralization and/or the metamorphosed and remobilized product of an earlier bulk gold stage is dated at ca. 2620-2605 Ma suggesting much younger tectonic, metamorphic and gold-bearing event(s) compared to events documented in the Superior Province.

The link between some of the Au-mineralization and magmatic fluids should be considered, as indicated by the presence of multiple generations of pegmatites, some of which are contemporaneous with part of the mineralization or its remobilization.

The deposit shows a spatial association with an unconformity at or near the contact between two subprovinces. It also indicates that contact between the sediment-dominated Opinaca, English River, Quetico and Pontiac with the volcanic-dominated La Grande, Uchi, Wabigoon and Wawa-Abitibi subprovinces, may be underexplored.

#### **MINERALOGICAL AND GEOCHEMICAL CHARACTERIZATION OF SECONDARY PHASES FORMED ON MINERAL SURFACES IN CONTACT WITH ACIDIC METAL-RICH TAILINGS WATERS AT THE COPPER CLIFF MINE TAILINGS DISPOSAL AREA**

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The treatment and disposal of sulfide tailings from base-metal mining operations leads to the generation of acid which can carry vast amounts of mobile and potentially toxic metals. Understanding the chemical reactions involved in these systems may lead to better ways of dealing with polluted metal-rich waters. Surface alteration-layers often coat mineral surfaces in acid-mine drainage systems and the characterization of their chemical composition is required in order to understand the uptake or release of potentially toxic elements by these secondary phases. Micrometer-thick coatings occur on the surface of outcropping bedrock in contact with acidic metal-rich tailings water at the Copper Cliff Mine Tailings Disposal Area in the Greater City of Sudbury, Ontario. The coatings were investigated using SEM, XRD, Mössbauer,  $\mu$ -XRF and LA-ICPMS techniques. All of the observed rock coatings were composed of an outer Fe-rich zone composed of precipitated Fe-oxyhydroxides and/or Fe-sulfate phases and an inner Si-rich 'transition' zone containing metal-bearing particles within an amorphous hydrous silica gel-like matrix. The transition zone was the result of weathering of underlying siliceous minerals and contained high concentrations of trace. The Fe-rich coatings, composed of secondary Fe-phases (e.g. jarosite, ferrihydrite and schwertmannite ect.), are the result of precipitation from super-saturated tailings solutions. The adsorption and diffusion of metals, metalloids and  $\text{SO}_4^{2-}$  through the upper Fe-rich coating resulted in the nucleation and crystallisation of metal-, metalloid- and sulfate-rich particles in the amorphous silica matrix of the transition zone. Iron-rich layers composed of jarosite-group minerals and Fe-rich layers from a near-neutral environment (pH 6.2) have low Fe : Si ratios and consequently have similar trace-metal concentrations to the transition zones. Iron-rich layers composed of schwertmannite and goethite have higher Fe : Si ratios and lower trace-metal concentrations than transition zones. Higher trace-metal concentrations in the Fe-rich layers with low Fe : Si ratios can be explained with the presence of jarosite-group minerals, higher adsorption rates of metals onto Fe-bearing minerals at near-neutral pH settings and a larger portion of hydrous silica gel-like matrix material. Calculated enrichment factors for trace metals and metalloids (relative to the pond solution) in transition zones and Fe-rich layers indicate that the mobility of trace elements in the tailings pond waters increase in the sequence  $\text{Pb} = \text{As} \geq \text{Cr} \geq \text{Cu} \geq \text{Zn} \geq \text{Mn} \geq \text{Co} \geq \text{Ni}$ .

#### **POLARIS PROJECT, PAST & FUTURE**

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POLARIS (Portable Observatories for Lithospheric Architecture and Research In Seismicity) was founded as a pool of shared geo-

physical instruments, technologist support, data archiving and research interests. Its motivation is economy of scale so that small groups or individual researchers have sufficient infrastructure to undertake projects at scales from urban earthquake hazard to continental-scale structures. Three seismic arrays formed the core of POLARIS at its start in 2001. A southern Ontario Array studied ground motions and earthquake hazard. A British Columbia Array studied subduction zones processes beneath the Vancouver region. A Northwest Territories Array characterized mantle lithosphere structures beneath diamond mines in the Slave craton. After ten years, these fundamental goals remain and these studies will continue for several more years. In the near future, POLARIS will also interface with its 'big brother' USArray to the south, when seismometers from both consortia will be intermingled for several years in eastern North America and perhaps in the Yukon-Alaska borderland. A second phase of POLARIS is also being planned that would expand its scope and instrument pool to include ocean bottom seismometers, instruments capable of operating year-round at high latitudes, and arrays of broad-band higher frequency seismometers to study seismicity and seismic wave propagation at high resolution in mine environments.

#### **USING APATITE AND BIOTITE AS MONITORS FOR THE FLUORINE AND CHLORINE CONCENTRATIONS OF ALKALINE FELSIC MAGMAS**

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The role of halogens in the petrogenesis of alkaline felsic magmas is a subject of continuing discussion in the petrologic literature. F and Cl concentrations in melts have been estimated from whole-rock F and Cl contents, melt inclusions and halogen containing minerals, notably biotite and apatite. Each approach gives a different picture of halogen concentrations in the magma.

The F and Cl content of apatite and biotite from nepheline syenites, syenites and granites of the Chilwa alkaline province (Malawi) and granites from western Argentina was determined by electron microprobe. For apatite the F and Cl content of the coexisting melt is calculated using the model of Webster et al. (2009). For biotite the fugacity of HF and HCl in the coexisting melt is calculated using the model of Munoz (1992) and then converted to F and Cl concentrations using the algorithms of Piccoli and Candela (1994).

For the Chilwa alkaline province the felsic silicate rocks show a range in both F and Cl whole-rock concentrations of up to 0.8 wt.% F and 0.7 wt.% Cl. Cl/F ratios >1 are found for a number of the silica undersaturated felsic rocks. For the syenites and granites F/Cl ratios are usually less than 1. The apatites are fluorapatites and calculated F-melt values fall in a restricted range between 0.248 and 0.303 wt.%. The apatites record the F content through much of the solidification history of the melt. For the biotites calculated F melt concentrations range from 0.1 to 1.0 wt.%. In almost all cases these values exceed the measured whole-rock concentrations and are generally greater than the F melt concentrations determined from apatite chemistry. The biotites appear relatively late in the crystallization history of the magmas and are thus recording F values for the residual melts. Calculated Cl melt concentrations range from 0.02 to 0.2 wt.%. In most cases these values are less than the measured whole-rock Cl concentrations.

Biotite is the principal halogen containing phase in the Argentina granites. For the San Blas pluton, which contains late stage mineralization, F melt = 0.27 to 0.54 wt.% and Cl melt = 0.03 to 0.11 wt.%. For the Achala batholith, which has associated U mineralization, F melt = 0.13 to 0.33 wt.% and Cl melt = 0.02 to 0.06

wt.%. These values are in the same range as those determined for the granites of the Chilwa alkaline province.

#### **PALAEOGEOGRAPHIC CONSTRAINTS PROVIDED BY SELECTED STYLES OF MINERALISATION**

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Palaeogeographic reconstructions during the Precambrian are frequently poorly constrained because of limited or ambiguous palaeomagnetic data, imprecise age constraints and the limitations inherent in geological and geophysical mapping. A number of aids to reconstruction have been proposed, for instance precisely dated igneous dykes, regional domains with unique geochronology or isotope composition, lithostratigraphic continuity, etc.

Studies of various mineralization styles during the past decade have demonstrated that several associations may be uniquely associated with geodynamic setting. For instance, volcanic-hosted massive sulphide deposits have been classified in several 'clans' which appear to have geodynamic significance, just as porphyry deposits and orogenic gold deposits are formed in settings which are consistently linked to subduction or collisional settings with distinctive vergence polarity at large scales. Utilisation of the age and setting of ore deposits provides another mechanism to help constrain or prioritise possible palaeogeographic reconstruction models.

The validity and use of this approach is illustrated using Phanerozoic and Precambrian examples such as the VMS deposits of New Brunswick and the Caledonides of Norway; porphyry copper deposits across Asia and Ni-Cu sulphide deposits in a global context; all utilizing information stored in the IGCP 509 (StratDB) database. Additional constraints are provided by geochronological and isotopic information captured in the DateView geochronology database. Plate reconstructions are performed utilizing both the Paleogis software package in a GIS environment and the standalone GPlates package.

#### **CHEMICAL COMPOSITION OF BIOTITE FROM CHAHFIRUZEH AND SARA PORPHYRY SYSTEMS, SOUTHEAST IRAN: IMPLICATIONS FOR DISCRIMINATION OF ECONOMIC AND NON-ECONOMIC PORPHYRY SYSTEMS**

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The Cenozoic Urumieh-Dokhtar magmatic arc (UDMA) of Iran hosts many porphyry type Cu±Mo systems. Two Porphyry copper systems, Chahfiruzeh (50 Mt at 0.45% Cu) and Sara (20 Mt at 0.15% Cu), 13 km apart, in southern UDMA are selected to investigate the composition of biotite and its bearing to the productivity of porphyry systems.

The two systems are associated with Miocene porphyritic plutons of quartz-monzodiorite to tonalite (Chahfiruzeh) and diorite to quartz-diorite (Sara) intruding into Eocene volcanic-pyroclastic rocks. Alteration assemblages typical of porphyry Cu systems are well developed in both systems; Chahfiruzeh is distinguished by a more extensive potassic alteration.

Three types of biotites (primary magmatic, reequilibrated, and neoformed) occur in the two systems. Magmatic biotite occurs as euhedral to subhedral grains, <1 mm to 4 mm in diameter. The reequilibrated and neoformed biotites are of secondary origin, developed through fluid/rock interaction in the course of hydrother-

mal processes. Reequilibrated biotite formed through partial to complete replacement of magmatic hornblende and biotite. Neoformed biotite formed as fine, <100 µm, scattered grains, or grain aggregates.

Biotite grains were analyzed in the Electron Microprobe Laboratory at Leoben University, Austria, using a JEOL JXA 8200 superprobe. The primary magmatic and reequilibrated biotites were analyzed in samples from the porphyritic intrusions, and the neoformed biotites analyzed in samples from the andesitic host rocks.

Various biotites lie in eastonite and phlogopite fields. Primary magmatic and reequilibrated biotites have higher XMg ratio (>0.62) than neoformed biotites (<0.62). All three types of biotites display narrow range of Fe/(Fe+Mg) ratios but variable AlIV contents. The neoformed biotites from both systems have higher AlIV in tetrahedral layer. There is a positive correlation between F (wt%) and XMg in the secondary biotites for both porphyry systems.

The neoformed biotites in both systems are characterized by higher Al<sub>2</sub>O<sub>3</sub>, FeO and K<sub>2</sub>O, and lower F, Na<sub>2</sub>O and TiO<sub>2</sub> contents, compared to the primary magmatic and reequilibrated biotites. No distinct differences in the composition of the neoformed biotites exist between the two porphyry systems.

Primary magmatic biotites from both systems contain higher TiO<sub>2</sub> compared to the secondary biotites. Magmatic biotite from Chahfiruzeh is enriched in AlIV, Cl and K<sub>2</sub>O and depleted in SiO<sub>2</sub>, TiO<sub>2</sub> and MnO compared to that from Sara. There seems to be a connection between the composition of primary biotite and productivity of porphyry systems.

#### **HOLOCENE CLIMATIC RESPONSE TO SOLAR FORCING: EVIDENCE FROM THE PLANT MACROFOSSILS AND DELTA-<sup>18</sup>O CELLULOSE RECORD OF MER BLEUE BOG, OTTAWA, ONTARIO**

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We present a ~9200-year, high-resolution oxygen isotope record of plant cellulose ( $\delta^{18}\text{O}_{\text{cel}}$ ) from a 6 m core collected from ombrotrophic Mer Bleue Bog, Ottawa, in Eastern Ontario to demonstrate its potential as a proxy for paleotemperature reconstruction in peat deposits. A novel combination of time-series analysis methodologies (spectral, wavelet) was carried out on digitized photographic images of the peat core, X-ray scans, and cellulose oxygen isotope data to determine the nature of any trends and cycles that characterized paleoclimate fluctuations in Eastern Canada through the last 9200 cal. yr. B.P.

The results indicate that the  $\delta^{18}\text{O}_{\text{cel}}$  record follows the general trend of Holocene paleotemperature variation for this region through the last ~5500 years and the Northern Hemisphere paleotemperature record for the last 2000 years. The > ~5500 yr BP  $\delta^{18}\text{O}_{\text{cel}}$  record was deposited in a non-ombrotrophic fen environment subject to ground water influence, which created noise in the paleotemperature reconstruction in this time interval. Three distinct time intervals have low  $\delta^{18}\text{O}_{\text{cel}}$  values: 200 to 800 cal. yr. B.P. (Little Ice Age); 2800 to 3400 cal. yr. B.P. synchronous to a cooling period reported elsewhere in North America, and; 4200 to 4600 cal. yr. B.P. corresponding to a cooling interval in the North Atlantic region. A fourth period of low  $\delta^{18}\text{O}_{\text{cel}}$  values between A.D. 1810 and 1820 may be related to the extremely cold "year without a summer" of A.D. 1817 and cooler subsequent years, which occurred in the aftermath of the Tambora volcanic eruption. This cooling may also have been associated with the early 19th century Dalton solar Minimum.

The trends, cycles and abrupt shifts recognized in the peat coloration, X-ray density and oxygen isotope data from the Mer Bleue peat core were correlated and compared with global solar

activity proxy records including  $^{14}\text{C}$  production rate, sunspot numbers, and solar irradiance. Our results show that solar activity fluctuations at the 150-year, ~200-250-year, ~1300-year, and ~2200-2500-year cycle-band had a major influence on regional climate. A shift in the isotope and sediment color cycle pattern from a ~1300 year to a ~650 year cyclicity at ~3500 yr B.P. is coincident with a similar pattern shift in solar activity cyclicity and corresponds to an onset of cool period from ~3400-2800 yr B.P. in eastern Canada and in the North Atlantic region.

#### **FLOC MICROBIAL IRON REDOX CYCLING IN ALGONQUIN PARK LAKES**

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Suspended floc is a distinct sedimentary compartment within aquatic systems, comprised of substantive organic (active biological, detrital) as well as mineral and bio-mineral constituents. Results of research to date have identified floc as a significant metal-sink, with floc-organics (microbial cells and associated EPS) as the critical foundation underpinning enhanced floc metal uptake through their structural role in role amorphous iron oxyhydroxide ( $\text{FeOOH}$ ) nucleation and/or trapping. However, floc metal retention may be highly dynamic, given the significant opportunity within floc for microbial redox cycling of Fe (i.e. dissimilatory iron reducing as well as autotrophic iron oxidizing bacteria) and thus dynamic dissolution/formation of  $\text{FeOOH}$ . This, in turn, would have important implications for trace metal dynamics and constraining these processes would further our understanding of the floc microbial control on aquatic metal bio-geochemistry across systems.

The objective of this novel research was to establish the potential for floc associated microbial iron oxidation and reduction in two contrasting lakes through targeted enrichments of iron reducing bacteria (IRB) as well as both neutrophilic ( $\text{pH}=6.3$ ) and acidophilic ( $\text{pH}=3.0$ ) iron oxidizing bacteria (IOB). These floc were collected from both aerobic and microaerophilic sections of the lake ( $\text{pH} \sim 6$ ) where iron should occur as  $\text{Fe(III)}$ . Such enrichments would establish for the first time the internal, microbially mediated, redox cycling of iron in natural aquatic floc. Results of targeted enrichments for IOB and IRB, phylogenetic and imaging analysis will be discussed.

#### **THE TRACE ELEMENT CHEMISTRY AND CATHODOLUMINESCENCE CHARACTERISTICS OF FLUORITE IN THE MOUNT PLEASANT Sn-W-Mo DEPOSITS: INSIGHTS INTO FLUID CHARACTER AND IMPLICATIONS FOR EXPLORATION**

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The Mount Pleasant Sn-W-Mo deposit comprises two hydrothermal breccia pipes and mineralized granite apophyses, namely, the Fire Tower Zone (FTZ) and the North Zone (NZ), that are approximately 1 km apart. The FTZ and NZ contain principally W-Mo with minor Sn, and Sn with minor W-Mo mineralization, respectively. In both zones, fluorite either predates or postdates mineralization. Pre-mineralization fluorite in the FTZ is associated with molybdenite and wolframite. In the NZ, pre-mineralization fluorite is associated with cassiterite and wolframite. Post-mineralization fluorite is either barren or occurs associated with sphalerite, galena, pyrite, and chalcopyrite.

Cathodoluminescence (CL) imaging reveals that fluorite associated with cassiterite and wolframite in the NZ is characterized by complex zonation. Fluorite associated with cassiterite has three main growth stages, and fluorite associated with wolframite shows evidence of significant dissolution and subsequent overgrowth.

Fluorite associated with molybdenite in the FTZ shows no evidence of growth zonation. Compared to fluorite associated with cassiterite and wolframite, barren fluorite and fluorite that is associated with base-metal sulphides show relatively simple zonation patterns with no dissolution features.

Laser-ablation inductively-coupled plasma mass spectrometry (LA-ICPMS) analysis shows that all fluorite types have flat REE patterns. Most crystals have negative Eu and positive Y anomalies; the exception is fluorite associated with base-metal sulphides, which has flat or positive Eu anomalies. These data are consistent with fluorite chemistry from other granite-related mineralization. Rare earth element concentrations are up to several orders of magnitude higher in fluorite associated with Sn-W mineralization than in barren or base-metal associated fluorite, and compared to fluorite outside of orebodies. Fluorite from the FTZ has significantly higher W/Sn ratios than fluorite in the NZ.

The zoning patterns in fluorite associated with Sn and W mineralization suggests a complex, dynamic fluid evolution during cassiterite and wolframite deposition that may reflect the interplay among fluids of different character and origin. This is in contrast to what is interpreted to be a more quiescent fluid environment during subsequent stages. These data also illustrate that fluorite chemistry correlates with the character of the mineralizing events and thus has possible applications in exploration for these types of deposits.

#### **THE NATURE OF DAUGHTER MINERALS IN COMPLEX FLUID INCLUSIONS-INSIGHTS FROM FOCUSED ION BEAM (FIB)-EDS ANALYSIS**

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Assemblages of liquid + vapour + solid (LVS) fluid inclusions occur along growth zones and in the cores of fluorite crystals that formed in close association with cassiterite mineralization in the Sn (-W-Mo) deposit in the North Zone, Mount Pleasant, New Brunswick. At least nine optically distinct solid phases are present in these LVS inclusions. The commonest and largest of these are: A) square, isotropic, colourless, moderate relief solids, B) anhedral, equant, isotropic, colourless, low relief solids, C) anhedral, birefringent, colourless solids, D) acicular, high relief, birefringent, greenish solids, and, F) rhombic, colourless, moderate relief, birefringent solids. In a given assemblage, phase ratios are consistent and except for an opaque solid, all solid phases melt prior to liquid-vapour homogenization, indicating that they are daughter crystals. The order of melting is solid F ( $56-140^\circ\text{C}$ ), solid C ( $126-145^\circ\text{C}$ ), solid B ( $244-308^\circ\text{C}$ ), solid A ( $251-375^\circ\text{C}$ ), and solid D ( $341-386^\circ\text{C}$ ).

Based on their optical properties, either solid A or B could be interpreted as halite, however, neither phase reacted to form a hydrate on cooling, which suggests that they are either not halite, or that hydrohalite did not form for kinetic reasons. Of these two, solid A has the higher melting temperatures and is more euhedral, suggesting that it is more likely to be halite. Traditional SEM-EDS and laser Raman spectroscopy have proven ineffective for solid identification due to an inability to analyze previously studied inclusions and host fluorescence, respectively. We have thus turned to focused ion beam (FIB) milling, in conjunction with EDS analysis, to characterize the solids in these inclusions. This technique allows characterization of solids and the fluid precipitate in situ, inside of previously chosen and studied inclusions. These analyses show that solid B is halite and that solid C is an Fe-Mn-K chloride. The composition of solid A has yet to be determined. Other solid phases comprise Sn- and As-bearing compounds and Pb-, Zn-, and

K-bearing chlorides. Residues precipitated from the inclusion fluids are enriched in Fe, Mn, K, Na, and Cl. These data showed that identification of solid phases based only on habit and optical properties, and in particular the interpretation of square isotropic solids with high melting temperature as halite, should be treated with caution. The FIB technique shows tremendous potential for the characterization of solid phases within fluid inclusions.

## SYN-CONVERGENT EXTENSION IN WESTERN ANATOLIA: CONSTRAINTS FROM NUMERICAL MODELLING EXPERIMENTS

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Western Anatolia is the site of lithospheric delamination, crustal thinning, and north-south oriented syn-convergent extension within the framework of lateral westward extrusion of the Anatolian microplate. Extrusion is driven by the convergence of Arabia with Eurasia, and accommodated by the North Anatolian (right-lateral) and East Anatolian (left-lateral) strike-slip faults. The cause of extension is still debated, but there are three mechanisms that have been postulated to contribute to the tectonic motion: gravitational collapse and spreading of the thickened, unstable lithosphere, subduction beneath the Aegean and Anatolian plates along the Hellenic trench, and counterclockwise rotation of the Anatolian plate. We use geodynamic numerical models that employ the plane strain viscous-plastic finite element code to constrain and provide insight into the extensional tectonics of western Anatolia, within a broader Mediterranean regime of convergence. In particular, we test the hypothesis that mantle lithosphere delamination is driving N-S extension. Results indicate that crustal extension occurs even within a regime of plate shortening, indicating contributions from trench retreat along the Cyprus trench and lithospheric delamination to the crustal thinning and extension.

## ZIRCON TEXTURES AND COMPOSITION: SENSITIVE RECORDERS OF MAGMATIC FLUID EXSOLUTION?

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Zircon studies have provided key insights into the evolution of felsic magma systems, particularly in regard to magma sources, magma recharge, and country-rock contamination. Here, we propose that zircon textures and compositions may also be sensitive recorders of magmatic fluid exsolution, with the potential to provide important information for mineral exploration. We have studied zircon from small-scale, highly evolved, late Paleoproterozoic granite intrusions on Melville Peninsula, Nunavut. Field, whole-rock chemical, isotopic, and textural data show that the granitic magmas exsolved U-rich fluids, whereas magma mixing or country-rock contamination played no significant role in their evolution. Zircon forms two main crystal populations, Type-1 and Type-2 zircon. Type-1 zircon is present in all intrusions, but is predominant in fine-grained granite. Crystals are euhedral and inclusion-rich, and show strong oscillatory zoning, relatively low concentrations of U (<2100 ppm) and Hf (<1.6 wt%), high Zr/Hf (~40-65), and pervasive alteration. Type-2 zircon forms distinct overgrowths on Type-1 zircon and is predominant in coarse-grained granite. Crystals are subhedral and inclusion-poor, and show weak oscillatory zoning, high concentrations of U (~2100-7400 ppm) and Hf (>1.5 wt%), low Zr/Hf (~37-44), and only local alteration. In individual crystals, compatible trace element concentrations and Zr/Hf ratios change sharply across the boundary of Type-1 to Type-2 zircon. Calculated mean weighted mean av-

erage <sup>207</sup>Pb/<sup>206</sup>Pb ages determined by SHRIMP preclude a significant hiatus between crystallization of the two zircon types. We suggest that strong oscillatory zoning and abundant inclusions of Type-1 zircon and its predominance in fine-grained granite indicate rapid crystallization during magma ascent or emplacement. Crystallization of Type-1 zircon ceased and crystals were altered once magmas reached fluid saturation. With time, fluids may have segregated or changed composition, and Type-2 zircon eventually crystallized. Weak oscillatory zoning and few inclusions of Type-2 crystals are in agreement with fluid-rich crystallization conditions. Local alteration of Type-2 zircon developed during subsolidus conditions. If these inferences are correct, zircon zoning and alteration textures and particularly U, Hf, and Zr/Hf compositional variation could provide better constraints on fluid evolution in felsic to intermediate magma systems, and be important exploration guides for certain mineral deposits, such as hydrothermal U deposits. Experimental and further field-based studies are necessary to test this hypothesis.

## VENUS: MAGMATIC AND TECTONIC HISTORY

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Venus preserves a vigorous history of intraplate (mainly basaltic) magmatism consisting of 1) individual volcanoes, those 100-1000 km in diameter having a plume origin, 2) annular structures termed coronae (and arachnoids) with diameters averaging 300 km, but ranging up to 2400 km, and having a diapir or plume origin 3) radiating graben-fissure systems (including novae) caused by underlying laterally-propagating dykes and extending up to 2000 km (or perhaps up to 6000 km; see below) away from volcanoes or coronae at their foci, 4) lava flow fields of scale comparable to terrestrial flood basalts, 5) regions of small shield volcanoes, often a few hundred km across, and 6) canali, narrow sinuous lava channels of lengths up to >7000 km. These are superimposed on earlier plains volcanism and deformed terrains (crustal plateaus and tessera). Differences such as the lack of water, and the absence of plate tectonics explain some differences in intraplate magmatic style from that found on Earth, but many useful cross-comparisons can be made with terrestrial Large Igneous Provinces and hotspots. Triple junction rifts (chasmata) are associated with plume-generated volcanic rises especially in the BAT (Beta Atla Themis) region. Ridge belts (dorsa) have a compressional origin but unclear setting. Some tectono-magmatic features may be much larger than previously realized. Artemis, a 2400 km diameter corona is linked by Hansen and Olive (2010) with a >5000 km diameter outer trough, a 12,000 km diameter radiating graben-fissure system (dyke swarm), and a 13,000 km diameter concentric wrinkle ridge system. Other large wrinkle ridge systems (2600-8000 km in diameter) circumscribing volcanic rises may belong to the same class of huge plume-related tectono-magmatic features. Fundamental questions remain: What is the detailed age distribution on the planet; crater counting provides a global average age estimate of about 750 Ma, but crater density is insufficient for regional chronology. Is there a strict lithological age progression following a major planetary resurfacing event, wherein the most/least deformed units are always the oldest/youngest, or are available constraints satisfied by a progressive time-transgressive resurfacing? Has lithospheric thickness increased toward younger times? The current Venus Express mission reveals regions of high thermal emissivity interpreted to reflect young unweathered volcanics indicating that Venus is actively resurfacing (Smrekar et al., 2010). Detailed and systematic mapping of the planet, including its widespread graben-fissure systems (underlain by dykes) is gradually sorting out the regional stratigraphy, essential for understanding Venus's magmatic and tectonic history.

## 100 YEARS AFTER WEGENER: CAN WE COMPLETE THE PLATE TECTONIC REVOLUTION?

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Almost a century after Wegener's groundbreaking proposals—that the present continents are dispersed fragments of a former supercontinent, Pangea—and nearly five decades after the “plate tectonic revolution” of the 1960s, a detailed picture has emerged of the kinematics and dynamics of our planet, allowing integration and synthesis of much of the younger geological record.

A much less detailed picture exists for the pre-Pangea world, although a substantial body of evidence suggests that there were previous supercontinents (Rodinia, Nuna,...). Break-up of these previous (super) continents severely fragmented and dispersed the older geological record. Only a full paleogeographic reconstruction of the approximately 35 main (and numerous minor) ‘puzzle’ pieces of preserved continental crust will allow us to see the full picture and synthesize the entire geological record.

There is sufficient high-quality information stored in the system to achieve meaningful reconstructions back to ca. 2.7 Ga and perhaps earlier. With a concerted effort this could be achieved in a short time and at only a moderate cost. The strongest constraints will not come from messy basement geology or other datasets that are fundamentally ‘fuzzy’. Instead, much of the pertinent information is contained in the record of large igneous provinces (LIPs) and their plumbing systems of regional diabase dyke swarms. This is because LIPs and their dyke swarms: 1) are naturally associated with break-up of pre-existing landmasses; 2) are emplaced in short pulses (typically 1 Myr or less); 3) have very large footprints (300–3000 km); 4) are relatively insensitive to uplift (vertical dykes); 5) contain rich geometrical information and yield superior ‘piercing points’; and 6) because they are the target rocks of choice for high-quality paleomagnetic studies, often yielding stable results that can be tested for their primary nature.

Significant advances in all aspects of U-Pb geochronology, together with the realization that almost all mafic rocks contain baddeleyite (ZrO<sub>2</sub>), now allow us to precisely date the short bursts of LIP magmatism. Multiple precisely dated events provide, in effect, magmatic ‘barcodes’ that can be compared between cratons and terranes, thus identifying original ‘nearest neighbours’. The inherent geometrical information can constrain relative craton configurations, while primary paleomagnetic information can further constrain azimuthal orientation, latitude, and relative longitude. Using this approach, we have launched a 5-year project, sponsored by an industry-government-university consortium, to date all LIP events and their dyke swarms around the globe and produce robust reconstructions back to 2.7 Ga ([www.supercontinent.org](http://www.supercontinent.org)).

## DETERMINATION OF ORIENTATIONS OF MAGNETITE MINERALS IN IGNIMBRITES BY COMPUTED MICRO-TOMOGRAPHY; A COMPARISON WITH AMS MEASUREMENTS

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## TEXTURAL COARSENING IN IGNEOUS ROCKS FROM SE-BIRJAND (EAST OF IRAN)

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Study area is located 120 km to SE of Birjand (East of Iran). Geologically, this region occurs in Sistan suture zone and is a wing of East Iran colored mélange. This study focused on the shallow level intrusive rocks with micro diorite- quartz diorite composition which are younger (oligomiocene) than ophiolitic complex. The porphyritic textures and clustering of crystals especially plagioclases are the main qualitative textural features. More than the 3200 plagioclase crystals in 9 thin sections were processed. The CSDs lie in 3 group: Group 1) concave up CSDs with minor curvature (Goodness of fit (Q) between 0.07 to 0.3), maximum crystal size (MCS) = 2.7-3.6 mm, characteristic length (L<sub>C</sub>) equal to 0.22-0.25 mm, Group 2) concave up CSDs with intermediate curvature (Q<0.001), MCS = 4 -5.9 mm, L<sub>C1</sub>=0.14-0.2 and L<sub>C2</sub>= 0.4 -0.7, Group 3) concave up CSDs with strong curvature, MCS= 6-7.5, L<sub>C1</sub>= 0.1 and L<sub>C2</sub>=0.6 -0.77. Shape of crystals shifted from tabular crystals (I≈L and I, L<3) in group 1 to more equant forms (with I, L<2) in groups 2 and 3. The SDP of plagioclase crystals as seen in the R value against porosity diagram are clustered (R= 0.8 – 1) and degree of plagioclases clustering increased in group 3 with change of crystal sizes and shapes. A dynamic model is proposed for the textural and minor chemical diversities in these rocks. Crystallization of plagioclase started following emplacement of dacitic magma at a depth of at least 5 km. Nucleation was probably heterogeneous that causes early clustering of crystals. CSDs in Group 1 developed by nucleation and growth in this chamber and final groundmass crystallization after dyking emplacement in the near surface. This process was interrupted by the injection of more mafic magma into the chamber as seen in petrographic evidence and modeled by mixing equations on chemical diagrams such as Ni vs. V, Rb/Zr vs. Sr/Rb and Ba/Rb vs. Rb and mass balance calculations. Under these conditions textural coarsening (Ostwald ripening) of plagioclase because of warming system occurred: crystals smaller than critical radius (or size) dissolved to feed larger crystals. The CSD became less steep and extended to larger crystal size. Then, nucleation and growth renewed after cooling in chamber and near surface emplacement that produced group 2 CSDs. A repetition of this cycle has generated group 3 CSDs. The shape and SDP of crystals also changed during these periods.

## EDIACARAN-CAMBRIAN GLOBAL PALEO GEOGRAPHY: UPDATE OF AN ENDURING ENIGMA

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The Ediacaran paleogeographic enigma involves two paleomagnetic datasets: (i) highly variable remanence inclinations from mainly intrusive rocks in eastern Laurentia and, with greater overall scatter, Baltica; and (ii) highly variable remanence declinations

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from mainly sedimentary rocks in Australia and Siberia. If these data are interpreted in the standard context of a uniformitarian, geocentric-axial-dipole (GAD) geomagnetic field, then Laurentia and Baltica would have migrated rapidly back and forth across paleolatitudes, whereas Australia and Siberia would have remained near the paleo-equator, undergoing large oscillatory changes in orientation. These styles and rates of motion are unfamiliar to Mesozoic-Cenozoic plate tectonics and favor an alternative explanation. Both subsets can be explained, in principle, by a model of oscillatory TPW--whereby the entire lithosphere, and likely the entire silicate Earth, swiveled relative to the rotation axis numerous times in response to imbalances in the planet's inertial tensor. In detail, the TPW model must be tested by precise age comparisons between groups (i) and (ii), but thus far the lack of dating from the sedimentary successions has precluded this test.

Paleomagnetic data from 600-550 Ma intrusive rocks in eastern Laurentia are crucial for testing the TPW hypothesis, because many results appear to suggest migrations across tens of degrees of latitude on the order of a few million years. The maximum rate of TPW is fundamentally limited by viscosity of the mantle, which must deform to accommodate the reorganization of its masses through Earth's rotational bulge. Yet (lower) mantle viscosity is highly uncertain today, and even more so for ancient times. The TPW model also generates predictions of relative sea-level change for each event, with a quadrantal global pattern. Very rapid TPW events as proposed to explain the 600-550 Ma Laurentian paleomagnetic data should generate significant transgressive and regressive signals across the continent, which can be tested against the Ediacaran sedimentary record that exists mainly in western Laurentia, yet the lack of precise ages for those strata remains a problem.

One may invoke a non-GAD geomagnetic field to account for the unusual dispersion of data. However, the Ediacaran polar paths are similar in pattern (though not in rate) to the mid-Paleozoic polar oscillations of Gondwana-Land, which are supported by the independent evidence of glacial centers migrating across that continent. Also, group (ii) data from sedimentary successions contain stratabound polarity reversals that appear typical of the Mesozoic-Cenozoic geodynamo.

## STRUCTURE AND TOPOLOGY OF DUMORTIERITE AND DUMORTIERITE-LIKE MATERIALS

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Dumortierite, approximately  $\text{Al}_{(6+x)}\text{Si}_3\text{BO}_{16}(\text{O},\text{OH})_2$ , has a complex and unusual crystal structure. Although traditionally described as a borosilicate mineral, dumortierite's borate and silicate groups are far from its most important structural features. The dumortierite structure is an open framework with large hexagonal channels that may have future applications in catalysis. This structure is shared by several rare minerals that are not traditionally grouped together, as well as by a growing number of synthetic materials. In the present work a generalized formula or structure-generating function for materials with the dumortierite structure is discussed, along with some geometric and crystallographic properties that derive from the structure.

Dumortierite has a strongly pseudo-hexagonal orthorhombic structure based on rod-like double chains of Al octahedra in a framework based on the 6.4.3.4 semiregular tiling. The large hexagonal channels contain chains of face-sharing Al octahedra attached to the framework by rings of  $\text{SiO}_4$  tetrahedra. Smaller triangular channels contain planar  $\text{BO}_3$  groups, while in other materials the triangular channels are occupied by tetrahedral or pyramidal groups. Holtite and magnesiodumortierite are isostructural with

dumortierite, while ellenbergerite, phosphoellenbergerite, ekatite and the synthetic materials have very similar structures with a hexagonal space group. These minerals and materials differ from one another in the identity of the metallic cations occupying the framework and face-sharing chains, and in the tetrahedral, pyramidal or triangular groups within the hexagonal and triangular channels. However, the crystal chemistry of the group as a whole can help answer outstanding questions about specific members.

Finally, some other materials with different but closely related structures are discussed: the mineral lyonsite and its large group of synthetic analogues, whose structures are also based on the 6.4.3.4 tiling but with single octahedral chains instead of double chains; satterlyite and holtedahlite, which have a similar framework of double chains based on a hexagonal tiling instead of 6.4.3.4; and angelellite, which contains staggered double chains of octahedra like the  $\text{Al}_2\text{-Al}_3$  sites in dumortierite.

## ÉVALUATION DU CONTEXTE D'EXPOSITION AUX INONDATIONS DANS UN CADRE D'ANALYSE MULTIRISQUES : ÉTUDE DU CAS DE LA RÉGION MÉTROPOLITAINE DE PORT-AU-PRINCE (HAÏTI)

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Port-au-Prince et sa population sont constamment exposées à de nombreux aléas pouvant générer des risques naturels, sanitaires ou sociopolitiques de grande envergure. Toute solution sur le long terme pour réduire la vulnérabilité d'ensemble doit être élaborée dans un cadre d'analyses multirisques pour renforcer l'aménagement du territoire. Dans cette communication, nous voulons évaluer le contexte particulier d'exposition du versant Nord du Morne l'Hôpital aux risques d'inondation.

Le bassin de Port-au-Prince est contenu dans deux provinces morpho-tectoniques à la jonction des deux ensembles géologiques formant Hispaniola (Île d'Haïti) ainsi qu'une double structure de failles complexes. Ce bassin contenu par les versants du Morne l'Hôpital s'étale sur moins de 100 km<sup>2</sup> et est drainé par deux rivières permanentes et plus de vingt ravines. Le Morne l'Hôpital culmine à plus de 1000 m d'altitude et est doté en amont de versants abrupts (60 à 80%) dénudés et formés de matériaux calcaires très friables. Ces versants débouchent rapidement sur la zone de piémont et la plaine alluviale. Dans ces deux dernières zones se concentre la majorité de la population de Port-au-Prince.

Au début des années 80, des travaux de drainage d'envergure ont été entrepris au niveau de la ville sans une mise en condition adéquate des versants du Morne l'Hôpital. Le système de drainage naturel des ravines n'ayant pas été conditionné en tandem avec le système d'égouts pluviaux, la capacité de ce dernier a été rapidement dépassée et s'engorge d'alluvions à chaque crue. Ainsi, les risques d'inondation et les crues torrentielles constituent une menace grave à récurrence quasi semestrielle occasionnant à chaque fois des pertes de biens et de vies humaines. La situation s'est considérablement empirée ces dernières années en raison des changements dans l'occupation du sol dans les versants du Morne l'Hôpital mais également en raison de l'établissement de différents tissus d'habitats denses et non viabilisés dans la majorité des points de déversements des ravines ou des égouts au niveau de la baie de Port-au-Prince.

Dans cette recherche, nous analysons les précipitations et la transformation de l'occupation des sols sur le versant Nord du Morne l'Hôpital pour redéfinir le potentiel en eau de ce versant, pour estimer le débit de crue solide potentiel et finalement pour simuler l'effet de certains types de zonages en vue de la réduction



de la vulnérabilité de cette portion du territoire du bassin de Port-au-Prince et aussi comme prototype pour améliorer les connaissances pour l'aménagement d'ensemble du territoire.

#### **EVALUATION OF GLACIOFLUVIAL AQUIFER HETEROGENEITY AND SEDIMENTARY ARCHITECTURE USING MULTI-FREQUENCY GROUND-PENETRATING RADAR**

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Glaciofluvial deposits are host to highly productive aquifers but their intrinsic heterogeneity and stratigraphic complexity can be a challenge for estimating hydrogeologic properties. In this study, spatial trends in heterogeneity and sedimentary architecture of a coarse-grained glaciofluvial deposit were investigated in a gravel pit near Limehouse, Ontario using multi-frequency ground-penetrating radar (GPR). The gravel pit is one of several sites in Halton Region being considered as possible locations for artificial groundwater recharge. The well-exposed outcrops in the pit (>10 m) allow direct comparison of radar and outcrop lithofacies, and provide an 'outcrop analogue' for regional glaciofluvial aquifers present in the shallow subsurface. GPR surveys were acquired using four different frequencies (25, 50, 100 and 250 MHz) over a 300 × 22 m grid on the gravel pit floor and along an adjacent outcrop and roadway. Profiles were acquired at 2 m line spacing using D-GPS positioning and processed to a quasi-3D volume in GPR-SLICE software. Selected profiles for each frequency were assembled in a single 2-D profile (>30 m depth) to optimize radar resolution and penetration depth.

Radar reflection patterns were grouped into radar facies and interpreted using architectural element analysis (AEA) with reference to a well-exposed outcrop and nearby geophysically logged borehole (MW-22). Using this approach several distinctive lithosomes were identified and their geometries mapped out over the pit base. The lithosomes include accretionary elements (AC), consisting of both horizontal and low-angle (2-5°) clinoformal reflectors and incised channel elements (CH), indicated by concave up reflectors that truncate underlying reflection patterns. The lithosomes and outcrop lithofacies are characteristic of deposition within a high-energy glaciofluvial environment such as a sub-aerial braided river (e.g. outwash plain) or sub-aqueous fan-delta.

Comparison of the radar profiles with borehole and outcrop data indicates that lithosome bounding surfaces are associated with major changes in sediment texture. Lithosomes defined using radar reflection patterns can therefore be used to predict changes in sediment grain size and associated hydrogeologic parameters (e.g. hydraulic conductivity). For example, spatial trends in hydraulic conductivity in the Limehouse deposit are likely to be strongly controlled by coarse gravel-filled channel elements (CH), and can be predicted from the spatial distribution and subsurface geometry of these elements. The results demonstrate that multi-frequency GPR is a viable approach for evaluating spatial trends in sedimentary heterogeneity and can be applied at other sites under consideration for artificial recharge projects.

#### **IRON-NICKEL-SULFUR SYSTEM. PHASE EQUILIBRIA AND THERMODYNAMIC ACTIVITIES IN SULFIDE LIQUID AND MONOSULFIDE SOLID SOLUTION AT 900°C**

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Phase equilibrium study and sulfur fugacity measurements were carried out in the Fe-Ni-S system at 900°C. Experiments were

done in evacuated silica tubes. The quench products were analyzed by electron microprobe and x-ray diffraction. Indirect sulfur fugacity measurements were done in the sulfide liquid and Mss fields by equilibrating the vapour phase above the Fe-Ni-S charge with synthetic pyrrhotites.

Combining our data with published  $f_{S_2}$  of liquid in the 1200 to 1400°C interval, indicates that, at constant composition, liquids with 38 to 46 at% S have  $\log f_{S_2}$  versus  $1/T$  plots that are linear over the entire temperature range. For the alloy-liquid equilibrium,  $f_{S_2}$  of liquid was measured as well as calculated from published activity-composition data of alloy. The measured and calculated  $\log f_{S_2}$  values of metal saturated liquid were found to be similar.

Our 900°C phase diagram is similar to the previously published phase diagram but iron-rich liquid has narrower stability field.

Measurements of d102 spacing of Mss were used to calculate the precise composition of Mss in equilibrium with sulfide liquid. Along the sulfur poor boundary of Mss, the sulfur content changes in a nonlinear manner; it is always higher than that of the hypothetical FeS-Ni<sub>0.972</sub>S pseudobinary. Cell edge and molar volume of Mss was calculated for compositions along the sulfur poor limit of Mss. The molar volume is close to that of an ideal solid solution.

Tie-line data and sulfur fugacity measurements at constant Ni/Fe ratio were used to calculate thermodynamic activities of Fe and Ni in sulfide liquid and Mss. Isoactivity contours of Fe, Ni and S are presented in the sulfide liquid and Mss fields. Thermodynamic properties of liquid and Mss are discussed. Changes in the excess partial molar properties of liquid with composition are probably due to formation of associated metal-sulfur species.

The experimental data was compared to published results of calculations based on thermodynamic models.

Equilibrium compositions of Mss coexisting with spinel were calculated. At 900°C, Mss with low Ni-content would coexist with nearly pure magnetite. This explains the common occurrence of magnetite in some magmatic Ni deposits and the absence of a Ni-rich spinel.

#### **THE CAMOEBIAN ASSEMBLAGES AS PROXIES OF SEASONALITY IN A NORTH INDIAN LAKE**

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Thecamoebians are testate Protists that occur in a variety of freshwater habitats and brackish environments. They have been successfully used as proxies for a variety of environmental and climatic parameters in limnological and paleolimnological studies. The perennial lake Sadatal is situated near a small town Mallanwan (Latitude 27°03'00" North and Longitude 80°09'00" East) in the Ganga-Yamuna Plains of North India. Sadatal is a shallow (maximum depth ~1.5 m during summer and ~3.0 m during July-August monsoon season) remnant of a past oxbow lake left by meandering river Ganga and its tributaries. The soil around this region is saline and sodium rich that can raise the soil alkalinity up to pH 10. This region shows strong seasonality and average atmospheric temperature (2005-2007) during winter (December-March) ranged between 7-20°C and during summer (April-June) ranged between 2-45°C. Sediment-water interface samples were collected by the Veen-Van grab sampler from periphery of this lake once each in May and December for three years (2005-2007). Average limnological data of Sadatal for December were pH (7.0), Dissolved Oxygen (11.8 mg/l), Salinity (0.4 ppt), Conductivity (0.8 mS/cm) and Total Dissolved Solids (TDS- 962 mg/l). These

measurements changed in May as pH (8.5), Salinity (1.9 ppt), Conductivity (2.98 mS/cm), TDS (1745mg/l) and DO (6.8 mg/l).

Taxonomically diverse thecamoebians were recovered showing distinct summer and winter assemblages for three years. Centropyxids and Arcellenids dominated the low humidity, low precipitation cooler months (October-March) whereas *Amphitrema* spp. and Diffflugids dominate summer and high precipitation, high humidity monsoon months (April-September). Dominance of *Amphitrema* spp. is related to abundance of aquatic weed *Lemna detritus* at the lake bottom during summer. Total counts of thecamoebians were higher during summer than winter.

## **RECOGNITION OF A NEW SYNVOLCANIC FAULT ARCHITECTURE IN THE MATAGAMI ZINC CAMP, ABITIBI (QUÉBEC)**

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The Matagami camp is the second largest Archean volcanic massive sulphide (VMS) hosted zinc-rich district in the world after Kidd Creek (Timmins, Ont.) with 5.3 Mt of Zn produced and in reserve. The Matagami district is a low density outcrop area covered with thick glacial deposits. Drilling information is plentiful only around known VMS deposits or prospects. Therefore, high resolution geophysics and the analysis of a large geochemistry database become efficient tools for the interpretation of the volcanic architecture. Spatial distribution of rhyolites, mafic intrusions, syn-mineralisation alteration, and magnetic and gravity anomalies were used to demonstrate that the eighteen VMS ore bodies were controlled by district scale synvolcanic faults. The VMS-rich stratigraphic pile consisting of the rhyolitic Watson Lake Formation is present in three distinct 20 km long by 1-2 km thick segments. The E-trending north flank and the SE-trending south flank are defined with respect to the Galinée Anticline cored by the mafic Bell River synvolcanic intrusion. The west flank corresponds to another SE-trending rhyolitic horizon located 15 km west of the south flank. The low to moderately-dipping strata (20-50°) within the low strain domain of the south Flank allows the characterization of the original VMS architecture. First and second order synvolcanic fractures can be identified by geochemical mass changes and a sharp break in the magnetism. All well-delineated alteration pipes are uniformly subvertical, independent of the strata dip. This observation suggests that the whole felsic volcanic pile along the south Flank was tilted prior to the VMS emplacement. The volcanic history of the more deformed north and west flanks may have evolved in a similar manner. The south and west flanks are interpreted as major bounded faults of a NW-SE oriented graben or caldera. These two faults control the emplacement of rhyolite flows, the multiple generations of dyke intrusions and the VMS. Unexposed mafic intrusions with a gravity response similar to the Bell River intrusion are inferred under some parts of this graben. Central to the graben, a new secondary structure is interpreted with the same NW-SE strike. This almost undrilled and unexposed area is characterized by magnetic highs and gravity lows interpreted as a possible main feeder structure. The proposed architecture compares well with numerical, analog, and gravity inversion models as well as with the morphobathymetry of recent submarine volcanoes.

## **URANIUM DEPOSITS AS PROXIES FOR GLOBAL TECTONIC EVENTS**

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Supercontinents have periodically existed throughout Earth's history. Zoned minerals such as zircon and monazite often have been used to determine the age of paleo-fluids associated with major tectonic and metamorphic events. Other minerals such as feldspars and micas when combined with an appropriate geochronometer (e.g. Ar-Ar or Rb-Sr) have provided valuable information regarding the timing of large-scale fluid events that can be important to the formation of mineral deposits. Instruments such as secondary ion mass spectrometers (SIMS) and LA-ICP-MS offer the capability of measuring isotope ratios on normal thin-sections with a spatial resolution of 1-100 µm. These instruments have been used to measure radiogenic isotopes in cores and rims of these minerals, thus providing an unprecedented understanding of fluid evolution related to orogenic and metamorphic events. However, uraninite is one mineral that has been largely overlooked as a mineral proxy for large-scale fluid and tectonic events. Recent techniques and standards have improved precision and accuracy to a level that approaches those of conventional techniques for U-Pb isotopic analyses of U-bearing minerals. SIMS work suggests that on the microscale, U-deposits can provide a detailed record of continental-scale tectonic events at a single location, with a potential time-depth extending to before 2 Ga. For example, in situ <sup>207</sup>Pb/<sup>206</sup>Pb ages from Athabasca unconformity-type U deposits, Canada, paleo-placer deposits, Canada and Oklo-Okélobondo natural fission reactors, Gabon, have preserved a nearly complete record of supercontinent accretion and dispersal, some of the few places in the world that record a nearly complete tectonic history of the continents over the past 2.4 Ga. Additionally, as most economic U deposits occur in sedimentary settings, they may offer one of the few approaches to developing a precise chronology of basinal-scale fluid-rock events. Although major U-deposits are relatively rare, U-deposits of some size are found in many major sedimentary basins around the world. Thus, if the chronologic detail suggested by this preliminary study proves to be common to U-deposits in general, they will provide an important new tool providing both a more detailed record of supercontinental accretion and breakup, and a new approach to precisely dating basinal fluid-flow events. This work will also significantly contribute to knowledge regarding processes that transport, concentrate, and modify radioactive minerals in near-surface environments as well as provide a tool for dating basinal fluid flow.

## **NATURAL ATTENUATION OF METALS IN A COLD-WATER ACID ROCK DRAINAGE STREAM AT THE "XY" Pb-Zn DEPOSIT, YUKON TERRITORY**

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An acid rock drainage (ARD) stream emanating from the Zn-Pb XY-deposit in the Yukon Territory was examined in order to evaluate the physico-chemical, geochemical and geomicrobiological processes governing the distribution of dissolved elements from the creek. The creek showed very high concentrations of metals (300 mg/L Fe, 500 mg/L Zn, 15 000 µg/L Ni, 1300 µg/L Cu and 4500 µg/L Cd), low water temperatures (1-12°C) and was acidic to moderately acidic (pH 3.1- 5.0). Iron-rich minerals, including schwertmannite, jarosite and goethite constituted the precipitates forming at low pH, while Al-rich minerals, including jurbanite and hydrobasaluminite comprised the minerals forming under moderately acidic conditions. Rare earth element Kd distribution patterns

suggest that microbes might have been involved in the precipitation of the Al-rich minerals, while the Fe-rich minerals appeared to have formed via inorganic processes. Microscopically, the Al-rich precipitates showed a similar appearance to mineralized cells and contained up to 5 atomic % Zn. Furthermore, some of the Al-rich precipitates showed anomalous Kd values for Zn, Cd, Ni and Cu when compared to other Al-rich precipitates forming in the creek, despite no major changes in metal speciation or mineralogy, which indicates that biosorption might be responsible for the accumulation of these elements.

#### MOBILIZATION AND PRECIPITATION OF HFSE IN THE T-ZONE, THOR LAKE RARE-ELEMENT DEPOSIT

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The Thor Lake rare-element (Y-REE-Nb-Ta-Zr-Be) deposit, one of the largest peralkaline pluton-related HFSE mineral deposits in the world, is located about 100 km southeast of Yellowknife, NWT, Canada, and comprises two main mineralized zones, namely the Nechalacho deposit and the T-Zone. The T-Zone is a zoned body comprising, from rim to core, a Wall Zone, Lower Intermediate Zone (LIZ), Upper Intermediate Zone (UIZ), and Quartz Core Zone, and exhibits both pegmatitic and hydrothermal characteristics. The principal HFSE minerals in the LIZ and UIZ include bastnäsite-group minerals (bastnäsite, synchysite, parisite), zircon, columbite, and xenotime. Most bastnäsite-group minerals and zircon occur as aggregates within pseudomorphs that display a prismatic to rhombic habit. Radiating bastnäsite aggregates in the pseudomorphs have grown from the wall inwards, which is taken as evidence of open space-filling. In some parts of the T-Zone, aegirine exhibits similar habits to the pseudomorphs and is partially to completely replaced by quartz + hematite, and is thus considered to be an important precursor mineral. Columbite and xenotime have also been observed in such replacement textures. These textures demonstrate a hydrothermal origin for most HFSE minerals. The initial replacement of aegirine by quartz + hematite  $[2\text{NaFe}^{3+}\text{Si}_2\text{O}_6 \text{ (aegirine)} + 2\text{H}^+ \longleftrightarrow 4\text{SiO}_2 \text{ (quartz)} + \text{Fe}_2\text{O}_3 \text{ (hematite)} + \text{H}_2\text{O} + 2\text{Na}^+]$ , likely resulted in a volume reduction, thus creating the space into which the HFSE minerals were precipitated. This may explain why most bastnäsite-group minerals and zircon are confined to the pseudomorphs. Primary and pseudosecondary fluid inclusions occur in bastnäsite and quartz. Those in quartz define growth zones and the edges of pseudomorphs, and in some cases contain trapped zircon crystals. They comprise aqueous liquid-vapour inclusions with minor amounts of  $\text{CO}_2$  and  $\text{CH}_4$ , and have salinities mostly between 20 and 25 eq. wt % NaCl. The relative consistency of the salinity is contrasted by considerable scatter in  $T_h$  (LV  $\rightarrow$  L), with most values between 100 and 250°C, but ranging up to 400°C. These data, in combination with field observations, indicate that the T-Zone initially crystallized as an alkaline granite pegmatite, but was extensively overprinted at low to moderate temperatures by hydrothermal fluids with moderately high salinities, and it was during this fluid rock interaction that most HFSE minerals were precipitated.

#### STRATIGRAPHY, PETROLOGY AND GEOCHEMISTRY OF SEDIMENT-HOSTED BARITE SEQUENCES IN THE MACKENZIE MOUNTAINS, NWT AND YUKON: UNDERSTANDING THE GEOCHEMICAL CONDITIONS OF BARITE MINERALIZATION IN THE SELWYN BASIN DURING THE MIDDLE TO LATE DEVONIAN

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The Devonian-Mississippian Earn Group in the Selwyn Basin contains a number of sediment-hosted barite sequences which outcrop in the Mackenzie Mountains, NWT and Yukon. These barite sequences were previously thought to be the distal expression of sedimentary-exhalative (SEDEX) Zn-Pb-Ba deposits as they are hosted by the Canol Formation, a sequence of mudstone, siltstone and shale found within the Lower Earn Group which is the same stratigraphy hosting known SEDEX deposits in the MacMillan Pass region of the Yukon.

Barite in all showings displays a remarkable variety of textures from laminations, to elongate to spherical, mm to cm scale nodules. A petrographic and geochemical study examining the stable isotopes and rare-earth element concentrations of the barite was initiated to understand the mineralogy of the sequences, and their relationship to hydrothermal fluids and/or seawater/porewater chemistry.

Both primary fine-grained barite laminations and secondary nodular barite are found to contain hyalophane and cymrite (Ba, K-feldspar and hydrous Ba-silicate respectively). These diagenetic minerals are likely related to burial and indicate a high degree of silica, potassium and aluminium mobility in shales during basin loading.

The  $\delta^{34}\text{S}$  values of laminated barite suggest that sulphur was seawater-derived.  $\delta^{18}\text{O}$  values in laminated barites range from +14 to +18‰ which is comparable with the composition of Devonian seawater sulphate.  $\delta^{34}\text{S}$  values for barite in nodules ranges from +31 to +56‰. Nodular barite, which is a product of sub-seafloor crystallization, has consistently elevated  $\delta^{34}\text{S}$  values relative to laminated barite. Bacteriogenic sulphate reduction (BSR) may cause such enriched values, and late pyrite intergrown with barite is considered to be an indicator of this process. This scenario would predicate a closed system with respect to sulphate in order to drive  $\delta^{34}\text{S}$  values to +50‰.  $\delta^{18}\text{O}$  values in barite nodules shows a wider range of values (+9.2 to +19.3‰) compared to laminated barite.

The rare earth element compositions of the sediments that host barite mineralization are relatively depleted compared to the Post-Archean Australian Shale (PAAS) standard, most notably in cerium; which may be indicative of a reducing environment. Positive europium anomalies occur as a result of barian feldspar formation. Canol Formation sediments stratigraphically below occurrences show similar REE composition to that of PAAS but also display a marked depletion in cerium.

These sediment-hosted barite sequences may represent a marker horizon throughout the Canol Formation and could be the product of a basin-wide barite mineralizing event.

#### CARBON ISOTOPE BIOSIGNATURES OF NEUTROPHILIC FE(II) OXIDIZING BACTERIA

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Bacteriogenic iron oxides in natural environments are characterized by an abundance of ferrihydrite precipitates intermixed with

bacterial structures that commonly resemble those produced by the lithoautotrophic microorganisms *Gallionella ferruginea* and *Leptothrix ochracea*. These species have been inferred to play a causal role in the formation of bacteriogenic iron oxides, providing a pathway for the reduction of CO<sub>2</sub> and the depletion of <sup>13</sup>C in the organic constituents of bacteriogenic iron oxides. In this study, stable carbon isotope fractionation was determined for bacteriogenic iron oxide samples collected from submarine hydrothermal vents (Axial Volcano, Juan de Fuca Ridge), subterranean (Äspö Hard Rock Laboratory, Sweden) and surficial (Chalk River, Canada) groundwater seeps, and cultures of *G. ferruginea*. Data were also collected from ferrihydrite samples lacking evidence of bacteria from Bounty Seamount in the vicinity of Pitcairn Island. The mean  $\delta^{13}\text{C}$  (‰) of ferrihydrite was determined to be  $-15.87\text{‰} \pm 4.96\text{‰}$  for the samples from Axial Volcano,  $-24.97\text{‰} \pm 0.43\text{‰}$  for Äspö,  $-27.80\text{‰} \pm 0.85\text{‰}$  for Chalk River,  $-29.3\text{‰} \pm 0.2\text{‰}$  for the microbial culture, and  $-8.43\text{‰} \pm 1.89\text{‰}$  for the samples from Pitcairn. Samples with the highest concentration of organic carbon also had the lightest  $\delta^{13}\text{C}$  in a logarithmic relationship. The consistency of carbon isotope values in relation to the presence of iron-oxidizing bacteria from natural and laboratory samples is interpreted as the ability of these microorganisms to fractionate carbon. The potential of this fractionation to serve as a biosignature holds promise when the resistance of carbon and bacteriogenic ferrihydrite to diagenesis is taken into consideration.

#### **METAMORPHIC PHASE EQUILIBRIA FOR VOLCANOGENIC ALTERATION SYSTEMS, AMULET F DEPOSIT, NORANDA DISTRICT, ABITIBI SUBPROVINCE**

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A detailed understanding of the dependence of metamorphic assemblage stability on effective bulk rock composition is required to utilize mineral assemblages as vectors towards massive sulphide deposits during exploration in highly metamorphosed terrains. This is accomplished by relating complex mineralogical patterns to chemical changes associated with hydrothermal alteration. Thermodynamic modeling provides insights into phase transitions due to changes in metamorphic conditions or bulk rock composition, assisting in the development mineralogical vectors.

Coupling the major element geochemistry with a characterization of the textures and mineralogy has facilitated the development of metamorphosed alteration facies for hornblende hornfels conditions. A metamorphic assemblage map of the Amulet F deposit reveals a concentrically zoned pattern characterized by four bulk composition controlled isograds that correlates with intensity of pre-metamorphic hydrothermal alteration. The isograds, in order of increasing alteration intensity, include: cordierite-in, orthoamphibole-in, cummingtonite-in, and biotite-out. Progressive hydrothermal replacement of dacite within the core of the alteration system has produced bulk rock compositions suitable for a cordierite-orthoamphibole-cummingtonite-biotite-quartz-gahnite-magnetite-sulfide assemblage to be generated during metamorphism. Associated with this assemblage is a magnesium and iron increase of 12.7 wt%, and a calcium, sodium and potassium decrease of 1 wt%, 2.6 wt% and 2.4 wt%, respectively. The mapped isograds correspond to the progressive removal of alkaline elements and enrichment in iron and magnesium during pre-metamorphic hydrothermal alteration, which is currently expressed by a gradational transition between metamorphic assemblages within individual lithofacies.

Meta-dacite samples from the Amulet F deposit provide an ideal suite for evaluating phase equilibria predictions because they

exhibit continuous compositional changes across various metamorphosed alteration facies. Preliminary pressure – temperature pseudosections for individual facies compare reasonably well with detailed petrographic observations, suggesting modern thermodynamics adequately predicted the assemblages for these compositions. Layering is inherently problematic for thermodynamic modeling; a quantitative x-ray map composition for the orthoamphibole sub-domains is used to estimate the effects, and provides insight to the growth history of the metamorphic porphyroblasts, further refining the methods used to model these compositions.

A temperature-composition (T-X) pseudosection for a model Millenbach alteration system predicted similar mineralogical zoning to the documented alteration facies. T-X pseudosections are effective for evaluating mineralogical assemblage changes as a function of temperature and progressive pre-metamorphic hydrothermal alteration. For the Amulet F deposit, a T-X pseudosection links individual alteration facies within the meta-dacite, creating a predictive map that relates the change in metamorphic assemblages to hydrothermal alteration intensity.

#### **APPLICATION OF ISOTOPE RATIO TRACING TO SOURCE RESIDENTIAL LEAD EXPOSURE IN CHILDREN IN ST. JOHN'S, NEWFOUNDLAND, CANADA**

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Lead isotopes were used to discriminate sources of residential lead exposure in children living in a range of housing stock in St. John's, Newfoundland. The project utilized blood and environmental samples collected as part of a larger project that is investigating children's exposure levels to lead-contaminated soil, tap water and house dust in St. John's. Environmental samples above a concentration of concern were analyzed for lead isotopes using a multi-collector inductively coupled mass spectrometer. The isotope study has a 3-level, nested research approach concentrating on the residential environment of participants who have the highest blood lead levels. In the first instance, we investigated the similarity in ratios from four lead isotopes (<sup>204</sup>Pb, <sup>206</sup>Pb, <sup>207</sup>Pb, <sup>208</sup>Pb) between a range of environmental media (soil, dust, water) in targeted locations (e.g. bedroom, play room, kitchen, garden, play area) in the participant's residential environment and those from the participant's blood. Next, the lead isotopic ratios of those environmental samples that were identified as contributing to participants blood lead were compared to determine whether there are characteristic ratios associated with specific environmental media (e.g. soil vs. dust vs. water) or sample locations (e.g. interior vs. exterior; entrance ways vs. window sills/troughs). Finally, those characteristic lead isotope ratios associated with exposure media and locations were compared with the ranges of isotopic ratios for the three main anthropogenic lead sources in St. John's (paint, coal, gasoline). This integrative approach is designed to better understand children's exposure to lead in their environment and to inform decision-making around mitigation and adaptation to lead contaminated housing in St. John's.

#### **DEFINING CANADA'S EXTENDED CONTINENTAL SHELF IN THE ATLANTIC REGION**

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The Canadian Hydrographic Service (CHS) and the Geological Survey of Canada (GSC) have a long history of coordinating and carrying out multi-disciplinary surveys on Canada's Atlantic coast.

With the advent of Canada signing the United Nations Convention on the Law of the Sea (UNCLOS) in 2003, Canada embarked on a program to define the outer limits of its continental shelf in the Arctic and Atlantic Oceans, applying the criteria as outlined in Article 76. The GSC and CHS have taken on the responsibility for the collection, interpretation and management of the information necessary to support Canada's submission. GSC (Atlantic) has extensive collections of geophysical information including seismic, gravity and magnetic data. CHS has substantial bathymetry data sets that map the continental shelf and the Labrador Sea from the United States Canada border south west of Nova Scotia to the tip of Cape Chidley, Newfoundland and Labrador.

After analysing the existing data, the GSC and CHS designed a program to acquire the additional data needed to define the outer limits. Three large bathymetric and geophysical surveys were conducted in the Atlantic to augment the existing data sets. This additional compilation of information has confirmed and indicated the approach for determining Canada's extended continental shelf (ECS) in the Atlantic.

The specific areas in the Atlantic encompass the region from the southern tip of the Scotian margin, through the Grand Banks and along the Labrador margin. In these three distinct regions the foot of the slope (FOS), the 2500 metre contour, morphology and geologic continuity as described under Article 76 will determine the extent of Canada's ECS in the Atlantic Region. The presentation will describe the preliminary data analysis of Canada's Atlantic program.

#### **MINERALOGICAL, STABLE ISOTOPE, AND FLUID INCLUSION STUDIES OF SPATIALLY RELATED PORPHYRY Cu(-Mo) AND EPITHERMAL Au-Te MINERALIZATION, FAKOS PENINSULA, LIMNOS ISLAND, GREECE**

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Spatially related porphyry Cu(-Mo) and epithermal-style Au-Te mineralization, Limnos Island, Greece, is hosted in a Miocene-age quartz monzonite and shoshonitic subvolcanic rocks that intruded Paleogene sedimentary basement rocks. Metallic mineralization formed in three stages in quartz ( $\pm$ calcite) veins. Early porphyry-style (stage 1) metallic minerals consist of pyrite, chalcopyrite, galena, bornite, sphalerite, molybdenite and iron oxides, which are surrounded by halos of potassic and propylitic alteration. Stage 2 is composed mostly of quartz-tourmaline veins associated with sericitic alteration, whereas stage 3, epithermal-style mineralization is characterized by polymetallic veins containing pyrite, chalcopyrite, sphalerite, galena, enargite, bournonite, native gold and various sulfosalts and precious metal tellurides. Stage 3 veins are spatially associated with argillic, silicic, and alunitic alteration.

Fluid inclusions in quartz from stage 1 (porphyry-style) mineralization are of five types. Type I, liquid-vapor inclusions, with homogenization temperatures (Th) of 189.5 to 403.3°C have salinities of 14.8 to 19.9 wt. % NaCl equiv. Type II, liquid-vapor-NaCl, type III liquid-vapor-NaCl-CaCl<sub>2</sub>, and type IV, liquid-vapor-hematite $\pm$ NaCl have values of Th of 209.3° to >410.0°C, 267.6° to >410.0°C, and 357.9° to >410.0°C, respectively. The porphyry-style inclusions are associated with type V, vapor-rich inclusions. Stage 3 quartz contains two types of fluid inclusions, type I, liquid-vapor inclusions that homogenize from 191.6° to 310.0° C with salinities of 1.40 to 9.73 wt.% NaCl equiv., and type II, vapor-rich inclusions. Mixing of magmatic fluids with meteoric water in

the epithermal environment was responsible for the dilution of the ore fluids in stage 3 veins. Eutectic melting temperatures of -35.4° to -24.3°C for type I inclusions in both porphyry and epithermal veins suggest the presence of CaCl<sub>2</sub>, MgCl<sub>2</sub>, and/or FeCl<sub>2</sub> in addition to NaCl in the mineralizing fluids.

Sulfur isotope data for sulfides show a range in  $\delta^{34}\text{S}$  of -6.82 to -0.82 per mil and overlap for porphyry and epithermal sulfides, which suggest a common sulfur source for the two styles of mineralization. The source of sulfur in the system was likely the Fakos quartz monzonite for which the isotopically light sulfur isotope values arose from changes in oxidation state during sulfide deposition (i.e. boiling) and/or from disproportionation of sulfur-rich magmatic volatiles upon cooling.

Metallic mineralization at Fakos Peninsula represents an early porphyry system that is transitional to a later intermediate- to high-sulfidation epithermal gold system. This system is similar to porphyry-epithermal mineralization found elsewhere in northeastern Greece (e.g. Pagoni Rachi, St. Demetrios, St. Barbara, Perama Hill, Mavrokoryfi, and Pefka).

#### **PILLARS IN THE PARK**

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Charleston Lake, some 25 km west of Brockville, Ontario is located on the east flank of the Frontenac Axis. Ripple marks, trace fossils, grain frosting, ventifacts and eolian cross-beds indicate the Axis knobs were elements along a wind swept equatorial estuarine margin during the Cambrian. An isolated plateau of Potsdam (Group) sandstone of Charleston Lake Provincial Park includes (marine?) cross bed sequences up to several meters thick, suggesting cyclical inundation, perhaps from tidal action along a margin. One of the last pre-diagenetic structures arrived in the form of sandstone cylinders or pillars.

Sandstone cylinders were reported from quarries north of Kingston as early as 1889. At least 8 cylinder sites are hosted by the sandstone plateau in the Provincial Park. These "water escape" features in the form of cylinders or pillars may be the lithified remains of water table spring conduits that developed in response to water flow through very clean and well sorted sand overlying undulating Precambrian surface topography. Various cylinder forms resemble active, lithified and unconsolidated structures reported from the USA and the Himalayas as well as some reported from more recent glacial sand deposits in Quebec.

#### **EVIDENCE AND HYPOTHESIS – HOW THE SANDSTONE CYLINDERS FORMED**

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On the Cambrian tropical Iapetan margin of southeastern Ontario and northern New York, cylindrical structures are distributed in an area of over 1500 square kilometres along the flanks of the Frontenac Axis-Adirondack basement upland. The structures are considered to represent the result of vertically upward water flow originating very near or at the Grenville basement to produce spring-like conduits of fluidized sand. The Axis-Adirondack upland forms the margin of a sand basin extending 200 km to the east and about 100 km north-south.

Inundation of the eolian terrain of frosted grains, ventifact conglomerate clasts and dunes supported a host of burrowing organisms and arthropods that left surface track widths approaching 15 cm. Cross bedded and ripple marked strata of metre-scale thickness may have resulted from tidal activity in the shallows and along beaches surrounding the basement knobs. Later the combination of fluctuating water table, basement relief on the order of 100 metres and well sorted mainly medium to coarse grained

quartz grains, enabled the formation of conduit structures of fluidized sand. The apparent lack of an aquifer cap suggests conduit formation resulted from an unconfined, water table aquifer as opposed to being artesian. Was this water marine or fresh?

The Grenville basement interface was the major water flow discontinuity. Immediately above the basement, a multitude of small, approximately decimetre-scale, water escape structures developed. Where flow conditions and sand thickness permitted, fluidized conduits 10s of metres in height and several meters in diameter developed. Changing water table conditions produced a variable internal conduit structure featuring truncated earlier structures and internal concentric annular rings. As the sand drained, the last part of the structure to freeze occupied the central part of the conduit. The later lithification of the central conduit compared to the periphery enabled the center structure to sag (convex down) producing characteristic dish-shaped structure in the cylinder centres. Late stage fluidization along or near the outer edges of conduits generated smaller, satellite conduits that truncate the earlier, larger cylinders.

Results from earlier grain size and fluidization velocity studies indicate a limited range of velocities from about 0.3 to 2.5 cm/s may have been sufficient to produce the cylinders. Post-lithification, stresses within cylinder structures produced brittle fractures directly through the cylinder center.

#### **ECLOGITISATION OF CRUST DURING THE CALEDONIAN OROGENY IN THE LOFOTEN ISLANDS, NORWAY: IMPLICATIONS OF THE DYNAMICS OF OROGENESIS**

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Eclogite-facies shear-zone rocks in the Lofoten Islands, Norway, are associated with continental collision during the Caledonian Orogeny (ca. 480-430 Ma). During this orogeny, Precambrian (ca. 2.6-1-7 Ga) granulite-facies rocks were subducted to great depths and subjected to eclogite-facies metamorphism ( $T=610^{\circ}\text{C}$  and  $P=14.5\text{ kbar}$ ). The country rocks are only partially transformed to eclogite, however, indicating that buoyancy may have been a major controlling factor in their exhumation.

It is commonly assumed that the metamorphic temperatures extracted from the eclogite assemblages represent the ambient temperature of the entire terrane. An alternative interpretation is that the bulk of the rocks involved in the subduction remained considerably cooler than the temperatures represented by these assemblages. Since the pristine granulite-facies country rocks were partially affected, the effects involved during the initial stages of eclogitisation are particularly well-preserved. The  $^{40}\text{Ar}/^{39}\text{Ar}$  method is being used to analyse minerals from the country rocks and from the eclogite shear-zone rocks to reconstruct the thermal history of the region and to examine the duration of an orogenic cycle (burial and exhumation).  $^{40}\text{Ar}/^{39}\text{Ar}$  step-heating results from biotite and amphibole clearly indicate that excess  $^{40}\text{Ar}$  has diffused into the minerals. The derived age spectra are characterized by apparent ages which are anomalously high within the first 10-15% of  $^{39}\text{Ar}$  released and then monotonically decrease in apparent age to a plateau age older than the Caledonian Orogeny. The existence of diffusion profiles in these minerals thus provides an excellent foundation for undertaking diffusion modelling to reconstruct detailed temperature-time histories. Future  $^{40}\text{Ar}/^{39}\text{Ar}$  laser spot-dating coupled with geothermometry and numerical modelling of Ar diffusion profiles will be used to infer the duration of the Caledonian thermal event in the Lofoten basement rocks and thus constrain the duration of the Caledonian orogenic cycle.

#### **COLUMBIA HILLS – AN EXHUMED LAYERED IGNEOUS INTRUSION ON MARS?**

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The rover Spirit has now performed some 107 chemical analyses on rock outcrops and boulders along its traverse across the Columbia Hills of Gusev Crater. The apparently “basaltic” compositions of most of these rocks, and the local presence of well developed layering, have lead to the perception that the Columbia Hills represent a mafic volcanic pyroclastic sequence. Such a model has problems, however, explaining the compositional variation observed within the Columbia Hills analyses. Strikingly, despite the small area surveyed by Spirit, the range in analyzed Fe contents rivals that observed in the basalts of the entire Solar System. The positive trend in Fe-Mg space exhibited by the rocks of the Columbia Hills contrast markedly with trends controlled by fractionation along a “gabbroic” cotectic and no plausible crystal fractionation scheme can explain the co-variation of Fe and Mg, if the analyzed rocks are assumed to represent volcanic compositions defining a liquid line of descent.

Positive arrays in Fe-Mg space are, however, common features in whole-rock data collected across cyclically-layered igneous intrusions. The repeated alteration of feldspar-rich versus mafic-rich cumulates in such intrusions results in whole-rock compositions that scatter along mixing lines between feldspar near the origin and the mafic cumulate phases, reflecting the magmatic sorting of cumulus crystals as opposed to crystal-liquid equilibria. There is in fact a striking correspondence between the Fe-Mg trends observed in the Columbia Hills data and the cumulate stratigraphy of a number of terrestrial layered intrusions. In the model proposed here, the stratification seen at number of localities along Spirit's traverse represents magmatic sedimentation in a layered igneous intrusion. According to this interpretation, the higher magnesium rocks are olivine-orthopyroxene and olivine gabbro-norite cumulates without cumulus magnetite. The majority of the rocks of the Columbia Hills, however, appear to be olivine gabbro-norites with cumulus magnetite, which are characterized by variable proportions of feldspar versus mafic silicates plus magnetite. Furthermore, the alkalis-rich rocks, which have previously been interpreted to be alkaline basalts, are better explained as gabbro-norites with cumulus apatite. The sequence of crystallization of the magma responsible for the Columbia Hills is therefore interpreted to be: olivine, followed by orthopyroxene, then plagioclase, magnetite, and finally apatite. If this interpretation is correct, then the Columbia Hills likely represent a Noachian layered intrusion that was exhumed by rebound following the meteorite impact that formed Gusev crater.

#### **PRECAMBRIAN METALLOGENY: CHALLENGES TO IMPROVE FUTURE EXPLORATION SUCCESS**

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Predictive genetic models must include better knowledge of the key mappable elements of lithotectonic development that underpin super-giant ore deposit formation. The certainty of the relationships between key regional geological elements and ore presence requires strengthening. Shield mines underpin our economy, primarily super-giant magmatic nickel-copper-PGE, orogenic gold, and volcanogenic massive sulfide districts.

The prolific Paleoproterozoic magmatic Ni-Cu-PGE mines (except Sudbury) are in ultramafic-dominant early-stage rifted continental margins or intracratonic rifts (Thompson, Raglan). Host ultramafic intrusions were emplaced into S-containing sedimentary melt-contaminant sources. Other Proterozoic extensional

zones lack ultramafics or crustal sulfur sources. Archean domains contain smaller komatiite-associated deposits (Timmins, Shebandowan). Some (Bird River) in larger mafic/ultramafic intrusions contain small Ni-Cu-Cr resources-poor cousins to the new Ring of Fire (ROF) synvolcanic ultramafic intrusions with giant chromite, Ni-Cu-PGE and small VMS deposits. Is ROF, formed in a bimodal backarc, unique?

Large VMS districts, formed in submarine extensional backarcs require major subvolcanic heat engines, the most important indicator of VMS potential, to drive convective leaching. Ultramafic (Kidd Creek) and mafic intrusions, manifestations of a super heat-flow regime, engendered the formation of felsic volcanics and upper crustal seawater convection. Major districts (Matagami Lake) are underpinned by large mafic synvolcanic intrusions; others (Noranda, Sturgeon Lake) formed during emplacement of the early mafic phase of a bimodal intrusive suite. Flin Flon, Snow Lake, and Bousquet are underpinned by felsic systems which contributed gold (?) and heat. The Trans Hudson is four-times as prolific (tonnes/km<sup>2</sup>) as the Abitibi, and forty times as the Wabigoon. Why are some belts so metal-endowed? Paleo-environment is key. What lithospheric conditions enabled less metal-endowed shallow-water arcs to be more buoyant and/or predominantly subaerial? Sectoral variations in lead isotope compositions indicate significant differences in lithospheric mantle composition (least radiogenic compositions equal deepest water camps).

Archean domains contain prolific, primarily “orogenic” gold districts. Gold-bearing fluid was generated at the amphibolite-granulite transition and transmitted along giant high-angle reverse transpressive faults (Abitibi, Slave). Seismic rupture induced gold precipitation at the brittle-ductile transition. A smaller deposit subset has a distinct magmatic  $\text{Te} \pm \text{Mo} \pm \text{sulphate}$  signal (Kirkland Lake, Hemlo). Orogenic deposits are spatially associated with conglomeratic extensional basins and small syn-tectonic QFP intrusions. What engendered melt development? Are the clastic basins related to fault-related extension? Why are Paleoproterozoic regimes gold-poor?

Sub-crustal lithospheric differences are key; we must integrate seismic and MT data with sectorally-variant geochemical signatures to develop better predictive models for all deposit types.

#### **SILVER VEINS TO SEAFLOOR: STEVE SCOTT'S LEGACY OF RESEARCH LEADING TO DISCOVERY**

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Efficient discovery of ore deposits is underpinned by establishing key measurable attributes, based on field and laboratory research, that underpin genetic models. The hallmark of the late sixties was the experimental synthesis of sulfide minerals. After Steve characterized the fluids that formed the enigmatic Cobalt-type silver veins, he joined the experimental “club” by addressing the factors affecting the Fe content of sphalerite. Steve and his graduate students challenged the sphalerite “geothermometer”, and definitively showed that the sulphur activity of the ore-forming fluid is the key control; it's a geobarometer! This inevitably led him to study volcanogenic massive sulfide deposits. Initially he determined the metamorphic conditions of the Broken Hill, the Caledonide and Appalachian deposits, but wisely he moved to the sub-greenschist Kuroko deposits, providing insights into their alteration and structural controls. He recognized the regular spacing of the extensional faults that control discharge, now applied in exploration to predict with remarkable precision the location of additional resources. Stepping out of the ore at Kuroko, Noranda and Bathurst he initiated studies of “what got away” in exhalite. Steve and his team recognized that these broadly distributed strata con-

tain many elements and minerals that are key ore-vectors, highly useful for exploration. In an epiphany from which we all benefited, Steve was the first mineral deposits researcher to study modern seafloor hydrothermal vents, attacking many of the enigmas of VMS systems! He applied fundamental geochemical principles to deposits in the Guaymas, Juan de Fuca, Lau, Woodlark and Manus extensional rifts, documenting multiple controls on gold enrichment; boiling generating high  $a_s$ , and magmatic fluid input both may contribute. By examining the volcanology, sphalerite compositions and alteration attributes, areas that may have the best gold potential can be predicted. His Scotiabank Marine Geology Research Laboratory churned out dozens of papers, from the study of the tiny melt inclusions to sedimentary geochemistry of broad basins. He remained very much the ore mineralogist, studying arsenopyrite, gahnite, Zn-Ga-Fe sulfides, bacteriogenic systems, chlorite-sulfide-oxide equilibria and more. And he followed a parallel track of intensive investigations of preserved VMS deposits, worldwide. With each study, our exploration guidelines became better refined, our exploration risk reduced. Steve not only made innovative contributions to our understanding of ore deposits, but it also inspired hundreds more to take up the research challenges of sustaining our future metal supplies.

#### **MODES OF RARE ELEMENT TRANSPORT IN ILÍMAUSSAQ ALKALINE COMPLEX**

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The mechanisms controlling the formation, and potentially, removal of rare elements in Ilímaussaq Alkaline Complex, South Greenland, are not well understood. The current study uses fresh drill cores of the lujavrite (arfvedsonite-nepheline syenite) ore and hand specimens collected on the surface. Preliminary results indicate that the REE containing Zr silicate eudialyte is only found in direct contact with villiaumite (NaF). In other parts of the complex the REE bearing minerals tundrite and rinkite are almost entirely found in direct contact with minute amounts of fluorite. It is therefore likely that fluorine rich fluids forming villiaumite are a primary carrier of rare elements. However, as villiaumite is water-soluble it also means that when villiaumite is dissolved and removed, it may also remobilize some rare elements.

Previous studies have shown that hydrocarbons are common in fluid inclusions in Ilímaussaq as in many other alkaline complexes. Ilímaussaq has been dated to approximately 1.16 Ga, so the origin of hydrocarbons is abiogenic. The reducing ability of hydrocarbons is broadly accepted to be able to transport immobile elements. In some pegmatites at the Kola Peninsula larger hydrocarbons have been found in form of bitumen. The bitumen contained small inclusions of especially REE minerals like belovite.

We will present data for complex hydrocarbons found in one zone of the lujavrite hosted rare element ore of the Kvanefjeld are of Ilímaussaq. The hydrocarbons form black spheres up to 1.5 mm in diameter completely enclosed in veinlets of pyrochlore. This type of pyrochlore is common in the Kvanefjeld ore body and other parts of Ilímaussaq, but to our knowledge large complex hydrocarbons have not previously been described. Interestingly, the area containing the hydrocarbons also hosts a Th-mineral of the steacyite group, although Th-minerals are scarce in Ilímaussaq. It is likely that larger hydrocarbons have played a role in transporting specific rare elements at Kvanefjeld and elsewhere in the Ilímaussaq complex.



## **PLIO-PLEISTOCENE DRAINAGE OF NORTHERN YUKON AND THE MACKENZIE DELTA: DETRITAL ZIRCONS, GLACIAL DIVERSIONS AND PERIGLACIAL MODIFICATION OF A FLUVIAL LANDSCAPE**

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Paleodrainage of northern Yukon is generally thought to have been ancestral to the Mackenzie River, flowing across (or through) the present day Richardson Mountains; only diverted into the Yukon River by the latest Pleistocene Laurentide Ice Sheet. Here, we investigate northern Yukon drainage using geomorphology, stratigraphy and sedimentology, along with ( $^{206}\text{Pb}/^{238}\text{U}$ ) detrital zircon chronologies, to reconstruct paleodrainage across the region. Easterly paleoflow directions are associated with Pliocene gravels in the Old Crow basin and dominated by late Devonian age zircons (ca. 350–400 Ma) reflecting ages associated with the Old Crow intrusions. Antecedent drainage across the Richardson Mountains is suggested by the Bell and Rat River valley system which includes large terraces more than 100 m above the modern valley floor. In general these terraces, likely dating to the Pliocene, have been stripped of their fluvial cover by cryopedimentation processes, but large fluvial gravels are present along the terrace margins. Samples of fluvial sand from one large terrace and the modern Bell River are similar to a sample from a terrace along the Rat River, all dominated by North American continental zircon ages with a secondary population between 300 and 600 Ma. The late Devonian ages from the Old Crow batholiths are muted and appear to be overwhelmed by local sediment contributions from North American margin rocks making up the Richardson Mountains. Samples from the modern Mackenzie River and the Late Pleistocene Kidluit Formation (ca. 50,000 years BP) are remarkably similar, featuring broad North American continental ages, with a prominent peak in the mid to late Mesozoic. These ages suggest that the Mackenzie River system was in its present position by at least this time.

## **FEMTOSECOND LASERS, MIXED GAS PLASMAS AND MC-ICP-MS: THE IDEAL COMBINATION FOR HIGH PRECISION, IN SITU, ISOTOPIC ANALYSIS**

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The coupling of laser ablation (LA) sampling systems to multi collector (MC) inductively coupled plasma mass spectrometers (ICP-MS) has created the capability of producing rapid, spatially-resolved, high-precision isotope ratio measurements for various isotopic systems. Critical needs for making such measurements are large ion beams and robust and controlled mass bias and interference corrections.

The simultaneous detection of ions by Faraday detectors minimizes the effects of ion beam instabilities and allows accurate and high precision isotopic analyses. The large ion beams required, however, necessitate high sensitivity, especially for high spatial resolution analysis of samples with limited volume or low target element concentrations. Femtosecond (fs) lasers have several characteristics which make them ideal sampling devices for these applications. Their high pulse energies and ultrashort pulse widths generate minimal thermal effects during interaction with the sample and create nanometer scale ablation particles, which facilitate maintaining original sample integrity through to the MC-ICP-MS detectors. The wide range of repetition rates (to several KHz) of laser pulses allows much larger ablation mass delivery to the ICP and, hence, generates much larger ion beams than other laser (ns) systems, which are typically restricted to repetition rates of 10–20

Hz. Another means of increasing sensitivity in ICP-MS is the addition of other gases into the plasma. Both hydrogen and nitrogen have been used and for many elements result in signal enhancements of 2–4 times as well as more robust plasmas and mass bias corrections (for nitrogen). Enhancements to MC-ICP-MS sensitivity through ICP-MS interface design enhancements are also being made.

Systematic studies of Sr isotope analysis for Ca-rich minerals demonstrates that comparable precision and accuracy can be obtained for in situ fs-LA-MC-ICP-MS analyses as for solution MC-ICP-MS or TIMS, when the same total number of ions are collected in an analysis. Indeed the precision for fs-LA Sr isotope analyses is largely controlled by Poisson counting statistics, unlike for ns-LA analyses. In addition, previously reported Ca argide and Ca dimer polyatomic ion interferences are not observed. In situ fs-LA Pb isotope analyses, with a mixed argon-nitrogen plasma and thallium used as a mass bias surrogate for Pb, demonstrate robust mass bias correction, increased sensitivity as well as accurate and precise Pb isotope ratios.

## **CANADIAN RESIDENTIAL EXPOSURE TO RADON, LEAD, AND AMPHIBOLE ASBESTOS**

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There are several potential pollutants inside Canadian houses with a geologic source. These would include the soil gas radon; lead from both local soil and consumer products; and amphibole asbestos, usually related to the use of vermiculite from the Libby, Montana mine. This presentation will briefly cover the health risks associated with these pollutants, discuss how they are introduced to the home, and relate how to minimize exposure. While the concentration will be on how to reduce residential exposure and risk, there will be some discussion of the geographical distribution of radon, lead, and asbestos in Canadian housing.

## **USE OF VOLATILE COMPOSITION OF FLUID INCLUSIONS IN QUARTZ FOR GOLD EXPLORATION IN METAMORPHIC TERRAINS: A PRELIMINARY ASSESSMENT**

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Volatile composition of fluid inclusions was analyzed from gold deposits hosted in the Archean Abitibi and Paleoproterozoic Birimian belts. The aim was to decipher links between gold content, geological setting and fluid compositions. Pure quartz was analyzed by mass spectrometry following the method of Gaboury et al. 2008 (Econ Geol). Volatiles ( $\text{H}_2\text{O}$ ,  $\text{CO}_2$ ,  $\text{N}_2$ ,  $\text{C}_2\text{H}_6$ , He, Ar,  $\text{CH}_4$ ,  $\text{SO}_2$ ,  $\text{H}_2\text{S}$ ,  $\text{H}_2$ ) are monitored during progressive sample heating under vacuum. This approach provides the relative abundance of volatiles from families of fluid inclusions decrepitating at specific temperatures (Td).

Quartz-vein samples were selected to provide a wide spectrum of mineralization in various settings. Samples from Casa Berardi mines (n=15) and Joanna deposits (n=13) cover various mineralization styles distributed over 5 km in sedimentary-dominated rocks. Some are hosted by Casa Berardi or Cadillac-Ladder-lake major faults. Samples from Beaufor mine (n=10) are from granodiorite-hosted quartz-tourmaline veins, away from major faults. Samples from Mana (Burkina Faso: n=4) and Libéri (Niger: n=4) are hosted in typical strongly foliated volcano-sedimentary rocks.

Fluids in gold deposits are aqueous-dominated with  $\text{CO}_2$  and  $\text{H}_2\text{S}$  in accordance with their fundamental role as gold-ligand ( $\text{H}_2\text{S}$ ) and for pH-buffering ( $\text{CO}_2$ ) of the gold-bisulfide solubility.

However, there is no correlation between CO<sub>2</sub> and H<sub>2</sub>S contents of trapped fluids and gold content of the sample. This implies that trapped fluids represent a marginal portion of the fluid history recorded by the veins. However, in barren quartz veins away from known mineralization CO<sub>2</sub> or H<sub>2</sub>S are absent. Wide H<sub>2</sub>O Td spectrum from 200–450°C and CO<sub>2</sub>–H<sub>2</sub>O Td offset are common, indicating phase separation as confirmed by petrographic observations. The content of other volatiles seems to be more dependant of the geological setting.

For gold exploration, quartz having CO<sub>2</sub>- and H<sub>2</sub>S-bearing fluid inclusions and Td range of 200–450°C has vectoring potential for gold exploration. Helium content may suggest proximity of a crustal-rooted fault, a critical parameter for gold mineralization. Methane and especially C<sub>2</sub>H<sub>6</sub> appear to be indicative of fluid buffering with organic-rich material as graphitic-shale. These rocks may provide an important primary gold reservoir from sedimentary metal-rich pyrite. Nitrogen-bearing fluid may be related to a magmatic component as proposed but our data are inconclusive.

## COMPOSITION AND STRUCTURE STABILITY IN THE MILARITE-GROUP MINERALS

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The milarite structure-type is stable for a wide variety of chemical compositions, and its constituent minerals show extensive solid solution. Examination of over 350 chemical analyses and structure refinements has defined the compositional limits of substitution at the A,B,C and D sites, and the solid-solution paths are rationalised on a chemical basis. The root end-member compositions are derived and a classification for the group is suggested. A methodology is developed which is applicable to any mineral group that shows solid solution. Combinatorial analysis of the range of charges that can be assigned to the sites of the structure, subject to the electroneutrality principle, gives a total of 75 possible combinations that result in end-member charge arrangements. There are currently 21 minerals in the milarite group, forming 12 root charge-arrangements, plus fourteen synthesized compositions that lead to one additional root charge-arrangement. The stability of proposed root charge-arrangements may be examined by bond-valence theory, by complying with its two key rules: (1) the Valence-Sum Rule which states that the sum of the bond valences around an ion is equal to its formal valence, and (2) the Valence-Matching Principle which states that a chemical bond may form when the Lewis-acid strength of the cation matches the Lewis-base strength of the anion. By adding Loop Equations to the valence-sum equations, a bond network can be solved in a mathematical system of equations for bond-valence values that exactly satisfy these equations. The question becomes whether there is a specific combination of cations and anions that can satisfy these bond-valence values in order to adopt this structural arrangement. Exhaustive assignment of chemistry to sites results in the definition of end-members of the group under study, where the path from one to another represents a solid solution system whose stability can be studied with the same approach.

## MULTIPLE ORIGINS FOR GAHNITE AT THE LALOR Zn-Cu-Au DEPOSIT, SNOW LAKE (MANITOBA), AND IMPLICATIONS FOR MINERAL STABILITIES DURING METAMORPHISM

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Peak metamorphic conditions reached lower amphibolite facies at Lalor, a zinc-copper-gold-rich volcanogenic massive sulphide

(VMS) deposit hosted in bimodal volcanic and volcanoclastic rocks of Paleoproterozoic age. The base metal mineralization occurs as massive to disseminated sulphides horizons with the main zinc-bearing ore being sphalerite. The mineralization is immediately underlain by a thick zoned alteration envelope of variable composition. Petrographic and electron-microprobe (EMP) investigation of selected drill core samples has shown that gahnite occurrence is restricted to the deposit footwall. Gahnite was identified in samples of various bulk-rock compositions, all of which have been moderately to highly altered by syn-volcanic hydrothermal processes. Variations in companion mineral assemblages for gahnite at Lalor suggest that bulk rock composition was not the main factor controlling its formation. Several textural and mineralogical settings for gahnite have been recognized. In most cases, textural relationships suggest that sphalerite was the precursor to gahnite. However, gahnite is locally observed in association with Zn-rich staurolite where textural evidence shows complex intergrowth between the two minerals. Although it commonly occurs in association with sphalerite, gahnite is typically found peripheral to the main sulphide lens; it generally is associated with thinner sulphide bands/veins (<15 cm in thickness) or zones of disseminated sulphide mineralization. Where associated with thicker sphalerite horizons, it generally displays textures suggesting late formation. One of the salient features of gahnite occurrence at Lalor is its prevalence in anthophyllite-rich layers. Petrographic observations combined with EMP analyses indicate that gahnite formed along with anthophyllite as the result of a reaction between tschermakitic amphibole, sphalerite and quartz. This contrasts with its mode of formation in most documented examples of VMS-associated gahnite, where it has been interpreted to have been the product of reaction between sphalerite and either garnet or an aluminosilicate (kyanite or sillimanite) phase. At Lalor, textural evidence suggests that some of the gahnite may also have formed by deposition from a metamorphic hydrothermal solution. Overall, data show that gahnite formed at various times in the metamorphic history by different mechanisms. Textural relationships indicate that gahnite formation generally postdated regional peak metamorphic conditions and was associated with late-metamorphic/hydrothermal fluids circulation. Thermodynamic modeling of the physicochemical conditions ( $f_{O_2}$ ,  $f_{S_2}$ ,  $a_{Al_2O_3}$ , pH) of formation of the various gahnite-bearing assemblages documented at Lalor has been combined with textural analysis, whole-rock geochemistry, and mineral chemistry to provide new insights into the factors controlling gahnite-genesis in metamorphosed volcanic massive sulphide deposits.

## SEDIMENT TRANSPORT OF HEAVY MAGNETIC MINERALS IN THE SWASH ZONE

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Sediment transport is one of the most widely studied subjects in coastal research because of its importance to sediment budgets and beach stability. Heavy (often magnetic) mineral concentrations are prominent features on many beaches, and they are often found in areas of erosion. The entrainment and transport behavior of magnetic minerals is not well understood, however, nor how their rates of transport compare with larger but lighter non-magnetic grains, which are dominant on most beaches. To investigate this problem, magnetic susceptibility was used to investigate the cross-shore and longshore movement of heavy magnetic grains, and fluorescent tracers to track the movement of light, non-magnetic grains. Fieldwork was conducted along the eastern shore of Point Pelee, a cusped foreland in western Lake Erie, and it was supplemented by laboratory investigations to examine the effect of grain burial and grain size on the susceptibility measurements.

Measurements were made, and core samples were taken, at regular intervals along a shore-parallel grid, in order to record the progressive dispersion of magnetic and non-magnetic grain samples. The non-magnetic grains were divided into two grain size fractions ( $>250\text{ }\mu\text{m}$  and  $<250\text{ }\mu\text{m}$ ). Because the grain size of the magnetic minerals in the study are naturally  $<250\text{ }\mu\text{m}$ , the smaller fraction allowed a comparison to be made between the swash behavior of magnetic and non-magnetic grains of similar size. Initial results indicate that the longshore movement of the heavy magnetic grains is minimal in a variety of wave conditions. The smaller ( $<250\text{ }\mu\text{m}$ ) non-magnetic grains did not travel as far alongshore as the larger non-magnetic grains, and they tended to become buried deeper in the beach face. The slowest movement was recorded by the magnetic minerals, which were rapidly buried as they settled through the larger and/or lighter, non-magnetic grains. The results suggest that magnetic grains become essentially immobile under normal wave conditions, and they are subsequently exposed and entrained only during periods of high wave energy.

#### **DETECTING BURIED MINERALISATION THROUGH LIMESTONE COVER USING SOIL GEOCHEMISTRY: A CASE STUDY FROM THE FLIN FLON BELT, CANADA**

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The mid-Proterozoic Flin Flon Belt of Canada is one of the most volcanogenic massive sulphide-rich mineral provinces in the world. However, the southern half of the belt is covered by up to 300 m of sediment consisting of Quaternary glacial deposits (up to  $\sim 50\text{ m}$  thick) and up to 300 m of well-lithified Paleozoic limestones and minor siliciclastics that were deposited in the vast epicontinental seas that covered North America in those times. In the "sub-Phanerozoic Flin Flon Belt" area the density of known deposits is  $\sim 10\%$  of that without Paleozoic cover, suggesting that there remains significant undiscovered deposits in the sub-Phanerozoic areas. Surface geochemical techniques are not generally used in such geological situations because explorationists have little confidence that metals have been transported through the cover sequences. To test the capacity for geochemistry to "see through" cover sequences two soil transects were sampled across the  $\sim 12\text{ Mt}$  McIlvenna Bay Cu-Pb-Zn VMS deposit, which has 5-15 m of Paleozoic dolostone cover and 0-10 m of Quaternary glacial till cover. The two transects cover the two types of surficial cover: mineral soils, and fens/bogs containing  $<3\text{ m}$  of organic peat. The mineral soil profiles in the area are complex, with brunisols, podsols, and gleysols intermixed, plus occasional buried paleosols. For the mineral soils, partial leaches designed to investigate the geochemical characteristics of adsorbed cations, manganese oxides and iron oxides all produced noisy pathfinder element results that failed to detect the buried mineralisation. By contrast, a sodium pyrophosphate partial leach of the topmost Oh horizon, designed to primarily investigate the geochemistry of humic and fulvic acids, produced a significant (4-6 times background) Zn anomaly immediately above the subsurface mineralisation on both the peat and mineral soil lines. Normalisation and multivariate statistical techniques enhanced the Zn anomaly and defined a coincident Pb anomaly. Black Spruce leaves also detected the mineralisation, although not as clearly. That metals are being transported through the cover sequences to the uppermost soil horizons implies that cations are likely complexed and thus not available for adsorption onto the abundant iron oxides of the B horizons. High pH can aid cation-organic complexation, and the abundant carbonates of the cover sequences may play an important part in providing suitable chemistry for cation transport.

#### **AGE, COMPOSITION, AND STRUCTURAL SIGNIFICANCE OF THE LYON INLET BOUNDARY ZONE, MELVILLE PENINSULA, NUNAVUT**

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The western Churchill province is comprised of a complex assemblage of crustal blocks preserving variable effects of Archean and Proterozoic tectonism. Understanding the detailed temporal evolution of transitions between blocks is important to understanding broader cratonization processes and resource formation. The Lyon Inlet Boundary Zone (LIBZ) is a term adopted to describe one such transition zone between the southern margin of the Paleoproterozoic Penrhyn Group supracrustal belt (Melville Peninsula, NU) and a poorly understood, dominantly orthogneissic and potentially Archean crustal block to the south. It is unclear at this point whether the basement granitoids are primarily Archean or Proterozoic in age, and the precise timing of the deformation sequence is unknown. Aeromagnetic data suggest that the LIBZ is a zone of moderate to strong transposition of lithologic boundaries with a significant dextral component. Magnetotelluric data suggests a steep and narrow conductive zone which appears to be continuous to the base of the lithosphere. This portion of the Churchill province (the southern boundary of the Rae sub-province) was previously mapped at coarse resolution. Presented here is a detailed map of a representative section of the LIBZ. Preliminary U-Pb dating (GSC-SHRIMP II) will also be presented that suggests presence of ca. 1.95 Ga granitoid within the LIBZ. Post-SHRIMP FEG-SEM (BSE, colour-CL, EPMA) analysis of LIBZ zircon and monazite, along with their inclusion mineralogy will be presented with the purpose of better interpreting the crystallization age of the granitoids in the area, as well as the characteristics of subsequent metamorphic mineral growth and deformation. This information will be integrated with concurrent regional scale mapping by the Geological Survey of Canada to gain more accurate reconstructions of the tectonic evolution and mineral resource formation environments of the central Canadian arctic.

#### **ENVIRONMENTAL GEOCHEMISTRY SURVEY IN A Pb-Ba MINERALIZATION AT NORTHEASTERN BRAZIL AND BIOAVAILABILITY OF METALS**

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The Pb-Ba mineralization is located in Camutanga municipality, Pernambuco State, northeastern Brazil. Within the same region the following geological units occur: gneissic-migmatitic complex (Archean to Paleoproterozoic), metasedimentary rocks (Surubim Complex: paragneisses, quartzites, and marbles; Neoproterozoic), and granitoid rocks (Neoproterozoic Magmatic Suite). The mineralization is vein type that occurs as fracture filling hosted in pegmatite. The minerals of economic interest are galena (PbS), barite (BaSO<sub>4</sub>), cerussite (PbCO<sub>3</sub>), and minor chalcopyrite (CuFeS<sub>2</sub>). Textural and structural evidences suggest that galena and barite originated from hydrothermal fluids. Arsenic and Hg have been qualitatively detected in galena microanalyses carried out by preliminary SEM-WDS.

As lead and barium are elements that can harm human health if ingested in relatively high concentrations, this study aimed to evaluate their total and bioavailable concentrations in the surrounding environment of mineralization, since there is an established community close to the mineralization.

Geochemical analyses in bottom sediment samples collected

in the mineralized area showed high concentrations of total Pb (digestion with HF-HNO<sub>3</sub>-HClO<sub>4</sub>-HCl) near the mineralization (45 to 51 mg.kg<sup>-1</sup>), while the limit set by Brazilian environmental legislation is 35 mg.kg<sup>-1</sup>. Furthermore, the bioavailable concentrations (digestion with HCl 0.5M) are also relatively high (21.4 to 24.4 mg.kg<sup>-1</sup>), reaching 47.8% of total concentrations of Pb. Barium is also present in bottom sediment in high concentrations (3,620 to 3,680 mg.kg<sup>-1</sup>), with bioavailable Ba varying from 214 to 225 mg.kg<sup>-1</sup>. The physico-chemical parameters of stream surface water show an environment with slightly alkaline pH (7.5) and oxidizing Eh (231-243 mV), suggesting that the environment could favour the mobilization of these metals into the water.

These results led to an investigation on the mobility of these and other hazardous elements for plants and soils, which are largely cultivated in the area of the mineralization (e.g. banana). Analyses are in progress.

#### **PALINURO, A HIGH TO INTERMEDIATE SULFIDATION, SHALLOW MARINE, HYDROTHERMAL SYSTEM IN THE SOUTH-EASTERN TYRRHENIAN SEA, ITALY**

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Seafloor hydrothermal systems in island arcs have seen increased exploration efforts by the scientific community and the minerals industry in the past years due to their resource potential. These hydrothermal systems are different to those commonly studied at mid-ocean ridges because of magmatic contribution of gases and possibly metals and their shallow water depths. The southeastern Tyrrhenian Sea in the Mediterranean is host to several shallow-water (<700 m) sites (Palinuro, Panarea) of hydrothermal activity that are associated with island arc volcanism and may be a modern analogue for deposits that form the transition from deep marine base metal volcanic-rock-hosted massive sulfide deposits to subaerial magmatic-epithermal precious metal deposits. Palinuro is a basaltic-andesite complex, 50 km-long volcanic feature that consists of five coalesced volcanic edifices lying along an E-W trending fault system. Semi-massive to massive sulfides with abundant late native sulfur were recovered in a sediment-filled depression using the lander-type Rockdrill I drill rig of the British Geological Survey. The uppermost portion (<1 m depth) is an exhalite and/or low temperature altered sediments comprising banded amorphous silica, pyrite ± barite, Fe-Mn oxides and oxyhydroxides, and rare orpiment. From 1-2.5 m depth consists of barite breccias with minor amounts of clay, pyrite, marcasite, sphalerite, galena, tennantite-tetrahedrite, famatinite, chalcocopyrite, covellite, stibnite, and Pb-, Sb-, and Ag-sulfosalts. From 2.5 to 4 m depth the mineralisation comprises semi-massive pyrite, barite, and traces of clay. The deepest core recovered (>4 m depth) contains massive pyrite with minor barite. Late veins of pyrite, marcasite and native sulfur occur. A number of atypical minerals, including enargite-famatinite, tennantite-tetrahedrite, stibnite, bismuthinite, and Pb-, Sb-, and Ag-sulfosalts, occur that do not commonly occur in mid-ocean ridge massive sulfides. Sulfur isotope values range from -40 to 0‰ for pyrite, -15 to 0‰ for native S and 0 to 25‰ for barite. These are the lightest sulfur isotope values recorded for hypogene seafloor mineralisation. Analogous to subaerial epithermal deposits, the unusual mineralogy and the presence of abundant native sulfur suggest an intermediate to high sulfidation and/or high oxidation state of the hydrothermal fluids in contrast to the near-

neutral and reducing fluids from which base metal-rich massive sulfides along mid-ocean ridges typically form. Oxidised conditions during sulfide deposition are likely related to the presence of magmatic volatiles (+boiling) in the mineralising fluids that were derived from a degassing magma chamber below the Palinuro volcanic complex.

#### **GEOLOGY OF THE KIDD CREEK DEEP OREBODIES – MINE D**

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The giant Kidd Creek Mine is an Archean Cu-Zn deposit in the Abitibi Greenstone belt and is one of the largest known VMS mines in the world, with total past production of 145 MT. The upper part of the mine consisted of three main orebodies accessed in the No. 1 Mine (800 to 2500 ft), the No. 2 Mine (2600 to 4600 ft), and the No. 3 Mine (4700 to 6800 ft). The North and South orebodies extended from surface to 3,400 feet; the Central orebody has been traced to the deepest levels of the mine (>9,800 feet or 2987 m) (Fig. 1 A). A Cu stringer zone underlies all three orebodies and can be traced from surface to the bottom of Mine D. The mine stratigraphy is remarkably continuous downplunge but is complicated by faulting and several stages of folding. Previous studies of the Kidd Creek deposit (Hannington et al., 1999) documented the major ore zones of the No. 1, No. 2 and No. 3 mines. These studies provided critical understanding of the deposit and an important benchmark for understanding the new ore zones being developed in Mine D. The massive sulfides in Mine D comprise a number of ore lenses which are interpreted to be the downplunge continuation of the Central and southern lenses (South and Triangle orebody or Greywacke Lens). These are referred to as the Main, West, and South lenses. The massive sulfides overlie a silicified rhyolitic unit at the top of a mixed assemblage of rhyolite flows, volcanoclastic sediments and ultramafic flows. Metal zonation and the distribution of Cu stringer mineralization suggest that the Main and West lenses may be part of a single massive sulfide body, with an intervening horizon of intensely silicified and brecciated rhyolite. The South Lens may be a detached body, separated by late gouge faults. The large Cu stringer zone beneath the Main and West lenses has a thickness of ~100 feet but extends along the entire length of the massive sulfide bodies. Drilling below the current mine levels indicates that the massive sulfide and Cu stringer zones continue below 10,200 ft. A number of features of the North, Central and South orebodies in the upper part of the mine (e.g. Serich halo around Cu-rich zones) have been recognized in Mine D and provide an important framework for correlating the deep Orebodies with the upper levels of the mine.

#### **A NEW GEOCHEMICAL TOOL TO ASSIST VMS EXPLORATION IN THE MATAGAMI MINING CAMP: THE POSITIVE EUROPIUM ANOMALY**

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The Key Tuffite (KT) is the main guide used for VMS exploration in the Matagami camp (Abitibi) for the last 50 years. All the major exploited deposits are located along this continuous and extensive tuffaceous and locally cherty unit. Despite the importance of this horizon and the numerous studies on it, attempts to develop geochemical vectoring tools to assist exploration were inconclusive.

Exploration drilling related to the Bracemac-McLeod VMS deposits provided an exceptional opportunity to sample the KT

around and away from the mineralization. Twenty three drill-cores where selected from more than 400 holes in an area of 1.4 by 2.6 km. Macroscopic observations revealed that the complex nature of the KT results at least from the mixing of 2 components in varying proportions: a tuffaceous component, represented by chlorite, and a chemical component represented by silica and sulfides. This last component is proximal to the lenses. Whole-rock litho-geochemistry was carried out on 42 samples. Chemically, the bimodal component of the KT is well illustrated by a linear regression ( $R^2=0.81$ ) between  $\text{SiO}_2$  and  $\text{Fe}_2\text{O}_3$ , where  $\text{SiO}_2$  represents the silica, and  $\text{Fe}_2\text{O}_3$  can represent chlorite and/or sulfides.

Single element and ratio element plots proved to be useless in an attempt to decipher any increase of elements relative to the spatial position of the sulphide lenses. However, europium anomalies showed a systematic increase towards the deposit. This anomaly is defined as  $\text{Eu}/\text{Eu}^* = \text{Eu}/[(0.67\text{Sm} + 0.33\text{Tb})/\text{MUQ}]$ , where MUQ (Mud of Queensland) is the normalization value. Away from the deposit, the anomaly is around 0.6 and reaches a maximum of 3.0 in the lens. This positive Eu signature is persistent up 200 m from the deposit.

Europium enrichment in VMS settings is a well known process induced by hydrothermal fluid flow. Because of the double valence of this element,  $\text{Eu}^{2+}$  is leached by hot and reducing fluids in the alteration area and then redeposited at the hydrothermal vent sites. In the KT, this enrichment may be related to hydrothermal alteration or seafloor precipitation. Even if the Eu anomaly acts as a proxy for VMS mineralization, there is no apparent relationship with the bimodal components of the KT. Specifically, europium-bearing phases remain to be established as well as the enrichment process. However a third component related to late hydrothermal influx along the KT following the capping of the hydrothermal system appears to be the best explanation for Eu enrichment.

#### **THE NEWLY MAPPED HELLROAR CREEK SHEAR ZONE IN THE NORTHERN MONASHEE MOUNTAINS OF THE CANADIAN CORDILLERA: THE BASE OF AN OROGENIC CHANNEL?**

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There is a tectonic conundrum in the northern Monashee Mountains. On the one hand, field-based studies indicated that rocks of the area were deformed and metamorphosed as a coherent block, which resulted in three phases of folding and a series of well-defined metamorphic isograds. On the other hand, later geochronological studies pointed to the presence of three domains with distinct timing of metamorphism and deformation, which would imply the presence of unrecognized shear zones or of spatially heterogeneous thermal/fluid flow events.

Our fieldwork conducted east of the town of Blue River (BC;  $52^\circ 7' \text{N}$ ;  $118^\circ 53' \text{W}$ ) revealed the existence of a major SE-striking shear zone, herein named Hellroar Creek Shear Zone (HCSZ). We mapped it for ~20 km along the ridge between Mud and Hellroar creeks and then east of Mud Creek valley. The HCSZ is characterized by a large volume (>60%) of highly sheared leucogranite and leucosome, whereas leucogranite in its footwall, although locally as abundant, forms a heterogeneous mesh of highly discordant intrusions. The HCSZ separates a low-strain domain in its footwall, with preserved stratigraphic polarity and dominated by SW- to W-verging structures, from a high-strain domain in its hanging wall, with rocks recording complete transposition by top-to-the-NNE to top-to-the-E shearing. Whereas rocks of its hanging wall are generally at the Sil-Kfs-grade, rocks in its footwall are at

the Ky-Ms-grade. Preliminary U-Pb in situ Mnz geochronology agrees with previous studies and indicates a retrograde path in the Sil field between ~90 and 75 Ma in hanging wall rocks, while footwall rocks were on a prograde path in the Ky field. The presence of pods of footwall rocks, with diameters ranging from < 2 m to >50 m, included in highly sheared rocks of the HCSZ, highlights the complexity of the zone.

Interestingly, the HCSZ is located along-strike from, and separates the same lithologic packages as the boundary between two of the geochronological domains previously identified ~20 km to the SE. We thus propose that the HCSZ connects with this boundary to form a >40 km long shear zone. The HCSZ is interpreted as the base of a channel flow system that was active for >30 Myr in the Late Cretaceous. If this interpretation is correct, the HCSZ would be the NE extension of the Monashee décollement that bounds the western flank of the Monashee Complex, ~60 km to the SSW.

#### **GEOCHEMISTRY OF RECENT SEDIMENTS IN THE ANZALI LAGOON, NORTHERN IRAN**

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The Anzali Lagoon in southern part of the Caspian Sea in northern Iran has been threatened by pollution from various sources. This lagoon has been strongly affected by anthropogenic activities, urban development, industry, shipping trade, agriculture, oil operations and tourism. Thus, it is expected that throughout the years pollution could have been gradually increasing and these activities could be threatening the environment.

One of the aims of this work is to determine the concentrations of heavy metals (As, Co, Ni, Cu, Pb, Zn, Cr and V), and other contaminants in the lagoon sediments and their impact on the environment. In addition, a detailed geochemical investigation was undertaken to characterize the different mineral phases, which trap these elements. Concentrations were determined in shallow sediment columns and some streams flowing into it using ICP.

Attempt has been made to discriminate between natural and anthropogenic inputs of particulate material and the trace element incorporated into the sediments. In addition, heavy metals concentrations and their temporal and spatial relations in shallow core sediments have been determined in different parts of the wetland. The spatial distribution and chemical forms of heavy metals in the lagoon sediments were closely related to the distribution of pollution sources (outlet of sewage) and to the local sedimentary and hydrodynamic conditions.

Enrichment Factors (EFs) were calculated to assess whether the concentrations observed represent background or contaminated levels. Using Al as a reference element, the metals were normalized and compared with their baselines to determine the EFs. To determine the anthropogenic influence, Principal Component Analysis (PCA) applied.

The results of EFs and PCA indicated that the concentration variations of Cd, Cu, Pb, Mn and Zn were mainly caused by the anthropogenic sources, and the concentration variations of Cr and Ni were influenced by both the anthropogenic and natural factors, while the other metals were mainly derived from the natural sources. The anthropogenic pollution must be viewed seriously within the lagoon with the heaviest contamination observed along the eastern segment of the lagoon, reflecting the high concentrations of pollutants. The Anzali lagoon has absorbed much of pollutants acting as a trap for heavy metal and in a way protecting the supporting the Caspian Sea.

## **MINERALOGICAL AND GEOCHEMICAL VECTORS TO ORE IN PORCUPINE ASSEMBLAGE SEDIMENTARY ROCKS AT THE HOYLE POND GOLD DEPOSIT, TIMMINS, ONTARIO**

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The Porcupine camp of northern Ontario represents one of the largest orogenic gold camps in the world. Mineralization is primarily hosted by mafic and ultramafic volcanic rocks of the lower Tisdale assemblage and coarse clastic sedimentary rocks of the Timiskaming assemblage. Due to their low iron content, turbiditic greywacke and mudstone of the Porcupine assemblage have been historically perceived as poor hosts of mineralization. Only recent deep drilling at the Hoyle Pond deposit intercepted significant mineralization within these sedimentary rocks. This study reports on the first comprehensive mineralogical and geochemical characterization of ore-related hydrothermal alteration of Porcupine sedimentary rocks.

Detailed logging of exploration drill core revealed cryptic hydrothermal alteration surrounding gold-bearing quartz veins hosted within a thick interval of normally graded greywacke beds. A subtle color change up to several meters away from the veins and the occurrence of abundant acicular arsenopyrite immediately around the veins are the only wall rock alteration features that are both observable in drill core and distinct to the gold-bearing veins.

Geochemical and mineralogical investigations confirmed that the gold-bearing veins hosted by Porcupine sedimentary rocks are enveloped by a sulfidation halo. Arsenopyrite is strongly associated with increased abundances of As, Sb, and Bi, which reach background concentration levels further than 0.8 m away from the veins. White mica replacement of feldspar within <2.0 m of the gold-bearing veins caused a pronounced enrichment of Rb, Cs, and Tl, in addition to systematic changes in the whole-rock  $K_2O/Na_2O$  ratio. Secondary tourmaline formation and associated B-enrichment of the sedimentary rocks reaches up to several meters from the veins. In contrast to these alteration styles, carbonate alteration was found to be widespread and does not show a direct spatial relationship with mineralization.

Petrographic investigations suggest that the formation of arsenopyrite and tourmaline predates the development of the mineralized quartz veins, which commonly contain tourmaline- and arsenopyrite-bearing host rock fragments as well as stylolites that are composed of tourmaline, arsenopyrite, and white mica. Native gold occurs along contacts to the wall rock fragments and stylolites, and locally forms small inclusions in paragenetically-late pyrite. Despite the comparably low reactivity of the Porcupine assemblage sedimentary rocks to the mineralizing fluids, the close textural association of gold and pyrite suggests that gold precipitation coincided with, or was controlled by, desulfidation of the gold-transporting fluids during wall rock interaction.

## **TREATMENT OF Se(VI) IN ANOXIC GROUNDWATER USING GRANULAR IRON AND ORGANIC CARBON: AN XAFS STUDY**

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The treatment of aqueous Se(VI) from a simulated groundwater by granular zerovalent iron (GI), organic carbon (OC), and a mixture of these reactive materials (GI-OC) was evaluated in laboratory batch experiments. The experiments were performed under anoxic conditions to simulate subsurface treatment of groundwater. Simulated groundwater used for the experiments contained

300 mg/L of Se(VI) prepared from sodium selenate. After reacting for 120 h, total Se concentrations decreased by more than 90% in the system containing GI, whereas 15% Se removal was observed in the OC system and 35% removal was observed for the GI-OC mixture. X-ray absorption fine structure (XAFS) spectroscopy was used to investigate the speciation and chemical structure of Se on the reactive materials. Analysis of the Se K-edge indicated that, after 6 h, all Se(VI) had been reduced to Se(IV) or Se(0) at the margins of the GI grains. After 72 h, Se(0) was the predominant form of Se present on the surface of GI grains with evidence of Se-Se bonding, suggesting the formation of elemental Se. The principal form of Se in the OC batches was Se(VI), and evidence of Se-O bonding suggested that the removal mechanism was consistent with sorption of aqueous selenate onto solids. Minor reduction to Se(IV) and Se(0) occurred after 120 h; however, reduced forms of Se were minor components of total Se. Selenium K-edge XAFS spectra for the GI-OC batches are consistent with the presence of Se(IV) and Se(0) on both GI and OC grains, suggesting that the addition of GI may have contributed to the reduction of sorbed Se(VI) on OC grains. These results suggest that GI is effective at inducing a redox change in anoxic aqueous systems to promote the precipitation of elemental selenium from aqueous Se(VI), and the presence of GI enhances removal on organic carbon.

## **SUBMARINE FIRE-FOUNTAIN DEPOSITS AT THE HINE HINA HYDROTHERMAL VENT FIELD, LAU BACK-ARC BASIN: BASALTIC PYROCLASTIC ERUPTIONS AT 1850 M WATER DEPTH**

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Present day rifting within the Lau Basin occurs along the Valu Fa Ridge, where the Hine Hina and Vai Lili hydrothermal vent fields are located on separate but overlapping ridge segments. Volcanism along the Valu Fa Ridge is largely dominated by effusive eruptions of basaltic and lesser “rhyolitic” flows. At Vai Lili, aa-type basaltic flows and younger pillowed flows, observed during the 2002 Sonne 167 cruise, have buried the hydrothermal field first observed in 1989. At Hine Hina the morphology, tectonic fabric and volcanological features have not changed significantly, and the hydrothermal field occurs on a ridge segment that is mantled, over a large area (more than 1 km along the ridge), by black, basaltic volcanoclastic deposits up to 5m thick. The deposits consist of mm- to cm-sized, vesicular to scoriaceous, equant basaltic lapilli, fluidal lapilli and sculptured, fluidal volcanic bombs up to 35 cm in size. The bombs have a thick, bread-crust textured glassy outer rind and a scoriaceous interior, typical characteristics of subaerial bombs, except for their thick glass margins. They are interpreted to have been ballistically emplaced during mild fire-fountain eruptions. The basaltic lapilli are interpreted to have formed from jetted magma during fountaining that was quench fragmented within the eruption column to form fall deposits that blanketed and smoothed the irregular flow topography that is so characteristic of other ridge segments. This interpretation is consistent with the significant volume of the volcanoclastic deposit. The common occurrence of ripples on the upper surface of the volcanoclastic deposits is a product of vigorous bottom currents that continuously re-work the top few cm of the deposit. A thin (<1–5cm thick) but extensive Fe-Mn oxyhydroxide crust that covers much of the upper part of volcanoclastic deposit may be a product of unfocussed, diffuse low temperature hydrothermal discharge that was, in part, facilitated by the permeability of the porous vol-

caniclastic deposits upon which it developed. Evidence of present day hydrothermal activity includes a thermal anomaly in the immediately overlying water column, shimmering water, and white–yellow biological mats.

#### **RECONSTRUCTION OF THE VOLCANIC AND SUBVOLCANIC ARCHITECTURE OF THE PLAEOPROTEROZOIC VMS-HOSTING FLIN FLON CAULDRON SUBSIDENCE STRUCTURE**

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The Flin Flon District, within the Flin Flon arc assemblage, contains the world-class Flin Flon-Callinan-777 VMS ore system which totals > 85.5 Mt grading 2.2% Cu, 4.3% Zn, 2.49 g/t Au and 38.16 g/t Ag. After considering the effects of post depositional deformation, volcanic strata west and east of the Flin Flon Lake fault provide two cross-sections through the Flin Flon cauldron subsidence structure defined by 1) thick but aerially restricted megabreccia deposits; 2) angular unconformities; 3) basaltic and rhyolitic dike swarms and vents localized within the cauldron; 4) numerous synvolcanic faults; and 5) high-temperature epidote-quartz alteration. Subsidence in the west section ended prior to VMS formation whereas in the east section subsidence persisted into the overlying younger formations. VMS deposits have only been discovered in the east section where they are associated with proximal, coherent rhyolitic domes and more distal rhyolitic volcanoclastic facies that occupy distinct fault blocks within the cauldron. The south structural margin of the cauldron is defined by an abrupt facies change from coherent flows outside the cauldron to intracauldron volcanoclastic rocks. Younger sediments (Missi Group) cover the north margin of the cauldron.

Results from a 3-D seismic survey, new age dating of the Cliff Lake Pluton and host volcanic strata of the Western Hooke Lake Block, and a  $\delta^{18}\text{O}$  study suggest that: 1) strata of the Hooke Lake Block can be tentatively correlated with VMS hosting strata of the Flin Flon Block; 2) the multiphase tonalite/trondjemite-quartz gabbro of the Cliff Lake Pluton is a subvolcanic intrusion that was emplaced into its own volcanic pile during a period of magmatic resurgence that followed cauldron subsidence and Flin Flon VMS deposit formation; and 3) volcanic strata along the upper contact of the Cliff Lake Pluton are, in part, enveloped within a high temperature reaction zone. These features are consistent with emplacement of the Cliff Lake Pluton within the thermal corridor that was responsible for the formation of the Flin Flon VMS deposits.

#### **VOLCANOGENIC MASSIVE SULPHIDE DEPOSITS OF THE PALEOPROTEROZOIC TRANS-HUDSON OROGEN AND THE ARCHEAN ABITIBI SUBPROVINCE: CHARACTERISTICS AND METALLOGENY**

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The Paleoproterozoic Trans-Hudson Orogen (THO) and the Archean Abitibi Subprovince (AS) are well known for their VMS deposits. The THO contains 36 VMS deposits totalling >250 Mt. The AS contains 85 VMS deposits totalling >700 Mt. The THO and AS deposits are dominantly of Bimodal-Mafic type, sharing common features including: metal zonation, footwall and regional alteration assemblages, an association with “exhalative sedi-

ments”, arc-like rocks, subvolcanic plutons, and footwall lithofacies ranging from mafic and felsic flow (typically F<sub>II</sub>, F<sub>III</sub>, F<sub>IV</sub> rhyolites) and volcanoclastic lithofacies, to siliciclastic lithofacies. Both contain Au-rich VMS deposits, and VMS formation spans a significant time range (35 Ma in the THO and 40 Ma in the AS) with extensional suprasubduction settings predominant. The most significant deposit- or assemblage-scale difference is that a few AS VMS deposits are directly associated with komatiites.

Despite the deposit and assemblage-scale similarities the two districts have distinct structural styles and interpreted geodynamic settings. Within the THO, VMS deposits occur in nascent and rifted, juvenile arc assemblages that are structurally juxtaposed with VMS-barren ocean floor and plateau assemblages. Assemblage boundaries are faults and several generations of thrust faults and folds are observed within assemblage blocks. The deposits occur in primitive and more mature arc assemblages and in younger, successor, sedimentary arc-rift assemblages. Within the AS, all volcanic assemblages have VMS deposits, all have plume and arc-like geochemical affinities, but assemblages with oceanic geochemistry are absent. In addition, boundaries between assemblages are submarine disconformities, and within assemblages thrust faults are not recognized as a dominant structural feature. The structural style of the THO and the existence of oceanic and arc terranes are consistent with allochthonous construction and subsequent accretion of oceanic and pericratonic terranes during ocean closure. In contrast, the AS consists of arc-like and plume-related assemblages, in which the continuity of mineralization through time and space could be explained by episodic but repeated interaction between plumes and rifting within a back arc environment resulting from subduction reversals and oblique convergence between microplates. Similar modern plume-arc interactions are unknown, although there is evidence for a plume contribution during initial rifting of the Lau and North Fiji back-arc basins.

#### **CHANGES IN DYNAMIC STABILITY OF CLIMATE AT THE MID PLEISTOCENE TRANSITION**

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Complex dynamic systems, such as climate, are characterized by rapid or sudden changes known as bifurcations. Such bifurcations have hitherto rarely been inferred on the basis of long paleoclimate proxies due to noise and the relative sparseness of observations. This paper presents a method of visualizing these bifurcations in the climate system by viewing sequential probability density plots of reconstructed phase space portraits of four separate paleoclimatic data sets calculated over overlapping time windows.

The climate system is normally regarded as a damped driven deterministic system, which can be defined by an  $n$ -dimensional phase space with coordinates  $x_1, x_2, x_3, \dots, x_n$ , in which the functions  $x_1(t), x_2(t), x_3(t), \dots, x_n(t)$  describe its time evolution. The evolution of the system is marked by the trajectory traced out by sequential plots of individual states with coordinates defined by the values of the  $n$  functions at each observed time. Although the identity of the different axes for the climate system is unclear, a topologically equivalent phase space can be reconstructed by using successively higher time derivatives of one observed variable ( $x_1$ ), or lagged observations of the same variable (e.g.  $x_1(t), x_1(t+\delta t), x_1(t+2\delta t), \dots$ ).

Four paleoclimatic data sets (two separate deep marine  $\delta^{18}\text{O}$  records; the magnetic susceptibility of loess; and the marine  $\delta^{13}\text{C}$  record) are studied: first by reconstructing their phase space portraits in two dimensions; then by contouring the probability density of the phase space portraits over successive windows in time. Areas of consistently high probability across several time windows



represent areas of stability. Two forms of stability are noted in each of the studied records: 1) Lyapunov stability, in which a single region of space represents areas of capture of the system and 2) limit cycles, in which the studied parameter varies in a regular pattern in which magnitudes and rates of changes are repeated over time.

Probability density plots of reconstructed two-dimensional phase space portraits of all four climate records show numerous regions of Lyapunov stability in the late Quaternary, but show limit-cycle attractors in the Early Quaternary. Thus one of the predominant themes in Quaternary climate change is a major shift in the nature of climate change from the Early to the Late Quaternary.

#### **CARBON DIOXIDE AND ITS IMPORTANCE IN REDISTRIBUTING ORE METALS DURING THE CRYSTALLIZATION OF LATE-STAGE SULFIDE-BEARING MAFIC PEGMATITES AT THE LAC DES ILES COMPLEX, ONTARIO**

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Mafic pegmatites in the platinum group element (PGE)-mineralized Roby zone, Lac des Iles Complex, northwest Ontario, Canada, comprise dikes, veins, and irregular pods of coarse-grained magnesiohornblende, pyroxene, and labradorite-andesine with minor biotite, apatite, Fe-Ti oxides and intercumulus quartz that grades into massive quartz or graphic quartz-base metal sulfide-vysotskite [Pd, Ni(S)] intergrowth at their cores. Quartz, apatite, and magnesiohornblende host primary and secondary assemblages of one- or two-phase carbonic fluid ( $\text{CO}_2 \pm$  up to  $\sim 10\% \text{ CH}_4 \pm$  minor  $\text{H}_2\text{O}$ ,  $\text{N}_2$ ) inclusions that contain ore metals (Ni, Cu, Pd, Bi, Te, Fe). Rare trails of late-stage, high-salinity, aqueous fluid inclusions are secondary in origin and therefore unrelated to the crystallization of the pegmatites. Assemblages of primary carbonic fluid inclusions show considerable variation in mode and temperature of homogenization, reflecting large fluctuations in confining pressure at the time of quartz crystallization of as much as  $\sim 1$  kbar (in single quartz crystals) and  $\sim 2.8$  kbars (all data). Independent thermobarometric methods constrain conditions for the following two stages of pegmatite formation (and carbonic fluid entrapment): (1) the crystallization of magnesiohornblende-plagioclase intergrowth at  $T \sim 650$  to  $850^\circ\text{C}$ , and  $P \sim 1$  to 3 kbars; and (2) the crystallization of quartz at  $T \sim 535$  to  $650^\circ\text{C}$ , and  $P \sim 0.4$  to 3.2 kbars, setting the maximum depth of emplacement of the Lac des Iles Complex North Roby zone magma at 10 to 12 km. The results indicate that aqueous-dominant volatile phases were absent during the crystallization of pegmatitic gabbroic rocks at Lac des Iles Complex and that water-poor, carbonic fluid entrapment persisted to well below solidus conditions. Carbonic fluid, rather than aqueous fluid, was the likely transport agent for ligands involved in the precipitation and remobilization of the PGE and base metals, and may have played a role in the evolution of other mafic-ultramafic complexes where carbon dioxide has been recognized as the dominant volatile species at near-solidus conditions.

#### **ORIGIN OF THE SALINITY IN THE KOKANEE Ag-Pb-Zn VEINS**

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Chlorine is the most abundant anion in most hydrothermal solutions and is the dominant metal complexing agent in many ore forming environments. Furthermore, Cl (and Br) have often been regarded geochemically fairly conservative elements in many sys-

tems, and, thus, have been used to elucidate the origins of metal bearing brines and other fluids. Stable chlorine isotopes ( $\delta^{37}\text{Cl}$ ) are a relatively new geochemical tool that may also help to constrain the origin of the salinity in mineralizing fluids and the role that hydrothermal fluids play in the global cycle of Cl. Thus far, studies have suggested that the crustal reservoir for Cl has values of  $0 \pm 1\%$ . The composition of the mantle is not well known but recent studies of mid ocean ridge basalts suggest that mantle values may range from 0 to  $-3\%$ .

Fluid inclusions from a series of metamorphic Ag-Zn-Pb veins from the Kokanee district of British Columbia were analysed. In general, the paragenetic sequence starts with siderite, sphalerite, galena and minor quartz, during a stage dominated by the saline metamorphic fluid, evolving gradually to quartz-sphalerite-galena veins with late dolomite and calcite, with progressive admixture of meteoric water. The Br/Cl molar data ranges from 0.14 to  $25.35 \times 10^{-3}$  and the  $\delta^{37}\text{Cl}$  values range from  $-0.47$  to  $0.33\%$ . The halogen data suggest that the mineralizing fluids ultimately derived their salinity from the dissolution of evaporites and, therefore, that the presence of evaporite bearing carbonate units in the area was a fundamental control on the ability of these fluids to complex Ag and base metals.

#### **PETROLOGY IN THREE DIMENSIONS: INSIGHTS FROM HIGH-RESOLUTION X-RAY COMPUTED TOMOGRAPHY COMBINED WITH IN SITU MINERAL CHEMISTRY AND MINERALOGY**

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High-Resolution X-Ray Computed Tomography (HRXCT) is a non-destructive technique allowing the 3D visualization at the sample scale (few centimetres to less than 1 millimetre in size) of rock texture, crystal size, shape and mineral intergrowth inaccessible by any other methods. Over the past few years, HRXCT has elucidated some fundamental problems in geosciences and opened new doors toward a better understanding of igneous processes and ore genesis at the micron scale. The combination of HRXCT with conventional 2D image analysis (e.g. backscattered electron images), and in situ chemical analysis using state of the art techniques including laser-ablation ICP-MS and synchrotron based X-ray fluorescence mapping has a wide range of applications in petrology with potential benefit in mineral exploration and extraction. Examples are: (i) New insights into the spatial distribution of platinum-group element minerals (mainly consisting of Pt-Pd sulphides, Pt-Fe alloy and Pt-Pd bismuthotellurides) in chromitites from the Merensky Reef of the Bushveld Complex (South Africa) with results illustrating the consistent relationship of PGM with the edges of magmatic sulphide blebs and chromite or silicate grain boundaries which strongly support an orthomagmatic origin for these PGM; (ii) Imaging of complex magmatic morphologies of chromite, magnetite and sulphide blebs and the determination of mineral proportions in komatiitic dunites from the Yilgarn Craton (Australia) and their relationships with whole-rock major and in situ mineral trace element (including Se, As, Te, Bi, Sb, Au, Ag, Pt, Pd, Ir, Os, Ru, Rh) chemistry providing insights on element mobility during alteration and metamorphism of komatiite-hosted nickel sulphide deposits.

## **U-Pb DATING OF DETRITAL ZIRCONS FROM THE TRIASSIC OF NORTHEASTERN BRITISH COLUMBIA AND ITS SIGNIFICANCE FOR SEDIMENT TRANSPORT PATHWAYS AND TIMING OF TERRANE ACCRETION**

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U-Pb dating of detrital zircons separated from Triassic clastic rocks in northeastern BC helps constrain sedimentary transport pathways during this time. Earlier paleocurrent evidence from the Triassic strata, including crossbedding and ripple marks, indicated transport predominantly from the east, implying derivation of sediment from the North American craton of northwestern Laurentia and deposition into the Western Canada Sedimentary Basin (WCSB). This interpretation was consistent with the evolution of the western edge of the continent as a passive margin until convergence with offboard volcanic terranes began during the Jurassic. To assess this model, new samples were collected for detrital zircon analysis from eight sections on Williston Lake in northeastern BC, as well as from one section farther north, close to the Halfway River. The ages of the detrital zircon samples have been ascertained using conodont biostratigraphy, and they span most of the Triassic, from the Smithian to the Rhaetian. The detrital zircons have been dated by the U-Pb method, using a LA-ICP-MS. Although the majority of grains yield ages consistent with derivation from the Proterozoic rocks that make up northwestern Laurentia, a subset of the detrital zircons yield anomalous ages that suggest either derivation from other sources, or from re-working of more local sedimentary rocks. These results require a more complex sedimentary transport system during the Triassic in the WCSB than has previously been assumed. This complexity may be related to the formation of a foreland basin in northeastern BC during the Triassic, as has been previously documented in eastern Yukon, related to collision of a pericratonic terrane (Yukon-Tanana terrane) with the continental margin.

## **DEVONIAN SHALE-HOSTED Ni-Zn-Mo-PGE SULFIDE DEPOSITS, YUKON**

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Nickel sulfide deposits hosted by Devonian black shale occur in the Richardson and Ogilvie mountains, Yukon. They display a distinctive stratigraphy that consists from the base upward of: 1) chaotic clastic unit composed of limestone and dolostone boulders; 2) black shale containing carbonate and barite concretions; 3) Ni-rich massive sulfide layer 10–40 cm thick with disrupted bedding textures; and 4) thin-bedded black chert. Geochemical redox proxies and the absence of bioturbation indicate anoxic bottom water conditions. Radiolarians 40 cm above the sulfide unit give an age between mid-Frasnian and early-Famennian (Late Devonian). The mineralized unit consists of pyrite, marcasite, vaesite (NiS<sub>2</sub>), gersdorffite (NiAsS), millerite (NiS), sphalerite, barite and apatite. Microscopic textures typically display a “cellular” morphology consisting of oblate structures filled by quartz and pyrite that are surrounded by a network of Ni sulfides. Framboidal pyrite commonly has a distinctive cross-hatch texture. The maximum element content of the sulfide interval is: S (28.9 wt.%), Fe (21 wt.%), TOC (7.0 wt.%), P<sub>2</sub>O<sub>5</sub> (7.5 wt.%), Ni (7.0 wt.%), Zn (2.3

wt.%), As (1.06 wt.%), Mo (0.33 wt.%), Se (5700 ppm), V (2400 ppm), Y (1000 ppm), Cu (660 ppm), Sb (389 ppm), Tl (390 ppm), Co (330 ppm), Cr (280 ppm), Ga (27 ppm), Ag (8 ppm), Hg (5.5 ppm), Pt (511 ppb), Pd (202 ppb), Ru (12 ppb) and Ir (10.9 ppb).

The genesis of shale-hosted Ni sulfide deposits is poorly understood. Several genetic models have been proposed but none adequately explain all the features of this type of mineralization. Clearly, any genetic model would have to elucidate the sequence stratigraphy in deposits separated by up to 400 km, the origin of high-energy clastic deposits, and the unusual textures, mineralogy and diverse suite of enriched elements. Based on these features alone, it is unlikely that these deposits formed from seafloor hydrothermal vents. However, the widespread distribution of Ni-rich sulfides with chondritic Ru/Ir ratios is consistent with a cosmogenic origin that may have involved the raining of impact-generated quenched glass droplets to the seafloor. The suite of enriched platinoid and siderophile elements that is similar to that documented for K-T boundary and impact ejecta layers supports this interpretation. The prevalence of Ni sulfides may reflect the limiting effect of H<sub>2</sub>S on the build up of dissolved Fe in a reduced water column and the seeding of this column with Ni and other metals that settled to the Earth’s surface following meteorite impact.

## **LANDSCAPE EVOLUTION OF THE EASTERN ARCTIC RIM, CANADA**

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The Eastern Arctic Rim extends from the Torngat Mountains of northern Labrador, along eastern Baffin and Devon Islands, to Ellesmere Island. Knowledge of the landscape evolution of the rim during and since rifting from Greenland has been indirectly derived from variations in sediment fluxes deduced from marine geophysical and sediment records, from chronology and interpretation of the Cape Dyer volcanic field, and from thermal and geodynamical models of rifting and margin subsidence. Besides the ECSOOT transect across the Torngat Mountains, no land-based crustal dynamics data exist. Timing of initial rifting, symmetry of rifting, relationship between volcanic vs non-volcanic margins and flank evolution, and roles of crustal roots on exhumation and rock uplift of the rim have remained intractable until now.

From Labrador to Devon Island, apatite and zircon (U-Th-Sm)/He measurements in over 200 samples collected along strategically oriented horizontal (margin parallel and perpendicular) and vertical transects, and randomly throughout the islands allow us to identify the location of crustal roots, establish rates of tilting and exhumation of the physiographic provinces, timing of drainage development, and the style of post-uplift flank evolution.

In the Torngat Mountains, rift flank uplift began at 150 ± 10 Ma, based on a 1400 m vertical transect, less than 10 Ma before the earliest sea floor spreading (Alexis Fm basalts and Bjarni Fm sediments). The two margin-parallel transects indicate a pre- or syn-Jurassic fluvial drainage controlled today’s fjord spacings. The margin perpendicular transect reveals significant west-down tilting across the entire Ungava Peninsula, and rates of exhumation are fastest near the highest peaks (up to 100 m/Ma over a 10 Ma period), supporting a pinned-divide exhumation model. In the North Central Baffin region, a pinned divide model is supported in the Foxe Basin-Baffin Bay horizontal transect, although rates of exhumation differ across the faults bounding the five physiographic provinces. Cooling ages in the Bruce Mountains vertical transect

all pre-date the late Cretaceous and indicate a slow gradual cooling since the Jurassic, revealing that this part of the rim lacks a crustal root that would have provided the buoyancy to accelerate rift flank uplift. Samples collected on Cumberland and Hall Peninsulas and eastern Devon will help locate other crustal roots and establish the history and style of exhumation along the margin. The ultimate goal is to link the thermochronology to marine sediment and geophysical records for an improved understanding of the rift and post-rift history of the rim.

#### **RADIUM-226 MOBILITY IN URANIUM MINE TAILINGS**

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A common practice for the uranium industry is to use secondary sulphates to sequester  $^{226}\text{Ra}$  for long term immobilization. Unpredicted and somewhat rapid increases in  $^{226}\text{Ra}$  concentrations have been measured at certain uranium mine waste disposal facilities after long periods of predictability and/or stability. The migration of  $^{226}\text{Ra}$  in the environment is of significance due to its long half life (1,600 years) and a high degree of radiotoxicity and bioavailability. The release of  $^{226}\text{Ra}$  has been the subject of a few studies. It has been hypothesized that  $^{226}\text{Ra}$  concentrations are affected by decreasing redox conditions by the direct microbial reduction and dissolution of Ra-bearing minerals, such as radio-barite or by indirect effects, such as the microbial reduction and dissolution of Ra-loaded sorbent minerals (e.g. iron and manganese oxyhydroxides). We investigated whether  $^{226}\text{Ra}$  remobilization was anecdotal or observed across mine tailings in Canada. A comprehensive database of Ra-226 tailings porewater and solids data from different uranium mine tailings facilities was developed along with ancillary concentrations such as pH, Eh, sulphates, sulfides, calcium, iron, manganese, and barium. Results from this study indicate that there are indeed zones of  $^{226}\text{Ra}$  remobilization scattered among some of the tailings, in which radium remobilization to pore waters is clearly taking place. However, when the data are pooled, it is apparent that radium concentrations in the waters at most of these sites are actually decreasing (or at least holding steady) over time. Comprehensive information on physical, chemical and biological interactions between radium and the surrounding environment needs to be evaluated and advanced. This is required to develop predictive numerical models of the key processes controlling the fate of radium in uranium mine tailings. The results of this on-going research program should allow to interpret and form a conclusion about how site conditions affect the long-term behaviour of  $^{226}\text{Ra}$  in uranium mine tailings and identify appropriate management strategies to prevent the remobilization of  $^{226}\text{Ra}$ .

#### **GEOLOGIC EVOLUTION OF THE WORLD'S MOST PROLIFIC ARCHEAN VMS-BEARING SEQUENCE: THE BLAKE RIVER GROUP, ABITIBI GREENSTONE BELT, CANADA**

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The Blake River Group (BRG) hosts the world's largest Archean VMS cumulative tonnage with 371 Mt of ore (production and re-

serves) from 30 deposits. It contains almost half of the entire Abitibi greenstone belt VMS tonnage (806 Mt). The 2704-2695 Ma BRG represents the youngest episode of abundant submarine volcanism in the Abitibi. Recent research conducted in the BRG shows that VMS-forming events occurred about every m.y. and that Au-rich VMS deposits were formed during two distinct events (Horne and Quemont at 2702-2701 Ma, and Bousquet 2-Dumagami and LaRonde Penna at 2698-2697 Ma).

Precise U-Pb geochronology, lithogeochemistry and volcanology indicate that the BRG is not the result of a simple gradual succession of tholeiitic to calc-alkaline volcanic units, a "layer-cake" succession of cycles, or a submarine megacaldera complex. Instead, the BRG was created by the simultaneous formation of different styles of volcanic edifices and settings associated with major extension and subsidence. Developed on a komatiitic-tholeiitic substratum (2710-2702 Ma Tisdale-Malartic-type units), the BRG construction started with the formation of a tholeiitic lava plain coeval with the development of bimodal volcanic centers (stage 1). The oldest VMS deposits of the BRG are associated with felsic centres of this stage (e.g. Horne and Quemont). This was followed by major extension and tholeiitic to transitional, mafic-dominated bimodal volcanism in the central part of the BRG where a graben structure was developed, and by transitional to calc-alkaline intermediate to felsic volcanism in the eastern and western parts of the BRG (stage 2). The typical Noranda-type VMS deposits (e.g. Amulet and Millenbach) are associated with the stage 2 graben and mafic-dominated bimodal rocks, whereas the Au-rich VMS deposits of the Doyon-Bousquet-LaRonde mining camp (e.g. Bousquet 2-Dumagami and LaRonde Penna) are associated with intermediate-felsic centres in the eastern part of the BRG. The last stage of volcanism is characterized by a new tholeiitic episode comprising abundant rhyolitic rocks, a large mafic-intermediate volcanoclastic basin, and local intermediate-felsic centres of transitional to calc-alkaline magmatic affinity hosting the youngest VMS deposits of the BRG (e.g. Bouchard-Hébert).

When compared to the other volcanic units of the Abitibi, the BRG shows a greater variety of volcanic styles and settings, which may explain its unique VMS endowment. The BRG was most probably formed in a back-arc basin setting and the associated arc, if it existed, may have been located north of the BRG.

#### **THE MAKING OF THE GEOLOGICAL MAP OF EASTERN LABRADOR**

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The Geological Survey of Newfoundland and Labrador recently released a 1:500,000-scale compilation map and 25 1:100,000-scale individual geological maps for eastern Labrador. The full-colour maps cover roughly 80,000 km<sup>2</sup>, which represents about 20% of the area of the Province or 0.8% of Canada. They are the final cartographic product of a 25-year reconnaissance mapping program in eastern Labrador.

The database that underpins the maps includes information from 28,732 field data stations, 24,505 structural measurements, 15,502 stained (for K-bearing minerals) rock slabs, 6,166 field photographs, 6,032 petrographic thin sections, 1,763 whole-rock geochemical analyses, 545 mineral occurrences, 318 paleomagnetic results and 355 U-Pb age determinations (plus other isotopic data). Other sources of information integrated into the maps include regional and more aerially restricted high-resolution geophysical data, grey-scale and infrared aerial photography and digital elevation model information. Except for small fringe areas (in NTS map sheets 13K and 13O), all geological mapping data from both federal and provincial previous projects, and from uni-

versity studies and mineral exploration company mapping have been included, utilizing original notebooks and petrographic thin sections.

Uncoloured preliminary editions of many of the 1:100,000-scale maps are already available, but the present versions can be considered as new products because of incorporation of extensive new petrographic, geochemical, isotopic and geophysical data; the utilization of geological knowledge from formerly unmapped adjacent regions; and revised interpretations facilitated by in-depth regional geological knowledge of the whole of eastern Labrador and beyond. Key and/or innovative features of the new maps are, (i) a common legend for all 25 1:100,000-scale maps, (ii) colour-coding of various dyke swarms, (iii) listing of data sources according to individual geoscientist that collected the data, (iv) comprehensive detailing of isotopic data, (v) tabulation of mineral occurrence information, (vi) locating paleomagnetic sites, (vii) cryptic extrapolation of geological features under inland and coastal water areas, and (viii) inset maps for areas of detailed information.

Much of the geological knowledge generated from the mapping has already been disseminated in the geoscientific literature, but regional features that the new maps particularly demonstrate to better advantage than previously are (i) the nature of the Grenville 'front', (ii) the configuration of the dextral ramp that terminates the eastern Grenville orogen, (iii) position of the northern boundary of the Pinware terrane, (iv) the disposition of a reclined regional fold in the Pinware terrane, and (v) the distribution of Iapetus-related faults and dykes.

#### **AN EMERGING LATE PALEOPROTEROZOIC Cu PROVINCE IN SOUTHERN LABRADOR**

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Steadily accumulating data from government geoscientific mapping and mineral exploration activities now provide sufficient justification to claim that a widespread region having significant Cu potential exists in the Grenville Province in southern Labrador. The host rock is mostly pelitic metasedimentary gneiss, with which psammitic gneiss and minor calc-silicate gneiss, mafic volcanic rocks (pillowform in part) and finely laminated quartz-rich rocks derived from a metasedimentary protolith (chemical precipitate?) are associated. The best estimate for the depositional age of the metasedimentary package is 1810-1770 Ma. Pyritic gossans are the most obvious indication of mineralization, some extending several kilometres along the regional structural trend and having widths exceeding 100 m. In detail, it seems that there is a spatial association with rocks derived from mafic volcanic and/or chert(?) protoliths. Copper mineralization is common within the pyritic gossans and analysis of hand samples has demonstrated Cu values exceeding 5% in some instances, accompanied by hints of anomalous Au. Although the existence of widespread trace Cu mineralization in the gossans has been known for several decades, it is only through relatively recent mineral exploration activity that it has become evident that grades might be high enough to be of economic interest. Only very minor drilling has been carried out. Metallogenic models that might be applicable include volcanic exhalative Sedex or Besshi type, plus the potential for beneficiation during later Labradorian (1710-1600 Ma), Pinwarian (1520-1460 Ma) or Grenvillian (1085-985 Ma) orogenesis. Regional geological reconstructions suggest correlation of the host rocks with metasedimentary gneiss in the Ketilidian Orogen in southernmost Greenland, where mineral exploration has resulted in the discovery of Au-As, Au-Cu and Fe-Cu-Zn mineralization of economic significance. Grenvillian tectonism has played a major role in modifying direct correlation by displacing, possibly by hun-

dreds of kilometres, correlative rocks in Labrador northward relative to their Ketilidian counterparts.

#### **FORMATION WATER AND GAS GEOCHEMISTRY OF THE SVERDRUP BASIN**

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Early drilling activity in the Sverdrup Basin produced significant data that was largely dispersed in paper copy records. Recent work to compile this into a coherent digital database provides the first opportunity to examine regional trends in formation water and gas geochemistry. Formation waters have highly variable salinity, with local brine development associated with salt piercement structures. In contrast, fresh water influx lowers salinities along the basin margins. This fresh water influx also appears to have initiated generation of biogenic gas by lowering TDS and concentrations of SO<sub>4</sub> below levels that would normally inhibit methanogenesis. This suggests the potential for biogenic gas plays along the basin margin, where gas may have been generated late in the basin history. Geochemistry and stable isotopes of gases in the basin centre are consistent with a thermogenic origin, with the basin showing a long history of gas escape features from Cretaceous time to present.

#### **EUROPA HERE ON EARTH – SUPRAGLACIAL SULPHUR SPRING SUPPORTING A DIVERSE MICROBIAL ECOSYSTEM, BORUP FIORD PASS, ELLESMERE ISLAND**

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Europa is a key target for astrobiological research as the icy moon of Jupiter could have a larger ocean than Earth. Sulphur compounds along fractures of the icy surface suggest a sulphur based ocean system. This along with strong geochemical and thermal gradients suggest the moon could support active biological systems. Upcoming deep space missions to Europa are driving interest in remote sensing of biosignatures in icy-sulphur systems.

Borup Fiord in Canada's High Arctic is the best terrestrial analogue for developing remote sensing of ice-sulphur systems. The site hosts unique sulfur-rich springs which discharge onto the surface of glacial ice, releasing H<sub>2</sub>S and forming deposits of elemental sulfur (S<sub>0</sub>), calcite, and gypsum, as well as the rare carbonate mineral vaterite. Springs occur on the southern end of a prominent valley glacier, but discharge sites vary significantly from year to year. Stratified layers of elemental sulphur are observed in proglacial icings suggesting that spring discharge may be perennial. Springs are Na-Cl rich saline waters (7000 mg/l TDS) that discharge at up to 8.4 l/s. The measured level of dissolved H<sub>2</sub>S, 143 mg/l, is one of the highest reported for any sulphur spring in Canada.

A thriving microbial community has been detected in the spring water and mineral deposits, with rapid cycling of sulfur between three oxidation states, as well as measured changes in S-isotopic signatures in the spring waters, indicating a complex series of biologically mediated redox reactions. Sulphur isotope data indicate that evaporites of the Otto Fiord Formation are the likely source of sulphur in the system, necessitating deep groundwater circulation under glaciated mountains in a region of over 500 m permafrost.

## **GEODYNAMIC MODELS OF ARCHEAN CONTINENTAL COLLISION AND THE FORMATION OF MANTLE LITHOSPHERE KEELS**

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The processes responsible for the formation of thick, strong and cold Archean sub-continental lithospheric mantle (mantle keels) beneath Archean cratons remain elusive. Here, the dynamics of some such processes are studied by forward numerical modeling of the thermo-mechanical evolution of continental lithosphere undergoing collision and orogenesis under Neoarchean-like conditions. The numerical experiments illustrate that depending on the composition of the crust and the degree of radioactive heat production (RHP) in the crust, three dominant modes of mantle lithosphere deformation evolve: (1) pure-shear thickening; (2) imbrication; (3) and a mode best described as underplating. All three modes of deformation result in the thickening and emplacement of plate-like mantle lithosphere to depths between 200 km and 350 km. The transition from pure-shear thickening to imbrication is largely dependent on the degree of RHP in the crust, while the transition from the imbrication style to the underplating style is dependent on the composition of the lower crust.

## **ESTIMATES OF TRANSITION METAL ABUNDANCES IN PRIMARY OCEANIC ISLAND BASALTS, RELATIONSHIPS WITH THE MANTLE COMPONENTS, AND A TEST FOR CORE-MANTLE INTERACTION**

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Literature data (GEOROC database) for “compatible” transition metal concentrations of Ni, Co, Fe, Cu, Cr, V, Mn and Sc in 13 suites of end-member mantle component, oceanic island basalts, are used to estimate element concentrations in primary magmas. The estimates involve regression of each metal against Mg/Fe ratios at each island and deriving metal concentrations at Mg/Fe = 1, which equals a Mg# value ( $Mg\# = 0.72 = Mg/(Mg + 0.9 \cdot Fe)$  atomic) of 0.72, the number expected for a primary magma. Analysis of the estimate results using exploratory statistics reveals that overall transition metal abundances correlate with mantle component type. This conclusion holds even if the concentration estimates for each island are adjusted to a common La/Yb ratio to compensate for different average percentages of melting at each island. Compared to Enriched Mantle (EM1 and EM2) basalts, HIMU (High Mu) basalts exhibit lower Zn (and Pb) and higher Cr supporting the presence of subduction-processed ocean floor in HIMU source regions. EM1 and EM2 magmas are very similar in terms of their transition element compositions except that EM1 has lower Cr. It has been proposed that large layered mafic intrusions with economic concentrations Ni, Cr, Co and Cu are associated with melting Archean subcontinental lithospheric mantle bearing an EM1 signature. If so, results here indicate that the tendency to form ore deposits is likely related to factors such as S or O fugacity because enriched mantle sources, at least in the ocean basins, do not appear to have higher concentrations of these elements. Most of the elements studied are likely to be substantially concentrated in the core of the Earth compared to the mantle. The observation that concentrations tend to correlate with mantle component type suggests that if there is interaction between the core and the mantle it has less influence on mantle concentrations of these elements than the lithospheric recycling processes that produced the mantle components.

## **A COMPARISON OF THE MARTIAN AND EARTH MANTLE; BULK COMPOSITION, MINERALOGY, AND RELATIONSHIPS BETWEEN THE DEPTH AND PERCENTAGE OF MELTING**

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Geochemical data for 13 basaltic Martian meteorites from the NASA “Meteorites From Mars” website are used to compare the mantles of Mars and Earth. Many incompatible transition metals have concentrations comparable to those in Earth basalts, though Cr is higher. Nevertheless, they suggest formation in a peridotite mantle similar to Earth. A plot of SiO<sub>2</sub> (pressure indicator) versus La/Yb or Nb/Y (melting percentage proxies on Earth) shows that, unlike on Earth, Martian basalts form over a narrow range of melting percentages that are high and that increase slightly with depth. The range of pressures (based on SiO<sub>2</sub>) appear similar to, or slightly lower than, those for oceanic island basalts (OIB) on Earth. The narrow range of melting percentages and positive relationship with depth resembles preliminary information for the Moon (based on KREEP) and may reflect restricted mantle convection in the interior of small planetary bodies. The relative incompatibility of ~30 incompatible “trace” elements is well established for the Earth. When the behaviour of ~150 incompatible element ratios (more-incompatible element in the numerator, based on Earth) in the Martian meteorites are compared, most ratios bearing elements with dramatically different bulk distribution coefficients (i.e. different incompatibility) show the same behaviour as in Earth basalts. This suggests similar mantle mineralogy for Mars and Earth. However, ratios involving a few elements (Ba, Eu, Zr, Th) behave the opposite of those in Earth basalts suggesting a residual phase or phases that retain these elements and cause concentrations to rise as melting increases. Amphibole represents a candidate that explains the behaviour of Ba, but there are caveats; the Martian mantle appears “depleted” and would not be expected to host residual incompatible-element bearing phases such as amphibole at the high percentages of melting indicated by Nb/Y and La/Yb ratios that resemble those in tholeiitic OIB. Comparison of OIB and Martian basalts using element ratios calculated from elements with similar incompatibility (i.e. ratios that reveal source region variability on Earth) shows that Martian basalts come from materials most-similar to depleted mantle on Earth. Absolute element concentrations lead to the same conclusion. Thus crust formation on Mars apparently led to a depleted mantle interior but there is no evidence for recycled lithospheric materials such as those that yield the mantle component sources of OIB on Earth.

## **GEOCHEMICAL VARIABILITY AND INTERPRETATION OF SOILS IN THE MARITIME PROVINCES, CANADA**

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A soil geochemical survey was undertaken in the maritime provinces of Canada. The survey, initially part of the North American Soil Geochemistry Landscapes Project, was designed to reveal the variability of the near surface geochemistry that is associated with underlying bedrock geology, effects of weathering, meteoric water infiltration, groundwater and anthropogenic activities. Soil samples collected from the O, A, B and C horizons from the Maritime Provinces of Canada were analyzed using four-acid digestion and ICP-OES/MS instrumentation. An additional soil layer profile, PH (Public Health) of 0-5 cm depth was defined as part of the A horizon and is of interest in health risk assessments.

A principal component (PC) analysis of the log-centred geochemistry from the four soil horizons reveals a distinctive set of inter-element relationships from the C horizon upwards into the B, A and PH horizons. Statistical dispersion of several elements increases upwards in the soil profile. Maximum data dispersion occurs in the PH and A horizon soils. Elements including Cd, S, P, Pb, Bi, Sb, Mo, Be, Zn and Cu are relatively enriched in the PH-A horizons (correlated with increasing organic carbon content) while elements including Ni, Mg, Cr, V, Co, Fe and Sc are relatively enriched in the C horizon, representing a mafic component of the protolith. The felsic component of the protolith is expressed as a relative enrichment of K, Rb, Zr, REEs, Li and Al. This lithologic trend is exhibited along the second PC axis. The relative associations revealed in the first two principal components enable the recognition of the underlying protolith, weathering, meteoric water and groundwater effects. The sources of these associations may be attributed to the underlying geology, anthropogenic activity, or a combination of both. The influence of bedrock geology, climate and geomorphology (ecoregions) can be used to characterize the regional variability of the geochemistry for environmental and population health risk assessments.

#### **THE USE OF STATISTICAL METHODS APPLIED TO MULTI-ELEMENT GEOCHEMISTRY FOR PHASE DISCRIMINATION IN KIMBERLITES-EXAMPLES FROM THE STAR AND WHISKEY KIMBERLITES.**

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The discrete eruptive phases of the Star kimberlite, Saskatchewan, and the Whiskey kimberlite, Ontario, Canada have been classified into distinctive groups using statistical methods applied to whole rock geochemical data. Based on the evaluation of petrography, mineralogy, major and trace element geochemistry, discrete kimberlite phases were constructed as geochemical groups. Multivariate statistical and cross-validation techniques including principal component analysis, k-means cluster analysis, analysis of variance, classification and regression trees were applied iteratively, to systematically refine the individual groups. Within the Star kimberlite, Ni, Si, Co, Mg and P contribute most to maximum discrimination between 5 recognized kimberlite phases. The Whiskey kimberlite can be subdivided into three distinct phases, defined by Ti, Al, Cr and Ni. The relationship between the geochemistry of the different kimberlite phases can be illustrated through graphical rendering of the statistical and classification procedures.

A portable hand-held X-ray fluorescence (XRF) spectrometer was used on crushed and powdered material from the three Whiskey kimberlite phases. The application of the same statistical methods to the powdered Whiskey kimberlite phases provided the similar phase discrimination results, thereby indicating that a portable XRF can be used to obtain geochemical signatures from which kimberlite phase discrimination can be carried out in the field.

#### **THE INTERPRETATION OF GEOCHEMICAL DATA – TACKLING THE PROBLEM OF CLOSURE AND THE USE OF MULTIVARIATE METHODS**

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Geochemical data can be in the form of systematic multi-element and multi-media geochemical surveys carried out by the exploration industry or government geological surveys. Geochemical survey data are commonly composed of thousands of observations and may be analyzed for 50 or more elements. This abundance of data provides an opportunity to discover and interpret a wide range

of geochemical processes through appropriate methods of data treatment and the application of multivariate statistical techniques.

Geochemical data are compositional in nature and therefore "closed". The application of standard statistical methods on such data are invalid and can lead to erroneous interpretations. In addition, the problems of missing and censored data (reporting values at less than the limit of detection) must be addressed. Modern methods of geochemical data analysis apply the use of log-ratios to overcome the compositional nature of the data and permit the application of standard statistical methods that were developed within the real number space. The study of geochemical processes requires knowledge about mineralogy and fluid speciation (including magma melts). Therefore the interpretation of geochemical data is multivariate in nature and the use of multivariate statistical tools can provide much information for the interpretation and quantification of geochemical processes.

The use of data analysis and statistical methods combined with geographical information systems provides an effective means of process identification and pattern discovery. It is a challenge to examine and interpret the significance of multi-element analyses, in terms of exploration potential, and to understand the relationships between elements. The application of multivariate data analysis and statistical techniques (exploratory and modelled) combined with geographical information systems can assist in the task of data interpretation and subsequent model building. Exploratory multivariate methods includes: scatterplot matrices, detection of atypical observations, principal component analysis, cluster analysis and knowledge based indices of association. Modelled methods of assessing multivariate data include: regression, analysis of variance, canonical variate analysis, and classification.

Examples of the application of these modern methods are provided along with a systematic framework on how geochemical data should be evaluated and interpreted.

#### **POTASSIC ALTERATION ASSOCIATED WITH THE ATYPICAL CANADIAN MALARTIC ARCHEAN GOLD DEPOSIT, QUEBEC**

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The Canadian Malartic gold deposit (238 Mt at 1.2 g/t of Au), Abitibi region, Quebec, is hosted by the metagreywacke of the Pontiac Subprovince that was intruded by a felsic to intermediate TTG-type porphyritic body, containing feldspar phenocrysts in a medium- to fine-grained, light gray groundmass. Potassic alteration (K-feldspar and biotite) is directly associated with the gold mineralization; carbonatization, sericitization and albitization also occur commonly, and have been locally overprinted by silicification and late stage chloritization. Pyrite accompanies all alteration types. Gold is associated with finely disseminated pyrite and narrow quartz  $\pm$  biotite  $\pm$  carbonate  $\pm$  pyrite veinlets with K-feldspar  $\pm$  biotite  $\pm$  pyrite alteration halos.

The intensity of potassic alteration is demonstrated by mass gains of K<sub>2</sub>O up to +139% in the greywacke and  $\sim$ +80% in the porphyry. Additionally, the greywacke is enriched in CaO (up to +125%), Na<sub>2</sub>O (up to +45%), S (up to +1075%) and SiO<sub>2</sub> (up to +216%). It is depleted in Mg (down to -12%) and underwent negligible Fe change. The porphyry is also enriched in CaO (up to  $\sim$ +15%), S (up to  $\sim$ +2310%), Fe (up to  $\sim$ +30%) and SiO<sub>2</sub> (up to  $\sim$ +90%). However, it is depleted in Na<sub>2</sub>O (down to  $\sim$ -15%) and MgO (down to  $\sim$ -20%).

In the greywacke, the Mg# (molecular Mg/Mg+Fe) of biotite increases with increasing alteration intensity from 0.5 to 0.75, whereas in the porphyry, it is relatively constant at an average of 0.6. The MnO content in biotite was depleted during alteration of

the porphyry, decreasing from 0.3 wt% in least altered rocks to 0.05 wt% in the most intensely altered rocks. The F content of biotite in the porphyry is relatively constant (avg. 1 wt%). By contrast, in the greywacke, it increases with increasing intensity of alteration; the metamorphic biotite contains an average of 0.2 wt% F, whereas in weakly altered greywacke hydrothermal biotite contains 0.5 wt.% F and in strongly altered greywacke is up to 0.8wt% F.

The grade of gold mineralization correlates positively with the intensity of potassic alteration as reflected in the mass percent of K<sub>2</sub>O to the rock (and with S because of accompanying pyrite formation). Most significantly, the grade of the gold mineralization also correlates positively with the F content of the biotite. These observations suggest a genetic model in which gold mineralization was the product of hydrothermal fluids originating from alkaline magmas.

#### **FRACTURE MINERALIZATION AND FLUID FLOW EVOLUTION: AN EXAMPLE FROM MIDDLE DEVONIAN CARBONATES, SOUTHWESTERN ONTARIO**

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The Middle Devonian Lucas and Dundee formations of southwestern Ontario are major oil producing units in this area. Field, petrographic, fluid inclusion and isotopic investigations reveal a variety of early to late diagenetic processes that also include the development of multiple fracture systems partly to wholly occlude by celestine, fluorite and calcite. The host carbonates display two types of dolomite fabrics that occur as replacive and cement phases. These are: (1) fine crystalline matrix dolomite (10-20 µm), and (2) idiomatic-E dolomites with average size of 100 µm. Stable oxygen and carbon isotope values for both dolomite fabrics shows a wide range of values ( $\delta^{18}\text{O}$  = -3.91‰ to -9.28‰, VPDB) and ( $\delta^{13}\text{C}$  = 0.4‰ to 3.38‰, VPDB). For late fracture-filling calcite  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values range from -5.88‰ to -9.44 and -0.04‰ to -7.71‰, respectively. The  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of selected dolomite and calcite samples range from 0.70798 to 0.70838, which are more radiogenic than contemporaneous Devonian seawater. Fluid inclusions in some late calcite cements fluoresce under UV light, suggesting the presence of hydrocarbons. Homogenization temperatures of these inclusions vary from 91.9 to 237.6°C with an average of 140.1°C. Ice-melting temperatures vary from -15.1°C to -17.9°C with an average of 18.61 wt % NaCl.

The  $^{18}\text{O}$ -depleted values of calcite and the radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  value suggest their precipitation from hot (about 140°C), saline basinal/hydrothermal brines. In addition,  $^{13}\text{C}$ -depleted calcites indicate carbon possibly contributed from oxidation of hydrocarbons introduced into the system. The presence of celestine and fluorite in fractures further supports this interpretation. These diagenetic fluids could have been originated from deeper parts of the basin and invaded Devonian carbonates through fractures and faults.

#### **ENHANCING K-12 EARTH SCIENCE EDUCATION IN SASKATCHEWAN**

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Several organizations are working toward enhancing Earth Science education in Saskatchewan. The Saskatchewan chapter of the Canadian Geoscience Education Network facilitates communication and collaboration among these organizations through meetings and email correspondence.

An exciting new development is the Ministry of Education's proposed introduction of Earth Science 20 and 30 as new high school science courses. These courses will be based on Pan-Canadian Science Framework Grade 11-12 Earth and Space science outcomes, and guidance from technical experts. Representatives from the Universities of Regina and Saskatchewan, Saskatchewan Mining Association (SMA), Saskatchewan Geological Society (SGS), Association of Professional Engineers and Geoscientists (APEGGS), Federation of Saskatchewan Indian Nations (FSIN), and others have expressed a willingness to help provide teachers with the enhanced knowledge and classroom resources required to teach these new courses; this will be done primarily through workshops for current teachers and teachers-in-training at the two universities.

Development of Earth Science classroom materials and delivery of professional development opportunities for K-12 teachers are ongoing. SMA conducts workshops and continues to offer "Rock'n the Classroom GeoVenture", a six day, all-expense-paid fieldtrip for educators to explore Saskatchewan's mining operations and link their experiences to the Saskatchewan curriculum. SMA continues to develop additional classroom activities to post on its website. SGS collaborates with educators, industry and other organizations including EdGEO, SMA, APEGGS, University of Saskatchewan College of Engineering's Outreach and Transition Programs (OTP) and the Ministry of Energy and Resources to offer teacher workshops covering basic Earth Science concepts and many aspects of Saskatchewan's geoheritage. SGS also plans to develop additional curriculum-related classroom activities for its Geoscapesask website. SMA, SGS, APEGGS, and University of Saskatchewan's OTP helped recruit and fund ten Saskatchewan educators who participated in a GeoCanada 2010 workshop in Calgary that focused on integrating Earth Science content into existing high school science curricula. APEGGS, in collaboration with students and teachers at a Saskatoon school, has developed a series of lesson plans linked to engineering and geoscience career posters.

Students from northern Saskatchewan are the primary target of the University of Saskatchewan's OTP. Initiatives include northern science ambassadors who provide hands-on experiences for students in their classrooms, and sponsored student visits to the Saskatoon campus. FSIN science programs, which focus on First Nations youth, include Science Festivals and Fairs, school presentations, and teacher workshops. School presentations are also given by faculty and students at both universities, and by members of other organizations.



## **THE JUNE 23, 2010 MW 5.0 VAL-DES-BOIS, QUEBEC EARTHQUAKE**

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On June 23, 2010 at 17:41 U.T., a magnitude Mw 5.0 (mN 5.7) occurred approximately 10 km southeast of Val-des-Bois, Quebec within the west Quebec seismic zone. It was one of the largest recent events to have occurred in eastern Canada. Due to its size and proximity to Ottawa (~55 km), this earthquake produced the strongest shaking ever felt in Ottawa. It was widely felt in eastern Canada (from Thunder Bay to Nova Scotia) and into the northeast United States, and as far away as Kentucky. Over 5250 felt reports were entered via the EarthquakesCanada website.

Analysis of the main shock indicates a focal depth of 22 km, with a predominantly thrust mechanism on planes trending north-west-southeast. These findings are consistent with the parameters of most other Western Quebec earthquakes. Six aftershock instruments were deployed in the epicentral region within 24 hours, including one real-time, continuous 6-component station VDBQ. More than 309 aftershocks above magnitude 1 have been recorded (to January 11<sup>th</sup>), 245 of which occurred in the first week. Eight were above magnitude 3, the largest of which was a mN 3.3 at 23:34 UT on June 23<sup>rd</sup>. Six of the aftershocks have been reported as felt.

There was light damage in Ottawa (mostly to chimneys and contents) and similar damage in the epicentral region (but also including failure of a bridge embankment and two large landslides in clay). The main event was well recorded by strong and weak motion instruments. A maximum PGA of ~8-10 %g was recorded by strong motion instruments in the Ottawa region, and 1.5% g in Montreal. Together with data from 11 weak-motion stations (at epicentral distances 20-160 km) these show that the shaking in Ottawa was well below the 1/2475 year design spectra in the 2005 National Building Code of Canada. The estimated return period for the shaking is ~150 years.

## **COMPARISON OF NEAR-INFRARED FEMTOSECOND AND NANOSECOND LASER ABLATION LASER ABLATION INDUCTIVELY COUPLED PLASMA MASS SPECTROMETRY ANALYSIS IN BIOMINERALS**

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Suppressed particle-size-related-fractionation (PSRF) and improved particle size distribution, makes femtosecond (fs) laser ablation the preferred solid sampling method over nanosecond (ns) laser ablation, especially for volatile elements and elements with high first ionization potentials. In this study, volatile elements such as Zn, Hg, and Pb in biominerals (fish otoliths and fin-rays) were analyzed by Ti:sapphire fs (~46 fs) near-infrared (785 nm) laser ablation inductively coupled plasma mass spectrometry (NIR-fs-LA-ICP-MS) and were compared with the results of Nd:YAG ns (~6 ns) ultra-violet (213 nm) laser ablation. In addition to the volatile elements, Sr, Ba, Cu, and Cd were also analyzed for comparison between the two laser ablation techniques. Concentrations of the elements were determined by using MACS-3, a pelleted calcium carbonate reference material obtained from US Geological Survey. The signal of <sup>43</sup>Ca<sup>+</sup> was used as an internal reference, correcting for variations in the laser ablation yield and transport efficiencies and sensitivity of the instrument. For NIR-fs-LA-ICP-MS, the influence of various laser parameters-beam diameters, focus positions relative to sample surface, repetition rates, laser fluences, and scan speed-on the ablation of biominerals is evaluated. Femtosecond laser ablation provided improved accuracy, superior to that obtained using ns LA-ICP-MS.

Furthermore, fs laser pulses significantly reduce the frequency and amplitude of spikes in sample signals commonly observed from ns laser ablation, and thus reduce fractionation at the laser beam sites. These reduced noise levels from fs laser ablation can contribute to more precise isotope ratio determination.

## **REMAGNETIZATION OF ca. 590 Ma GRENVILLE DYKES BY HYDROTHERMAL FLUIDS ASSOCIATED WITH THE 577 Ma CALLANDER BAY COMPLEX**

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A paleomagnetic investigation has been carried out on the ca. 590 Ma Grenville dyke swarm at its western end, in the vicinity of the French River. Nearly all dykes weather low such that they underlie channels (like the French River), often leaving only chilled margins available for sampling. The few interior samples obtained have low coercivities, magnetite is indicated from susceptibility-temperature data, and the highest unblocking temperature upon thermal demagnetization seldom exceeds 500°C. Often both a precipitous drop in intensity and chaotic magnetization directions occur at or slightly above this temperature. Additionally, the chilled margins often produce a red mud when drilled. During heating the fine-grained margin samples tend to explode and thus thermal demagnetization data from them could not be obtained. Based on AF methods, the chilled margins carry a steep down to the SE component (A) but in some cases a co-existing primary component is partially revealed at higher coercivities. Component A can be clearly separated from a PEF component and is ubiquitous, especially in dykes which are close to the main E-W channels/faults/lineaments which occur along and on either side of the French River. The A direction is virtually identical to that obtained previously from the 577 Ma Callander Bay complex at the eastern end of Lake Nipissing. Chemical analyses of the reddened chilled margins yield anomalously high values of CO<sub>2</sub> and crystalline water. The red colouration suggests the presence of secondary hematite. A dyke within about 20 km of the Callander Complex carries component A, has a brecciated margin, and a matrix with high CO<sub>2</sub> and crystalline water concentrations. We speculate that fenitizing solutions, emanating from the Callander Bay complex, exploited the dyke margins and caused oxidation and remagnetization of the dykes. The paleomagnetic direction associated with the Callander complex and the French River area dykes may be significantly younger than the 577 Ma igneous emplacement age of the complex because the duration of fenitization is unknown. The inferred capability of the solutions to travel more than 100 km from the Callander complex suggests that remagnetization associated with 530 to 580 Ma alkaline complexes within the Grenville may be more widespread than suspected.

## **MULTI-STAGE BREAKUP OF RODINIA IN NORTHWESTERN LAURENTIA: STRATIGRAPHIC, GEOCHEMICAL, AND GEOCHRONOLOGICAL CONSTRAINTS FROM THE YUKON**

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Integrated stratigraphic, geochronological, geochemical, and structural data from the Neoproterozoic inliers of the western Yukon provide important new constraints on the tectonic evolution of northwestern Laurentia. On the northern margin of the Coal Creek inlier, early Neoproterozoic syn-sedimentary normal fault-

ing initiated a northwest-facing shelf-break marked by prograding stromatolite reefs during deposition of the lower Fifteenmile Group (lower assemblage). The lower assemblage of the Fifteenmile Group appears to correlate with the basinal/platformal assemblage of the lower Little Dal Group in the Mackenzie Mountains, implying both successions were related to a single basin-forming event. An 811.5 Ma tuff above the reef complex constrains the timing of passive margin development and the onset of the Bitter Springs negative carbon isotope anomaly. The 780 Ma Gunbarrel igneous event is manifested in a major unconformity that developed beneath the Callison Lake Dolostone in the upper Fifteenmile Group. The Dawson Thrust, which is the southern limit of Neoproterozoic carbonates in the Yukon, is interpreted to be a reactivated, south-facing normal fault that marks the southern edge of a rifted margin that formed ca. 720 Ma. Extension was accompanied by emplacement of the 717.4 Ma Mount Harper Group Volcanics in the Coal Creek inlier and the correlative Pleasant Creek Volcanics in the Tatonduk inlier, which are the southwestern-most expressions of the Franklin igneous event. Magmatism continued through deposition of the basal Rapitan Group glaciogenic diamictites, which contain a 716.5 Ma tuff that pins the age of early Cryogenian snowball glaciation. A thin and incomplete late Cryogenian–Cambrian section, as compared to the Wernecke and Mackenzie mountains, suggests that the western Yukon was a paleo-high during much of the late Neoproterozoic. Together, these new data and interpretations point to a multi-stage break-up of the northwestern margin of Laurentia from Rodinia, perhaps related to a long-lived plume.

#### **NATURE AND TIMING OF METAMORPHISM AND DEFORMATION ON CUMBERLAND PENINSULA, BAFFIN ISLAND, NUNAVUT**

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A new metamorphic map calibrated with the first U-Pb metamorphic monazite ages for Cumberland Peninsula (CP), Nunavut, is an outcome of the GeoMapping for Energy and Minerals (GEM) initiative which provides a context for mineral exploration strategies for Baffin Island. Regional metamorphism on CP shows a continuous range in grade from low pressure, middle amphibolite facies conditions (comprising staurolite, andalusite and sillimanite zones) to low-moderate pressure, upper amphibolite facies conditions (garnet+sillimanite+K-feldspar+leucosome zone). The majority of the map area comprises upper amphibolite facies rocks, with the lower-grade, middle amphibolite facies rocks occupying a northeast trending, ~100 km by 15 km corridor extending from Touak to Sunneshine Fiord in the eastern part of the map area. The lowest-grade staurolite±andalusite-bearing mineral assemblages equilibrated at approximately 580–600°C with pressures corresponding to bathozone 2 (3.5±0.5 kbar), whereas the upper amphibolites facies assemblages equilibrated at approximately 650–710°C and 5.5±1.3 kbar. Granulite-facies contact aureoles, which predate the regional metamorphism, occur around Opx-bearing monzogranite intrusions, informally designated the Qikiqtarjuaq Suite, and include Bt-absent Crd-Sil-Grt-Qtz-Pl-Leucosome metapelites and Opx-Bt-Qtz-Pl metapsammities.

Two main regional deformation events, D<sub>1</sub> and D<sub>2</sub>, are defined by structural and fabric relationships. D<sub>1</sub> is characterized by thick-skinned, in- and out-of-sequence thrusting, and resulted in predominantly planar, bedding-parallel fabrics. Thrusting was followed by penetrative folding, D<sub>2</sub>, which generated north-dipping, transposed fabrics and south-verging, northwest-plunging folds

and mineral lineations. Peak regional metamorphism occurred following D<sub>1</sub> and before or during D<sub>2</sub>, based on the observation that garnet, staurolite, and andalusite porphyroblasts overprint an early fabric and are wrapped by D<sub>2</sub> fabrics.

In situ SHRIMP U-Pb monazite geochronology constrains the timing of the metamorphic and deformation. Cryptic Neoproterozoic ages of 2785±4 Ma and 2701±6 Ma support the existence of Archean sediments and metamorphism. Monazite dates from ca. 1900 to 1760 Ma record a protracted Paleoproterozoic metamorphic history. Monazite included in a garnet porphyroblast in a contact aureole adjacent to a Qikiqtarjuaq Suite intrusion yield an age of 1897±8 Ma, within uncertainty of its crystallization age. Sillimanite partially included in this monazite grain demonstrates it is metamorphic in origin and not detrital. An age population of ca. 1860 Ma in foliation-parallel monazites from several samples suggests D<sub>2</sub> occurred at or after 1860 Ma.

#### **THE SENSE OF PRECAMBRIAN MAGNETIC REVERSALS OBTAINED FROM HIGH PRECISION U-Pb GEOCHRONOLOGY: A WAY TO REMOVE POLARITY AMBIGUITY IN CONTINENTAL RECONSTRUCTIONS**

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Precisions of 1 Myr or less for the ages of Precambrian mafic dykes can now be achieved routinely by U-Pb dating of baddeleyite (and/or zircon). Dyke swarms ranging in age from 500 to 2500 Ma often contain dykes of opposite paleomagnetic polarity. Exceptions are dyking events such as the ca. 1270 Ma Mackenzie and ca. 2076 Ma Fort Frances swarms in Canada and the ca. 2367 Ma Dharwar swarm in India, which have a single polarity due to the short duration (<5 Myr) of their associated magmatic events. However, the ca. 2170 Ma Biscotasing and ca. 585 Ma Grenville swarms of similar short duration capture a reversal due perhaps to a greater frequency of polarity reversals at those times. Other events represented by the 2446 to 2473 Ma Matachewan and 2101 to 2126 Ma Marathon swarms are more protracted and show more equal dyke populations of opposite polarity. Geochronology and paleomagnetism together are now at the threshold of being able to define the frequency, age and sense of polarity reversals within the constraint of the ~1 Myr resolution of the U-Pb data.

An example of reversal dating and its use in paleocontinental reconstructions is provided by the 1635 to 1622 Ma Melville Bugt dyke swarm in Greenland, in which dykes of one polarity differ in age from those with the opposite polarity: an older magnetization down to the SW, and a younger one up to the NE. A tentative correlation of this reversal, in terms of both age and sense, with one associated with the Sipoo diabase and quartz porphyry dykes in Finland, leads to a fit between Fennoscandia and Greenland (Laurentia) such that the Melville Bugt swarm could be fed laterally from the Fennoscandian rapakivi province during its initial stages of magmatism. This configuration is contrary to many previous paleomagnetic fits that choose to use the alternative polarity option for the Laurentian data.

# EVIDENCE FROM FLUID INCLUSION MICROANALYSIS AND STABLE Cl ISOTOPES FOR THE INTERACTION OF MAGMATIC FLUIDS WITH SALINE GROUNDWATER AT THE SUDBURY IGNEOUS COMPLEX, ONTARIO: A REVISED MODEL FOR FOOTWALL-STYLE MINERALIZATION

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Along the northern margin of the 1.85 Ga Sudbury Igneous Complex (SIC), Canada, veins and dikes of a granitic rock type known as the footwall granophyre preserve evidence of the interaction of magmatic fluid and groundwater. Textures and cross-cutting relations show that the emplacement of the footwall granophyre created favourable sites for the later deposition of footwall-style (high Cu, Pd, Pt) sulfide veins. Geochemical modeling shows that the rock type represents a mobilized (injected) silicate melt residue from the crystallizing SIC. Primary fluid inclusions in the footwall granophyre contain mixtures of a high salinity (44-70 wt% Na-Cl<sub>eq</sub>), metal-poor Na-rich aqueous magmatic fluid and a lower salinity, Ca- and Sr-rich groundwater. The magmatic end-member is considered to be an SIC-derived volatile phase. Estimates of the mixing proportions show that primary and secondary inclusions in the footwall granophyre contain 60-100% and 20-70% of the magmatic end-member by mass, respectively. The chlorine isotope composition of biotite in the footwall granophyre shows <sup>37</sup>Cl enrichment ( $\delta^{37}\text{Cl} = 0.98\text{‰}$  to  $1.61\text{‰}$ ). In contrast, biotite from the Archean country rocks ( $\delta^{37}\text{Cl} = -0.88$  to  $-0.53\text{‰}$ ) and associated groundwater are <sup>37</sup>Cl-depleted.

The results of this study lead to two important conclusions concerning genetic and exploration models for the footwall ore zones. First, early magmatic fluids introduced into the footwall contained very little Cu (<100 ppm), the main ore metal in footwall ore deposits. This result is in contradiction with existing hydrothermal models for footwall ore formation that hypothesize that Cu and other ore metals were remobilized from sulfide deposits along the SIC contact by saline fluids and redeposited in the footwall. Rather, the data presented here supports the emplacement of sulfide liquids as the main mechanism of footwall ore development. Second, although stable Cl isotope and fluid inclusion analyses confirm that magmatic fluid was introduced into the footwall, this magmatic end-member fluid was common to both mineralized and barren segments of the footwall. Therefore, detection of this magmatic component alone will not serve as a useful exploration method for sulfide deposits. In contrast, mapping the distribution and abundance of the footwall granophyre rock type may be ore-predictive since its emplacement and higher abundance in mineralized areas appears to have been a structural and textural prerequisite for footwall ore development.

## METAL FLUXES TO THE ARCHEAN OCEANS

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Estimates of crustal heat flow in the Archean oceans range from 2 to 3 times present-day values, with far greater numbers of tectonic plates and correspondingly greater ridge lengths (8 to 27 times present-day mid-ocean ridges). Heat loss to the oceans by hydrothermal convection along these ridges was at least an order of magnitude greater than it is today. In addition, increased ocean temperatures would have required a significantly larger flux of seawater to cool new crust forming at the ridges. However, the

quantitative implications of an early hotter Earth for the metal endowment of the Archean oceans have not been considered in detail. The total ridge length in today's oceans is 89,000 km (including back-arc spreading centres). Axial hydrothermal circulation is sufficient to circulate the entire volume of the world's oceans through the ridges every  $\sim 10^6$  years. Archean oceans would have been cycled through the crust  $\sim 10$  times faster, resulting in correspondingly greater mass transfer and an essentially mantle-buffered ocean. The flux of high-temperature 350°C fluids today is estimated to be  $5 \times 10^{12}$  kg/yr, carrying  $\sim 1 \times 10^9$  kg/yr of metals and sulfur to the seafloor. In the Archean oceans, global fluxes of metals and sulfur would have been on the order of 10 million tonnes per year. This is likely a minimum estimate, as the higher salinities of Archean seawater (2-3 times present-day seawater) would have greatly increased the capacity of the fluids to leach and transport metals. Today's mid-ocean ridges are estimated to host  $\sim 1,000$  active vent sites, each with a mass flux equivalent to about 100 black smokers. The total amount of massive sulfide deposited in the neovolcanic zones (<1 m.y.) is estimated to be on the order of 600 Mt, containing about 30 Mt Cu+Zn. If present-day rates of massive sulfide formation on the ridges can be extrapolated to the Archean, then significantly more metal must have been accumulating on the Archean seafloor. Assuming that the total ridge length or axial hydrothermal flow was 10 times greater, as many as 10,000 deposits of comparable size, or  $\sim 6$  Gt of massive sulfide, could have been present along the neovolcanic zones of Archean ridges. These observations have potentially important implications for understanding the metal endowment of the Archean crust.

## NEW GEOLOGICAL EVIDENCE SUPPORTING A METEORITE IMPACT ORIGIN FOR PASFIELD LAKE IN THE EASTERN ATHABASCA BASIN, NORTHERN SASKATCHEWAN, CANADA

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Recently obtained geological evidence supports a meteorite impact origin for Pasfield Lake, a large oval-shaped lake, 27 km long by 13 km wide and up to 120 m deep, located in the eastern Athabasca Basin of northern Saskatchewan. A meteorite impact origin has been postulated for some 30 years based on: (a) the roughly circular shape of the main body of Pasfield Lake; (b) discontinuous arcuate highland ridges and concentric and radial lineament patterns surrounding the lake; and (c) estimates of shallow basement beneath the lake by Geological Survey of Canada geophysicists in 1969. Triex Minerals Corporation operated a Joint Venture uranium exploration program at Pasfield with Thelon Ventures Corporation between 2005 and 2009. Airborne VTEM and gravity surveys refined coincident, 8 to 10 km diameter, roughly circular, but complexly zoned magnetic and gravity features centered on Pasfield. Follow-up ground ATM surveys across Pasfield, over two consecutive winters, provide evidence for a complexly uplifted basement block below the lake. The first three diamond drillholes in the region, in over 25 years, successfully intersected basement gneisses beneath the lake at 300 m depth, at least 600 m above the regional basement depth of 900 m. These holes did not intersect Athabasca Group sandstone, nor any pre-Athabasca basement regolith, indicating total destruction of at least 900 m of Athabasca sediments, plus an unknown amount of basement rocks. This is reconciled by a major meteorite impact having a central rebound structure. Up to 200 m of poorly consolidated mudstone and unconsolidated sand and gravel overlie the basement and are

inferred to be post-impact crater-fill sediments. Furthermore, the drillholes intersected black, glassy vesicular dykes and green, alkaline, matrix-supported breccias within the gneisses. Petrographic analyses identifies these rocks as impact melt rocks and impact-induced breccias based on features such as: (a) multiple sets of deformation lamellae in quartz; (b) ballen-textured quartz; (c) glasses formed from melting of different minerals; (d) vesiculation of various minerals; and (e) glassy matrices in both rocks. Geological mapping along the eastern side of Pasfield has identified parts of the uplifted crater rim, with sandstone outcrops dipping concentrically away from the lake. The mouths of several canyons excavated into Athabasca sandstones, approximately 4 km from the lake shore, are interpreted as part of the crater wall or one of the 'steps' of the crater margin. Considerable work is still needed to refine and bolster the impact model for Pasfield. Diamond drilling will provide the most specific data toward the model, as will surface mapping, structural studies, geochemistry, and hydrogeology to name a few.

#### **A REMOTE PREDICTIVE MAPPING (RPM) PRODUCT FOR CENTRAL BAFFIN ISLAND AND THE HALL PENINSULA: AN EVOLVING METHODOLOGY FOR MAPPING SURFICIAL MATERIALS OF ARCTIC CANADA**

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The Remote Predictive Mapping (RPM) project which forms part of the Geological Survey of Canada's Geo-mapping for Energy and Minerals (GEM) program is developing protocols for producing surficial material maps of large portions of the Canadian Arctic that are not well-mapped. Using Landsat and DEM data, a large area of central Baffin Island and the Hall Peninsula has been mapped. These maps will contribute to infilling "grey space areas" assisting the Tri-Territorial compilation of surficial geology maps, an ongoing project also under the GEM program.

Central Baffin is a rugged area extending over 600 km from the Labrador Sea to the Foxe Basin and 300 km from the Frobisher Upands in the south to the Baffin Upands to the north. Physiographically it consists of the Precambrian crystalline Hall uplands of the Hall Peninsula in the east and low lying Carbonates of the Foxe Basin Lowlands in the west. Surficial deposits across the Hall Uplands are generally thin and predominantly till. In the eastern Hall Peninsula there are a number of small glaciers, the largest of which covers <300 km<sup>2</sup>; to the west, surficial deposits are predominantly carbonate-derived till, and marine sand and fine grained sediments.

The predictive mapping methodology is based on a supervised classification approach utilizing defined training areas of typical surficial materials identified on the basis of airphoto interpretation and fieldwork. Preliminary modeling of the area uses Landsat, MERIS and SPOT satellite imagery together with a digital elevation model (DEM) and associated surface derivatives. As the resulting predictive maps are based on remotely sensed imagery, accompanying maps showing the certainty of the classification are also produced using a Monte Carlo technique (Iterative Classification Method (ICM)) to bracket both statistical and spatial uncertainty associated with the classification process. Work is also ongoing to evaluate the relative importance of each of the various imagery bands and DEM derivatives using a statistical regression tree approach to optimize the accuracy and efficiency of the classification routine. The eventual aim is to develop a standardized method for producing preliminary predictive surficial geology

maps where required, thus facilitating regional exploration activity and infrastructure development throughout Canada's North.

#### **A STATUS REPORT ON HYPERSPECTRAL REMOTE SENSING FOR NORTHERN GEOLOGICAL MAPPING AND MINERAL EXPLORATION**

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Spectral methods have been shown to be highly effective in mapping lithologies and in recognizing and delineating zones of hydrothermally altered rocks that are spatially and temporally related to mineralization. However most of the research on the efficacy of hyperspectral survey data for mapping and exploration has been carried out in hot arid and desert terrains; to date, there are relatively few case studies from Canada's cold north above the tree-line. Over the past decade several airborne surveys have been flown over parts of Canada's North in various geologic terranes. This paper summarizes the research that has been undertaken to date by Natural Resources Canada with respect to the application of hyperspectral imagery to geological mapping and exploration.

Along the coast of Baffin Island various lithologies including carbonates, metasediments and metatonalites have been spectrally mapped and differentiated. Coastal areas within the Slave province (Hope Bay) show great promise for detecting and mapping alteration mineral associated with orogenic gold mineralization, whereas inland areas including Hackett River and Izok Lake present challenging environments for detecting alteration minerals associated with VMS deposits, excepting the delineation of iron oxide-dominated gossans.

Preliminary analysis of the data indicates that certain lithologies and alteration styles can be recognized and mapped, but lichen cover which approaches 100% in some inland areas of the North, seriously impedes the extraction of diagnostic spectra from the airborne hyperspectral data. Thus, to advance the application of hyperspectral data for exploration and mapping in Northern environments requires a more quantitative understanding of the spectral characteristics of surface constituents. This includes furthering understanding of the impacts of weathering styles of the various lithologies in cold environments, the nature and quantity of vegetative cover, and the relationships between these surface components with the underlying and exposed bedrock. We are presently undertaking quantitative experiments which will reveal to what degree lichen impedes the spectral recognition of various alteration minerals associated with VMS and gold environments.

#### **SPATIO-TEMPORAL CHARACTERIZATION OF THE DENSITY OF WASTE IN A BIOREACTOR LANDFILL VIA MICROGRAVITY SURVEYS**

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The density to which waste is compressed in a bioreactor landfill is critical to the survival of fuel producing bacteria. Maximum compaction minimizes the landfill footprint; however, it might not provide the optimal environmental conditions for bacteria development. This research project pilots the use of repeated microgravity surveys to map the density of waste in a bioreactor landfill. The goal is to relate density changes to compaction effort and waste settlement.

Over the duration of 2 to 3 years, several microgravity surveys will be conducted on a new cell at the bioreactor landfill in Sainte-Sophie, Quebec as it is gradually filled with waste up to a height of 25 m. Thus far, two surveys have been conducted in the

cell over an area of approximately 70 m by 275 m. The first survey was completed in July 2009 when the cell contained no waste. The second survey was performed in June 2010 over a thickness of waste of approximately 5 m. A third survey is planned for March 2011 when the waste thickness will have reached approximately 14 m. Several sensors, including a settlement gauge, have been installed in the waste column in the same area, providing additional data.

During placement, machinery is used to compact the waste. Assuming a density of 0.8 Mg/m<sup>3</sup> for fresh waste, numerical modeling has provided estimates of the magnitude of the gravity anomalies to be expected for several compaction scenarios. Anomalies between successive layers of waste should be on the order of 1 mgal, while the microgravity method is capable of a precision on the order of 10<sup>-2</sup> mgal. Surveying in an operating landfill, however, is very challenging due to the presence of machinery, and uneven and soft ground conditions.

At the microgravity scale, several corrections need to be applied to obtain accurate results. The most important is the free-air correction to remove the gravitational effect of elevation above the datum, which is, in this case, the cell floor. In order for this correction to be applied correctly, the gravity data are geo-referenced using differential GPS – elevation being the most sensitive coordinate recorded. Other corrections include instrument drift, the Bouguer correction for excess mass above the datum, and tidal corrections to account for the gravitational pull of celestial bodies.

#### **METALLOGENY AND MINERALIZATION IN ARASBARAN COPPER BELT**

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The Arasbaran Metallogenic Belt, straddling the Iran-Armenia border (NW of Iran) between 46° to 47°.50' E and 38°-39° N (Iranian part and the study area) is one of the most significant porphyry copper and epithermal gold deposits in Iran. It was formed on Cenozoic magmatic arc in southern margin of Lesser Caucasus. According to this research, tectonic and magmatic evolutions in this area differ from Urmia-Dokhtar Volcanoplutonic Belt. The zone containing of Sungun and some other deposits is one of the important porphyry copper and epithermal gold regions in the Alpine Copper Belt.

The geology of the district is dominated by the Upper Eocene to Upper Pliocene calc-alkaline volcanic and volcano-sedimentary succession overlying on the Cretaceous basement that consists of predominantly limestones, pyroclastic and metamorphic rocks. Commencing and evolving of tectonics and subduction events during Lower Paleocene lead to the occurrence of vast magmatic activity in the Arasbaran zone. The magmatic arc activities, which had been started from Late Cretaceous to Paleocene in an active continental margin with calc-alkaline-tholeiitic like affinity in a thin continental crust and close to assumed trench of Meso-Tethys continued during Late Eocene in the form of shoshonitic volcanism. Continental crust components had great influence on changing the composition of source rock (amphibole-bearing peridotite lherzolite in the Paleocene to phlogopite and garnet-bearing peridotite in the Oligocene) of parent magma. During Oligocene, this area became the arena for the formation and emplacement of various and wide granitoids with medium to high-K calc-alkaline affinity. Some of these granitoids that have formed in final stages of tectonic and magmatic evolutions are the 46-40 Ma Ordoubad intrusive unit (northwest of the arc) consisting of diorites and granodiorites, the 30-26 Ma Shayvar and Ahar intrusive units (east and southeast of the arc) including in granites and monzonites, the 27-20 Ma Sungun and Haftcheshmeh shallow depth intrusions (center to northwest of the arc) containing of diorite and granodi-

orites, and the 10-9 Ma Mivehroud, Mazraeh and Anjerd intrusive units consisting of diorites and micro granites.

After Paleogene to Early Oligocene, the governing of compressional tectonic regime and the intrusion of basaltic magma deriving from mantle of long-lived subduction zone formed a thick crust (45-50 km) with garnet-bearing amphibolite rocks at the base of the arc. After finishing subduction, because of the existence of thick crust, dehydration of amphibole in high temperatures and pressures and dehydration of detached fragments of subducted slab (heat and water contents resulted from base amphibolites) caused partial melting of rocks. Adakite-like subvolcanic bodies such as Sungun, Haftcheshmeh, Kighal, Astamal, Shallou and Niaz are generated from this process in a MASH zone. Major porphyry copper mineralization has appeared with subvolcanic bodies in Early Miocene.

#### **THE CONTINENTAL SHELF PROJECT OF THE KINGDOM OF DENMARK: THE CONTINENTAL SHELF OF THE FAROE ISLANDS**

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The outer continental shelf north of the Faroe Islands is bound by the 200 nautical miles distance lines of the Faroe Islands, Iceland, Jan Mayen and the mainland of Norway. Issues regarding overlapping claims were agreed upon between the relevant States prior to the continental shelf submissions to the Commission on the Limits of the Continental Shelf, which were made in November 2006 by Norway and in April 2009 by Iceland and Denmark/Faroes, respectively.

The Northern Continental Margin of the Faroe Islands is characterized by a number of ridges and elevated seafloor highs that extend seaward from the shelf and slope region. The most pronounced of these seafloor highs are the plume related Faroe-Iceland Ridge and the extinct Ægir spreading ridge, the latter protruding well beyond the 200 nautical miles distance line from the baselines of the Faroe Islands. The Danish/Faroese partial submission in this region documents an outer continental shelf of ~90,000 km<sup>2</sup>. The partial submission is a result of several years of work involving acquisition, processing and interpretation of bathymetric and seismic data, etc. A Danish/Faroese task force was established in 2008 under joint chairmanship of Jardfeingi and GEUS with the purpose of preparing and finalizing all the submission documents.

In December 2010 Denmark/Faroes submitted a second partial submission to the Commission covering ~608,000 km<sup>2</sup> of seabed of the Faroe-Rockall Plateau Region to the south-west of the Faroe Islands. The area is limited by the 200 nautical miles distance lines of the Faroe Islands, Iceland, the United Kingdom and Ireland, respectively, and the neighbouring coastal States have overlapping claims to parts of the Faroe-Rockall Plateau Region. Ireland and the United Kingdom submitted their claims to the Commission in March 2009, whereas Iceland has still not submitted its claim with regard to parts of the same area. Issues regarding overlapping claims are still subject to discussion between all four States.

In plate tectonic terms, the Faroe-Rockall Plateau is a continental fragment formed during breakup of the Pangaea. The land mass of the Faroe Islands and its submerged prolongation throughout the Faroe-Rockall Plateau Region is by and large volcanic with an underlying deep-seated continental crust. Another distinct geomorphological and geological feature of the Southern Continental Margin of the Faroe Islands is a continuous rim of contourite drifts along the entire middle and lower slope regions of the Plateau.

Challenges with respect to the outer continental shelf claims of the Faroe Islands include ridge issues and the application of the constraint formulae of the United Nations Convention on the Law of the Sea, namely Article 76 (5-6), in addition to issues related to the identification of the applicable base of the continental slope in geomorphological environments which are characterized by different slope-related processes.

#### **THE SOUTH BARNAT ZONE, CANADIAN MALARTIC DEPOSIT QUÉBEC: AN INTRUSION-RELATED GOLD SYSTEM?**

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The Canadian Malartic deposit in Abitibi's prolific greenstone belt represents one of the largest gold resources in Canada at 9.2 million ounces gold. Contributing to the resource is the South Barnat zone (42.5 Mt at 1.64 g/t Au), the eastern extension of the 3000 m long east-west striking Canadian Malartic mineralized system, along the southern edge of the Cadillac-Larder Lake tectonic zone. An Au-porphyry exploration model was adopted based on voluminous, low-grade, disseminated gold mineralization accompanied by widespread potassic alteration and an associated felsic to intermediate porphyry intrusion. However, structurally controlled alteration and a metal signature deficient in base metals (but enriched in Bi-Te-W in addition to Au) may be more consistent with an intrusion-related model.

Five hydrothermal assemblages characterize the system at South Barnat: (1) pre-mineralization; (2) main ore stage; (3) late ore stage; (4) remobilization; and (5) late stage veining. In the early and main stages, potassic metasomatism is the most important alteration type and is intimately associated with gold mineralization. Gold mineralization (mainly native gold; gold tellurides are also present) is found in and around quartz-pyrite-carbonate veinlets with biotite  $\pm$  K-feldspar alteration haloes. It occurs most commonly near vein margins, as inclusions in pyrite, and at pyrite-pyrite and pyrite-silicate grain contacts. Locally, it is present as inclusions in K-feldspar and amphibole. Sulphur isotopic compositions of pyrite ( $\delta^{34}\text{S}_{\text{pyrite}}$  and  $\Delta^{33}\text{S}_{\text{pyrite}}$  data) in the porphyritic rocks are isotopically distinct from those of pyrite in the ultramafic rocks (higher  $\delta^{34}\text{S}_{\text{pyrite}}$ ) and overlap completely with those of pyrite in the greywackes.

The above relationships, coupled with preliminary thermodynamic modeling, suggest intermediate oxygen fugacity and near-neutral to higher pH conditions of mineralization (assuming  $T = 350^\circ\text{C}$ ,  $P = 500$  bars,  $a_{\Sigma\text{S}(\text{aq})} = 0.1$ ). These conditions are consistent with the high fineness ( $(\text{Au}/\text{Au}+\text{Ag}) \times 1000$ ) of native gold (836-944), which is inferred to have precipitated at conditions near the aqueous sulphide-sulphate predominance boundary; silver dissolves predominantly as chloride complexes, which are not stable at these conditions. A model is presented in which sulphur-bearing auriferous fluids exsolved from felsic magmas were buffered to near neutral pH by the porphyries and greywackes and to higher pH by the ultramafic rocks. This interaction led to differential fractionation of the magmatic sulphur and deposition of isotopically heavier sulphur in pyrite hosted by the ultramafic rocks. Ore deposition resulted from sulphidation of the host rocks, which caused destabilization of aqueous gold bisulphide species, leading to the precipitation of native gold.

#### **HYDROGEN ISOTOPE AND TRACE-ELEMENT SIGNATURES IN AMPHIBOLE AND BIOTITE FROM THE STRONTIAN GRANITE, SCOTLAND**

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The trace-element and D/H isotope signatures have been examined in strongly zoned amphibole and unzoned biotite crystals from the Strontian granite in the south-west Highlands of Scotland. The Strontian granite is most famously associated with minerals such as strontianite and others from which the element strontium was first isolated. The intrusion is a large composite body consisting of an earlier phase with two lithologies (tonalite and granodiorite) and a later biotite granite. In addition, the pluton are cross-cut by appenite intrusions, probably of late-Caledonian age, and a considerable number of dolerite dykes likely both Carboniferous and Tertiary in age. The intrusion is generally thought to have been emplaced at ca. 425 Ma (U-Pb age of zircon) into a splay of the Great Glen fault and is late-tectonic. The currently accepted model for magma formation of this and other late-Caledonian intrusions involves slab break-off and upwelling of mantle creating both mafic and crustal melts. The Strontian pluton is clearly hybrid and composite in nature and also locally displays mafic enclaves suggesting several phases of magma mixing which supports this theory. In order to investigate this further we have examined the trace-element and D/H isotope composition of several large hornblende crystals. These are commonly zoned and have therefore recorded both a record of both chemical and potentially fluid fluctuations during crystallization of the intrusion. In general, incompatible trace-elements such as REE, and HFSE were considered likely to be relatively immobile whereas the D/H isotopes were assumed to have re-equilibrated with later fluids. A micro-mill was employed to extract small volumes from these crystals from core to rim to allow the zonation to be examined. Aliquots were then run for D/H isotopes and trace-elements from these samples. Interestingly, the results suggest a strong correlation between both the D/H isotopic composition (and thus the magmatic fluid evolution) of these crystals and their trace-elements signatures. These data both suggest an initial mantle magmatic signature being overprinted by more evolved crustal signatures. On the other hand, biotite crystals have clearly equilibrated with later stage fluids and have non-distinctive trace-element signatures. Detailed results will be presented and discussed.

#### **THE NASHOBA TERRANE OF SE NEW ENGLAND: RECENT FINDINGS ON ITS ORIGIN AND EVOLUTION**

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The fault-bounded Nashoba terrane lies on the eastern side of the Appalachian Orogen in SE New England along the boundary between the Avalonian and Ganderian terranes. It consists largely of a series of mafic volcanic (Marlboro Fm.) and sedimentary (Nashoba Fm.) rocks, now metamorphosed to the mid- to upper amphibolite facies and intruded by an extensive suite of mid-Paleozoic plutons of granitic and calc-alkaline intermediate composition. New U-Pb data on metamorphic zircons is consistent with the electron microprobe monazite dates of Stroud et al. (2009), and indicates that the terrane experienced at least four periods of metamorphism between ca. 420 Ma and ca. 330 Ma.

Trace element geochemistry of the oldest volcanic rocks indicates the terrane formed in an arc/back-arc setting. These results are supported by recently determined initial  $\epsilon_{\text{Nd}}$  values for these rocks that range from +4 to +7.5. The mafic volcanic rocks plot close to the Nd depleted mantle evolution curve, indicating little crustal contamination in the basaltic melts at this time. However, initial  $\epsilon_{\text{Nd}}$  values ranging from -0.75 to +1.16 and TDM ages of

1.2–1.5 Ga for the intermediate and felsic rocks from this period reflect the incorporation of older, isotopically evolved crustal material.

The youngest detrital zircons found in metasedimentary units associated with the oldest volcanic rocks (Marboro Fm.) are ca. 480–470 Ma, indicating a Cambrian–early Ordovician age for the terrane, since it is cut by granitic plutons at ca. 450 Ma. While the youngest detrital zircons (in the Nashoba Fm.) of the terrane are ca. 440–450 Ma, all the metasedimentary units contain zircons with an approximate continuum of ages throughout the Neoproterozoic and Mesoproterozoic with some mid-Paleoproterozoic and rare Archean grains. Furthermore, these same units have Sm/Nd depleted mantle model ages of ca. 1.6–1.7 Ga, also reflecting older source material input.

Both the detrital zircon suites and the Sm/Nd depleted model ages of the Nashoba terrane are more consistent with those found in Ganderia than those in Avalonia. We therefore infer that the Nashoba terrane represents a southward continuation of arc systems found to the north in Ganderia, such as perhaps the Popelogan–Victoria arc.

#### **ASTROMATERIALS RESEARCH IN CANADA: MOVING FORWARD**

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Astromaterials are defined as solid samples of other planetary bodies in the Solar System, including meteorites from asteroids, the Moon and Mars, and samples returned by robotic and human missions. The major public meteorite collections in Canada comprise an estimated 6000 specimens of 1500 meteorites from around the world (Herd, R.K. et al. 2008, LPSC #2241). Most of the range of meteorite types is represented within these collections, including HED type meteorites (derived from the asteroid 4 Vesta), the unique Tagish Lake carbonaceous chondrite, the main masses of several meteorites from the Moon and Mars, and the bulk of the specimens of major Canadian meteorite falls. As such, Canada is home to a remarkable assemblage of planetary materials that provide unique research opportunities. Research in this area is growing, as evidenced by an increase in the number of presentations on astromaterials at GAC-MAC meetings within the past several years, especially by students. Researchers are realizing the benefits of access to these specimens in increasing our fundamental understanding of the origin and evolution of our Solar System.

What greater benefit can and should astromaterials have for Canadian science? Arguments have been made about how astromaterials can support space exploration efforts (e.g. Herd, R.K. et al., 2008, LPSC #2241). This is particularly true as Solar System sample return missions increase in scope and diversity, and meteorites are used in support of ongoing or upcoming missions (e.g. HED meteorites for DAWN at Vesta, Martian meteorites, etc.) and in order to learn best practices in curation and handling (e.g. Herd, C.D.K. et al., 2010, GeoCanada). Astromaterials research can also drive technological advancement – the analysis of astromaterials often requires that special handling needs are met, and the analytical methods often require specialized approaches. Establishing these in a given lab can expand the lab's capabilities and the expertise of the lab researchers.

Where do we go from here? In 2009, the Astromaterials Discipline Working Group of the Canadian Space Agency outlined the major needs of the Astromaterials community in a White Paper entitled, Preparing Canada for Astromaterial Sample Return. The needs of the community remain. A modest amount of support with the objectives of increasing access to collections, enabling the use of existing analytical instrumentation through travel and analytical

costs, and training of HQP would significantly grow the Astromaterials community, to the benefit of planetary research in Canada.

#### **ON THE PETROLOGY OF CHONDRULES AND CHONDRITES: INSIGHTS FROM DETAILED SYSTEMATIC PETROGRAPHY**

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Chondrites are the most common type of stony meteorites, made up at least in part of spherical chondrules or fragments of them. Yet they are complex to study and astromaterials researchers avoid them. Chondrules consist of varying proportions of silicates (olivine, pyroxenes, feldspar, and their alterations), oxides, sulphides, phosphates, metals and other compounds. They date at least from the earliest origins of our Solar System. Both observational and theoretical research indicates that the components of chondrites are derived from multiple sources of different ages; some may be older than our Solar System. Chondrules, even those in the same chondrite, may have been produced by many different processes over millions or billions of years, e.g., by Solar System processes that modify and re-modify pre-Solar components. They show textural evidence of repeated multi-stage processing including melting, quenching, slow cooling and annealing. Deciphering the processes that formed different chondrules may allow those with similar origins to be identified, in the same chondrite or in different chondrites, even in chondrites of different classifications or grades.

A systematic petrographic approach, using scanning-electron microscope (SEM) images of chondrules in ordinary chondrites, allows observers to record the mineralogy and textures, and while doing so to consider the possible origin, of each chondrule. Textures are described as megacrystic, macrocrystic, or microcrystic (for the relatively largest to smallest chondrule contents), and nanocrystic or cryptocrystic (for the smallest phases or mesocrysts in the chondrule mesostasis). Each chondrule may therefore have up to 5 associated size groups within which its major and minor phases occur and recur. Crystal habit (e.g. elongate, equant; angular, rounded) and inter-relationships within and among the phases and size groups (e.g. zoning, overgrowths) are observed. A notation system records the observations and effectively classifies each chondrule based on the mineralogy and textures of its size groups and their relationships, without assumptions about chondrule chemistry or origin(s). Chondrules with the same classification, i.e., size group sequence of mineralogy and textures, may have undergone the same processes and be of similar origins. Those with different classifications under this new system probably do not have similar origins, even though they are grouped together by existing traditional classification systems.

#### **NON-DESTRUCTIVE STUDIES ON PRISTINE SAMPLES OF THE BUZZARD COULEE METEORITE**

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The National Meteorite Collection of Canada has obtained 18 individual fragments of Buzzard Coulee, an H4 chondrite that fell with an accompanying spectacular fireball, south of Lloydminster, Saskatchewan on the evening of November 20, 2008. The masses range over an order of magnitude from 109.14 g to 8.80 g. Most are fully to almost-fully crusted and were collected within three weeks of the fall event, before the winter of 2008–9. Most were purchased with the assistance of a Movable Cultural Property



grant accorded by the Department of Canadian Heritage under the terms of the Cultural Property Export and Import Act.

In the interest of documenting these samples in their original condition, and studying them as excellent representatives of variable mass of the same meteorite fall, they are being characterized using a number of non-destructive techniques. Each was weighed and photographed upon acquisition, and the laboratory work has been tracked with checks on weights and with photographs at all stages. Here we report the results from measurements of bulk volume and density (by silica beads and 3D laser imaging), grain volume, grain density and porosity (by helium pycnometry), magnetic susceptibility (by two different methods) and from X-ray micro-CT scans.

These studies define a methodology for preliminary examination of new meteorite falls and finds, or of specimens from sample return missions to space. Digitized data is preserved on samples for archival and curatorial purposes, and can be used to select subsets of them for further research. Variations in their physical properties may be linked to internal variations such as concentrations of metallic minerals or zones of shock. The micro-CT scans in particular may be used to select portions of the meteorites where polished thin-sections would yield critical details of mineralogy and texture.

#### THE DISPERSION OF $^{129}\text{I}$ IN THE NORTHWEST CANADIAN ARCTIC AND SOUTHERN CANADA

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Nuclear fuel reprocessing has released large amounts of anthropogenic  $^{129}\text{I}$  in a number of specific locations, which has led to an increase in the concentration of  $^{129}\text{I}$  and its  $^{129}\text{I}/^{127}\text{I}$  ratio in the environment. As a biophilic and mobile radionuclide,  $^{129}\text{I}$  is a major contaminant of concern for long term radioactive waste storage. Therefore, a detailed understanding of its movement and concentration in the environment is essential. The Arctic has been identified as a location that may be affected by  $^{129}\text{I}$  fallout from fuel reprocessing in Europe and Asia. A comparison of  $^{129}\text{I}$  concentrations between Arctic watersheds and water from southern Canada is a valuable tool to judge the amount of contamination in both environments. The most likely source of anthropogenic  $^{129}\text{I}$  in southern Canada is atmospheric fallout from the nuclear fuel reprocessing facility in West Valley, NY that closed in 1972. Water samples from large watersheds were collected in the Yukon Territory, Canada starting in Whitehorse (60°43'00"N) and moving north to Tsiigehtchic, Northwest Territory (67°26'26"N). Water samples were also collected in southern Canada at 18 locations from New Brunswick to Saskatchewan. The results have shown that values of iodine up to  $27 \times 10^6$  atoms/L are present in north-west Canada. These quantities substantially exceed literature values for waters containing only geogenic or cosmogenic production. This implies that the contribution of anthropogenic  $^{129}\text{I}$  in the Arctic is significant. However, these values are up to five times lower than the levels found in southern Canada, where values reaching  $196 \times 10^6$  atoms/L were measured in southern Ontario. The large differences between the north and south suggest that the Arctic environment is still relatively unaffected compared with southern Canada but that human nuclear activities have caused  $^{129}\text{I}$  to become a very widespread contaminant.

#### THE FOSSIL RECORD OF VMS ASSOCIATED VENT FAUNA ASSEMBLAGES

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There are now at least 27 known fossiliferous volcanogenic massive sulphide (VMS) deposits ranging in age from the Ordovician to the Eocene. The oldest and most productive for finding fossil fauna are VMS deposits found in the Ordovician to Devonian oceanic arc sequences of the Uralides. Other productive regions include the Mesozoic Tethyan ophiolite belt through Cyprus, Georgia and Oman; the Pontide belt in Turkey; the Jurassic of North America and Mesozoic to Tertiary volcanic arcs of the Pacific. The deposits contain a range of fossils including inarticulate and rhynchonellid brachiopods; gastropod, bivalve and monoplacophoran molluscs; and a small diversity of worm tube morphologies, some of which are attributed to alvinellid polychaetes and vestimentiferans. Physical traces of bacteria are also found in both the sulfides and associated hydrothermal sediments. The fossils are largely preserved as external moulds composed of sulfides consistent with the biomineralization processes that have been observed at modern hydrothermal vent sites. These data are confirmation that the seafloor environments around ancient VMS systems were similar to those measured in active deep-ocean systems today and so there have been no systematic changes in these parameters through geological time. Most of the discovered fossil taxa found in VMS assemblages are new to science. However, the lack of original shells and organic tubes makes phylogenetic classification difficult. Yet it is clear that by comparing fossil vent assemblages with modern vent communities, vestimentiferans, alvinellid polychaetes, bivalves, gastropods, monoplacophorans and perhaps brachiopods are shared between the sites at higher taxonomic levels. The lack of direct ancestor-descendant relationships between the fossil and modern vent molluscs and brachiopods shows that modern vent sites are not refuges for known Paleozoic and Mesozoic shelly vent taxa. It follows that taxonomic groups have moved in and out of vent ecosystems through time. Further work also shows that deep sea vent and seep communities have not been affected by some of the deep-sea anoxic/dysoxic events casting doubt on the proposed global extent of some of these.

#### ICE-PROXIMAL LABRADOR SEA HEINRICH LAYERS: A SEDIMENTOLOGICAL APPROACH

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During Late Pleistocene Heinrich events distinct, decimetre to centimetre thick layers of ice-rafted debris (IRD) were deposited in North Atlantic that are characterized by high detrital carbonate concentration, low foraminifera content, a high percentage of *Neogloboquadrina pachyderma* (sinistral) among the planktonic foraminifera, high magnetic susceptibility and high grey colour values. In the Labrador Sea, Heinrich layers (H-layers) reach meter thickness in some proximal core sites near the iceberg source off the Hudson Strait ice stream (HSIS) and show low magnetic susceptibility and low grey levels on the colour scale. The great thickness of ice-proximal Labrador Sea H-layers is due to the supply of vast amounts of terrigenous sediments eroded from the country rocks underlying the north-eastern sector of the Laurentide Ice Sheet (LIS) and transported to the deep-sea by processes much more efficient than ice rafting involving sediment lofting and low-density turbidity currents. Four distinct depositional facies termed Heinrich layers type I to IV have been differentiated: Type I H-layers occur within 300 km from the presumed

Hudson Strait Ice Stream terminus and consist of stacked thin layers of graded muds containing IRD. The graded muds spiked with IRD resulted from the deposition of fine-grained lofted sediment that collected dropstones and –grains under the iceberg route. Type II H-layers on the levees of tributary canyons to the Northwest Atlantic Mid-Ocean Channel (NAMOC) occur at greater distance from the Hudson Strait outlet on the slope and rise south of the strait. They consist of alternations of thin mud turbidites with intercalated laminae of IRD. Type III H-layers on the levees of NAMOC consist of layers of IRD alternating with fewer fine-grained spill-over turbidites, reflecting the lower spill-over frequency from the deep channel compared to the less deep slope canyons. Type IV is made up of bioturbated hemipelagic muds with coarser IRD and occurs in regions between canyons not reached by spill-over turbidity currents and in the distal open ocean or on seamounts. Transport of significant portions of the sediment in H-layers by suspended sediment columns lofted from sand-carrying fresh-water turbidity currents (type I) and by low-density turbidity currents (types II and III) explains the anomalously great thickness of individual H-layers on the slope and rise off the Hudson Strait. Isopach maps for H-layers 1-3 give hints on the drift routes of the lofted suspended sediment during its ascent to the surface and on iceberg drift directions in the Labrador Sea.

#### **OXYGENATION OF THE ATMOSPHERE AND UNCONFORMITY-RELATED URANIUM MINERALIZATION**

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The Great Oxidation Event (GOE) is one of the most profound expressions of co-evolution between the geosphere and biosphere the Earth has ever experienced. The GOE occurred between ca. 2.3 and 2.4 Ga and is thought to have been the result of cyanobacterial oxygenic photosynthesis. Although there is biomarker evidence for cyanobacteria as early as 2.9 Ga, recent molecular clock analyses suggest that a major diversification at ca. 2.4 Ga was likely a major contributor. The long lag between the advent of oxygenic photosynthesis and the onset of the GOE may also reflect a period of inertia where oxygen-consuming chemical reactions prevented the rise of photosynthetic oxygen.

Aside from the impact of the GOE on biological evolution, it was equally important in the evolution of mineral systems. Nowhere is this initial oxygenation of the Earth more important than in the development of unconformity-related uranium deposits. Unconformity-related uranium deposits are a direct consequence of Earth oxygenation because U is soluble under oxic conditions. What is poorly understood is their almost exclusive association with late Paleoproterozoic continental sedimentary basins, ca. 600 Ma after the oxygenation of the atmosphere, such as the Athabasca, Thelon, Komolgie, and Otish basins.

Oklo in Gabon (ca. 2.1 Ga) is currently the oldest known uranium deposit produced by flow of oxic groundwater, suggesting a ca. 200 Ma lag between the GOE and groundwater in sedimentary basins with enough oxygen to mobilize and transport uranium. This 200 million year interval may represent a period in which oxygen was consumed in oxidation of metals and bacterially-produced organic matter in sedimentary basins, but it may also reflect a period when tectonic conditions were not conducive to uranium mineralization.

We postulate that the GOE supplied enough oxygen to mobilize and concentrate U along stratigraphic surfaces, but since con-

tinental settings were devoid of plant matter (intra-basin reduction), Phanerozoic-style roll-front deposits could not form. Uranium was leached from detrital phases in basins and was carried in diagenetic aquifers and associated unconformities by oxygenated groundwater; mineralization occurred when U-bearing groundwater encountered reducing conditions. Understanding unconformity-related U mineralization in Paleoproterozoic basins highlights the interconnected role that oxygen, sedimentology, stratigraphy, and diagenesis played in creating these deposits. We present an integrated basin evolution model for Archean, Paleoproterozoic and Phanerozoic basins that highlights the relationship between oxygenation of the atmosphere and uranium mineralization, and provides a framework to evaluate basin uranium mineralization potential through time.

#### **INDICATOR MINERAL AND TILL GEOCHEMISTRY DISPERSAL FROM THE IZOK LAKE Zn-Cu-Pb-Ag VOLCANOGENIC MASSIVE SULPHIDE DEPOSIT, NUNAVUT**

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The application of indicator mineral methods to diamond exploration is well established and much research has concentrated on indicator mineral suites characteristic of diamondiferous kimberlites. VMS deposits also have a suite of representative indicator minerals, however, little research has been carried out to define which minerals may be useful to exploration in glaciated terrain and few indicator mineral case studies have been conducted down-ice of known VMS deposits. Queen's University, Minerals and Metals Group (MMG) and the Geological Survey of Canada's Geo-mapping for Energy and Minerals GEM (2008-2013) are examining the indicator minerals that characterize the Izok Lake Zn-Cu-Pb-Ag VMS deposit, Nunavut, and document the glacial dispersal of these minerals down-ice.

The Laurentide Ice Sheet sculpted the landscape of the Izok Lake area and deposited glacial sediments of varying thickness. Surficial geology of the region is dominated by a silty-sand till, which is an ideal sample medium for indicator mineral methods. The ice flow chronology of the Izok Lake area consists of an oldest ice flow towards 255°, a weak ice flow at 315°, a sustained ice flow at 292° which most of the landforms trend, and a rock polish east of the Iznogoudh Lake area which is a product of the youngest ice flow that trends at 318°.

Bedrock and till samples were collected around the Izok Lake deposit in 2009 and 2010. Petrology, Scanning Electron Microscopy, specifically using Mineral Liberation Analysis (MLA), and the Electron Microprobe, have all been used in the examination of indicator minerals and till geochemistry. A preliminary list of indicator minerals of the Izok Lake VMS deposit includes: chalcopyrite, sphalerite, galena, pyrite, pyrrhotite, gold, gahnite, spessartine, Mn-axinite and kyanite and these minerals show a SW and WNW dispersal. Aqua regia-Zn, Cu, Pb, Au, Fe, and Ag have been identified as pathfinder elements for the deposit in the <0.063 mm fraction of till. Pathfinder elements show a dispersal pattern ~8 km long trending towards the northwest.

#### **BEYOND CLASSICAL NUCLEATION: A CELLULAR AUTOMATA MODEL**

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The kinetics of crystal formation plays an essential role in the genesis of minerals in geochemical systems. The first step in the formation of a new phase in such a system is called nucleation. For

many years, the theoretical handling of nucleation has been described by Classical Nucleation Theory. Many authors have noted the necessity to move beyond one of its underlying assumptions (that the surface tension is uniform and equal to its bulk value) and to account for the complex geometrical structure of a nucleating cluster. In order to incorporate the kinks and corners of reality, we use a microscopic, particle-by-particle approach to simulate nucleation of a precipitating phase out of an aqueous solution. This Lattice Gas Automata model is implemented to demonstrate precipitate nucleation and growth in a 2-dimensional diffusion field on a fixed-directional grid. Input parameters include water particle-to-solid particle and solid particle-to-solid particle bond energies, initial concentration of particles in the system, temperature, and the proportion of next to nearest neighbour bonding interactions. The role of surface tension in the nucleation process is explored by varying the latter parameter. The growth rate of the new phase, the concentration field at the surface of the cluster, and the equilibrium concentration of the system have been investigated and found to compare favourably to analytical solutions. Data has been obtained for the nucleation rate and critical nucleus size for various supersaturations. A key benefit of this modeling approach lies in its generality and simplicity.

#### **THE SAINTE-SOPHIE DIABASE DYKE SWARM, CANADA – GEOLOGY, GEOCHEMISTRY AND PALAEOMAGNETISM**

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A small swarm of diabase dykes occurs about 50 km of Montreal near Ste Sophie, just northeast of St-Jerome. The presence of diabase dikes in this region was noted in 1960, but few details were published, except for a K-Ar age of 530 Ma. We have found about 20 dykes up to 5 m wide in an area of ~100 sq kms. Most dykes are approximately vertical and E-W. All dykes were vesicular, typically with 2-5% spherical vesicles 0.1-1 mm in diameter, and up to 10 mm for one dyke. Margins are always fine-grained and in one case glassy over 5 mm. Both these features suggest emplacement very close to the present surface. The most common phase is plagioclase, followed by olivine and, in one dyke, pyroxene. Crystals are generally millimetric, except for one dyke with plagioclase crystals to 12 mm long. Alteration is extensive: plagioclase is partly sericitised and olivine is converted to serpentine and magnetite. Zeolites and carbonate are developed in the vesicles and matrix. The much more extensive Grenville dyke swarm occurs just to the east and has the same general orientation. However, major element compositions of the Ste Sophie dykes are clearly distinct from those of the Grenville dykes: they have lower SiO<sub>2</sub> contents, 44-48%, and higher K<sub>2</sub>O contents, mostly around 1%. Two samples have exceptionally higher K<sub>2</sub>O contents around 6% and it is not clear if they form part of the same swarm. On a TAS diagram most of the dykes lie along the alkaline-subalkaline boundary. Paleomagnetic analysis gives both steep and shallow paleopoles with both polarities in each group. These results have been confirmed by baked contact tests showing that a primary magnetization is carried by magnetite. Such anomalous behaviour has been also seen in many other rocks of this age, but the origin is not clear.

#### **WHAT USEFUL TEXTURAL INFORMATION CAN BE OBTAINED FROM PHASE MAPS IN 2D AND 3D?**

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An important component of the texture (microstructure) of a rock is the geometrical arrangement of crystals and glass. A crystal map is a simplified representation in 2D or 3D of this, in which the nature and geometrical form of each individual crystal is distinguished. However, many analytical techniques do not clearly distinguish adjacent crystals and can only produce 2D or 3D phase maps in which contiguous crystals of the same phase are amalgamated (e.g. stained rock surfaces, X-Ray tomographic images). The question is: what textural parameters can be extracted from 2D and 3D phase maps? There are several stereologically exact parameters that can be determined 2D phase maps with any orientation even in rocks with a strong fabric. These parameters are determined by the placement of randomly orientated test lines and the measurement of intercepts (phase boundary intersections) and intersection lengths. The best known is the volumetric phase abundance, which can also be determined by point counting. Another important parameter that is easily determined from 2D maps is the surface area per unit volume (interface density, specific surface area). The fabric of a rock can also be quantified from 2D phase maps but three orthogonal sections are needed. Quantification is again in terms of intercept lengths, aggregated by orientation. The same method can be applied to 3D phase maps. Crystal size distributions (CSD) can be determined from 2D crystal maps using stereological methods and from 3D crystal maps by direct measurement. For phase maps, if the concentration of a phase is low, the crystals are homogeneously distributed in space and equant then the mean intercept length in 2D can be linked to the mean crystal size and can give some information on the CSD. In 3D under the same condition the CSD can be determined directly. However, as the abundance of the phase increases, or the crystals become clumped, the size information from intercept measurements become less precise and useful.

#### **MAGMATISM ASSOCIATED WITH THE OTTAWA-BONNECHERE GRABEN AND THE OVERALL IAPETUS LARGE IGNEOUS PROVINCE**

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The breakup of the supercontinent Rodinia at the end of the Neoproterozoic, more specifically the separation of Amazonia and Laurentia, is recorded by widespread magmatism in eastern North America. This magmatism has been termed the Iapetan Large Igneous Province (LIP), and includes that associated with the Ottawa-Bonnechere (O-B) graben. This LIP is somewhat abnormal as it extends over about 100 Ma, and some workers have subdivided it into 4 or 5 shorter events. The earliest manifestation of this event appears to be the emplacement of kimberlites in Central Quebec at about 630 Ma. Kimberlite emplacement continued until about 550 Ma, but there are none associated with the O-B graben. This was followed by diabase dike swarms, mostly from about 620 to 580 Ma. The Grenville swarm is one of the largest of these and was emplaced along the O-B graben at about 590 Ma. In the west it follows the O-B faults, but to the east it cuts the graben faults obliquely. Between 580 and 560 Ma a number of plutons were emplaced in eastern Laurentia, including those of the Callander Bay complex (ca. 577 Ma) in the O-B graben and the giant Sept Iles Intrusive Suite (564 Ma) in the St Lawrence rift. Flood basalts, now preserved in the Appalachian Mountains, were erupted between 560 and 550 Ma. It is likely that similar basalts also flowed to the north on the shield, but they have not been pre-

served. The final phase of magmatism at ca. 530 Ma is well represented in the eastern part of the O-B graben where it consists of two silicic intrusions, the Mont Rigaud and Chatham-Grenville plutons, and the minor Ste-Sophie dyke swarm. This dyke swarm is parallel to the earlier Grenville swarm, but compositionally different. The presence of vesicles and glassy margins attest to the high level of emplacement, hence it must have fed a flood basalt field that is now eroded.

#### **COLLISIONS, SLAB FAILURES, LARGE-SCALE STRIKE-SLIP TRANSLATIONS, AND MAGMATISM WITHIN THE CORDILLERAN OROGEN OF NORTH AMERICA**

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The currently accepted hypothesis for the development of the Cordillera in a Jurassic-Tertiary back arc setting is problematic because: (1) there is no evidence for deformation of the North American shelf from the Cambrian to Cretaceous; (2) there is a marked lack of latest Neoproterozoic-early Cambrian volcanic rift basins on the North American margin; (3) Mesoproterozoic metamorphism and deformation in rocks of the Belt-Purcell are unknown in cratonic northwestern North America; and (4) the presence of persistent mafic magmatism throughout much of the Paleozoic in rocks considered to represent parts of the passive margin, such as the Selwyn Basin, is difficult to reconcile with a passive margin setting, as is the presence within rocks of the Belt Supergroup and its Paleozoic cover, of a suite of 664-486 Ma alkaline plutons – one of which was deroofed during the Upper Cambrian.

Instead, the Cretaceous-Tertiary Cordilleran orogeny was likely caused by westerly-directed subduction of the western margin of North America beneath the composite arc-bearing superterrane of Rubia in a Philippine-type opposed subduction scheme. Eastward subduction along the western side of Rubia had started after the 159 Ma accretion of the Smartville arc-Coast Range ophiolite and a period of slab failure magmatism that led to the Independence dyke swarm and the bimodal, alkaline Ko Vaya plutonic suite.

Based on widespread deposition of intraplatformal gravels directly beneath the foredeep, the collision, which generated the Sevier-Rocky Mountain fold-thrust belt and its foreland basin, started at about 124 Ma. The collision was marked along the western side of Rubia by a sudden and voluminous influx of clastic debris into the trench.

At 80-75 Ma, terminal collision and cessation of subduction along both margins led to (1) shut down of arc magmatism, (2) exhumation of blueschists within accretionary complexes along the western side of Rubia, (3) a linear belt of slab-failure magmatism within the Sonora-Mojave region and the then adjacent Coast plutonic belt, (4) oblique northward migration of Rubia, concomitant with thick-skinned deformation south of the Lewis & Clark lineament and thin-skinned thrusting north of it. Core complexes formed at different times in each segment: Great Basin-Paleocene, Canadian-Eocene, and Sonoran-Miocene and reflect different ages of major crustal thickening in each. New easterly directed subduction started beneath the amalgamated collision zone at about 53 Ma and has continued to the present.

#### **EARLY APPALACHIAN THRUSTING OF PALEOZOIC METASEDIMENTS WITHIN A PROTEROZOIC BASEMENT MASSIF OF THE SOUTHERN LONG RANGE INLIER OF NEWFOUNDLAND**

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The Long Range Mountains of western Newfoundland contains one of the largest exposures of Proterozoic crystalline basement rocks within the Appalachian Orogen, the Long Range Inlier. Recent regional bedrock mapping in the Silver Mountain and Bonne Bay areas suggests that it is not a simple stratigraphic inlier, but rather represents a massif reactivated during early Appalachian deformation. The approximately 8500 km<sup>2</sup> of basement rocks comprise the largest portion of the external Humber Zone, considered to be the foreland belt of the Appalachian Orogen. The Inlier forms a structural culmination that is bounded to the west, north, south and locally to the east, by Proterozoic to Paleozoic volcano-sedimentary cover rocks.

The southern part of the Long Range Inlier is broadly divisible into the following tectonic divisions: a) high-grade Long Range gneiss complex; b) weakly to strongly foliated plutonic rocks; interpreted to be Grenvillian in age; c) mafic dykes (Long Range dyke swarm); d) thin remnants of a latest Neoproterozoic to Early Paleozoic cover sequence (previously interpreted as Grenvillian in age); and e) Early Silurian gabbroic intrusions (ca. 430 Ma Taylor Brook gabbro) and minor felsic dykes, sills and porphyries.

The latest Neoproterozoic to Early Paleozoic cover sequence is a quartzite-marble-dolomite sequence that is restricted peculiarly to the flanks of the Taylor Brook gabbro near Silver Mountain. These strongly recrystallized rocks compare to polydeformed Paleozoic metasediments that lie below, and are carried unconformably upon, thrust Proterozoic basement near Bonne Bay Big Pond at the southwest of the inlier. This indicates that the inlier may be thrust above the cover sequence along its southern edge. In the Silver Mountain area, the metasedimentary units flank the Taylor Brook gabbro and could either be thrust onto the Long Range Inlier, the structure later utilized during emplacement of multiple magmatic pulses of the gabbro, or form part of the footwall to the Long Range overthrust that was elevated during emplacement of the intrusion. The early Silurian age of the Taylor Brook gabbro however suggests that the timing of these structural relationships and emplacement of the massif is early Appalachian (Taconic or Salinic) and is likely to have profound implications for understanding the timing of emplacement of the Taconic allochthons in the western Newfoundland Humber Zone.

#### **APPLICATION OF VISIBLE/INFRA-RED SPECTROMETRY (VIRS) TO VOLCANOGENIC MASSIVE SULPHIDE HYDROTHERMAL ALTERATION PRODUCTS, TULKS VOLCANIC BELT, CENTRAL NEWFOUNDLAND: AN ADDITIONAL EXPLORATION TECHNIQUE?**

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Volcanogenic massive sulphide deposits generally have zoned mineral alteration systems related to the hydrothermal circulation cells that led to their formation. In ideal situations it is possible to use field observations of such alteration to vector towards potential ore horizons. However, in many cases, such reasoning relies on subsequent detailed petrographic and lithochemical investigations as the fine-grained and cryptic nature of much of the alter-

ation may prove insurmountable. A relatively new technique that may alleviate such issues is the use of portable reflectance spectrometers that provide visible/infrared spectrometry (VIRS). VIRS allows rapid field identification of alteration minerals along with compositional information that may constitute vectors to potential ore horizons.

VIRS methods were applied to three of the volcanogenic massive sulphide deposits in the Tulls volcanic belt of central Newfoundland, namely the Daniels Pond, Tulls East and, Boomerang deposits. These deposits have ubiquitous white mica and chlorite alteration, but mineralogical zonation in the field is difficult to see. Identification of mineralogical zonation is further hindered by the lack of outcrop in the vicinity of the deposits, as well as inherent overlaps in the compositions of alteration products related to VMS systems with regional greenschist facies metamorphism products.

Results from the three deposits, and regional rock samples, highlight significant compositional variations in alteration products and typically illustrate a distinct shift in the wavelengths of the Al-OH absorption feature in white micas from distal to proximal environments. The Al-OH absorption feature in white micas distal to ore is generally at >2000 nm (i.e. muscovite to phengite composition), whereas the absorption feature shifts to lower wavelengths (<2000 nm) in samples proximal to ore (i.e. paragonite composition). The VIRS data thus record subtle variations in alteration mineral chemistry that would otherwise be difficult to detect, and which may provide a directional indicator (vector) to favorable horizons.

## THE FUTURE OF MARS EXPLORATION - CANADA'S ROLE

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The last decade has been extraordinarily productive for Mars exploration. The strategy of 'Follow the Water' strategy that drove mission selection has been very successful in discovering both interesting morphology (gullies), mineralogy (phyllosilicates, perchlorate), and reservoirs of ice stretching from the poles to mid-latitudes. Next decade missions will focus on habitability and seeking signs of life, topics that are also scientific priorities for the Canadian community and detailed in the CSEW9 report.

Canada will contribute to three of the four planned Mars missions in the next decade: NASA's Mars Science Laboratory (launch 2011); the ESA-NASA ExoMars Trace Gas Orbiter (launch 2016), and the ESA-NASA 2018 mission which includes the ESA ExoMars rover. This talk will outline recent scientific highlights. It will describe Canada's mission involvement, and review needs for, and progress towards, longer term goals such as Mars Sample Return and Mars life detection.

## A FIELD CELL AND HUMIDITY CELL STUDY OF Mo AND Zn ATTENUATION BY WASTE ROCK MIXING IN NEUTRAL DRAINAGE CONDITIONS AS A PART OF THE ANTIMINA WASTE ROCK PROJECT

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The Antamina Waste Rock Project is an ongoing multi-scale study of mineral dissolution, metal release, solute transport, and attenuation mechanisms in waste rock under neutral drainage conditions at the open-pit Cu-Zn-Mo Antamina mine in the Peruvian Andes. The objective of the project is to better understand these mecha-

nisms under controlled and/or monitored hydrological, geochemical, and microbial conditions. Results are being used to assist in refining the current waste rock classification scheme, developing methods for on-site waste rock classification, and assessing the use of field- and laboratory-derived scale-up factors and reactive transport modeling to predict waste rock drainage quality.

This presentation focuses on a geochemical study of the attenuation of two key contaminants of concern at Antamina – Mo and Zn. The study consists of two experiments: 7 stacked field cells installed at the Antamina site, and a set of 18 humidity cells installed at the University of British Columbia containing the same waste rock material as the field cells. Both experiments were designed to determine if and how the concentrations of Zn and Mo may be diminished as a result of mixing different types of waste rock found at the mine site.

Results indicate that contact with Pb-bearing marble waste rock considerably reduces the Mo concentrations in leachate, likely due to wulfenite (PbMoO<sub>4</sub>) precipitation. Similar reductions in Zn concentrations have been observed where Zn-rich leachate comes in contact with grey hornfels waste rock. Previous laboratory studies in the Antamina project suggested that adsorption may be responsible for the removal of Zn, but further investigation is required to confirm this mechanism.

Results from this study will provide insight into the use of layering to attenuate metals of concern in leachate before it drains from waste rock dumps. This insight could be used when dealing with waste rock disposal at mines that exhibit neutral drainage.

## CHEMICAL DICHOTOMY OF CARBONATITES AND FENITES NEAR GATINEAU, QUEBEC

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In Gatineau Park, two small fluorapatite-rich, uranopyrochlore-bearing magnesiocarbonatite dykes intrude aplite, with magnetite the sole primary iron oxide, titanium minerals not observed, and P>S, Sr>Ba, U~Th. Amphibole fenite extends outward from carbonatite with increasing oxidation and Na, U enrichment, but with K depletion. Fluorine and Nb are highest in a richterite-fluorite-phlogopite-fenite selvage near the carbonatite contact (F 5.5 ave wt %, Nb 66 ppm), lower in richterite-fenite 50 cm from the carbonatite (F 4.2%, Nb 48 ppm), and lowest in carbonatite 10 cm from the fenite (F 1.6%, Nb 7 ppm). Average LREE declined, but HREE were selectively removed as follows: carbonatite (Ce 630 ppm, Yb/Ce × 1000=10.4), fenite selvage (Ce 128 ppm, Yb/Ce × 1000=8.4), distal fenite (Ce 93 ppm, Yb/Ce × 1000=6.6). Magnesium number (84) and agpaitic index (1.4) were constant across the fenites. These systematics resemble those of two small carbonatite dykes at Fen, Norway but the latter are notably richer in Fe and Nb (author's sampling).

In Cantley Municipality, a small calciocarbonatite dyke, holding barite and parisite and associated with hematite-rutile intergrowths, cuts biotite gneiss and has the following characteristics: S>P, Ba>Sr, Th>U. Fluorine is highest in the selvage (F 2.65 wt%), and correlates well with Ti and Nb (F>Ti>Nb) in all sample sites (phlogopite-fenite selvage > aegirine-distal fenite > parisite-barite-proximal carbonatite). Cerium declined from distal fenite (1100 ppm), to carbonatite (734 ppm), to fenite selvage (531 ppm), however, with respect to LREE, HREE were continuously depleted with distance from the carbonatite (Yb/Ce × 1000=12.9, 2.0, 1.4). Magnesium numbers decreased from fenite selvage (50.6), to distal fenite (35.8), whereas agpaitic index increased (from 1.62 to 3.11) in this interval. The chemical composition resembles that at Mountain Pass, California, but at Cantley P is comparatively high, and the Mountain Pass carbonatites are greatly

enriched in REE and lack well developed fenite envelopes (published data).

Geochemistry of the and Gatineau Park and Cantley occurrences characterizes carbonatite and fenite suites on the west and east sides of the Gatineau River, respectively. The oxidized nature of the rocks suggests a higher level of emplacement of suites on the east side, separated from the western occurrences by the north-west-trending Meech Lake Fault, with a down-dropped block on its northeast side.

#### **CHARACTERIZING CLAY-MICROBE-METAL INTERACTIONS: IMPLICATIONS FOR METAL IMMOBILIZATION**

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Clay minerals and Fe-reducing bacteria have been identified independently of one another as important geochemical agents which influence metal mobility in aqueous environments; in the context of metal immobilization, however, the numerous interactions occurring between bacteria and clays remain largely undescribed. This study examines the immobilization of metal cations from aqueous solution by clay samples from a natural bentonite deposit, together with clay-endemic and augmented metal-tolerant Fe-reducing bacteria. The objectives of this laboratory study are to 1) identify clay samples which excel at immobilizing toxic metals and assess the influence of two enrichments of Fe-reducing bacteria on metal uptake by the clays; and 2) identify the bacterial-clay characteristics involved in metal uptake by the substrates. Preliminary results of the modified batch adsorption experiments, along with supporting mineralogical data, will be presented to illustrate the adsorptive properties of several clay samples, with and without the influence of Fe-reducing bacteria. These results will be discussed in terms of their implications for bacterial clay metal geochemistry and will highlight the opportunities for novel bioremediation approaches using clays and endemic or augmented bacterial communities.

#### **REALIZING THE POTENTIAL OF NICKEL-COPPER-PGE DEPOSITS IN THE MIDCONTINENT RIFT OF NORTH AMERICA**

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Recent discoveries of copper-nickel-platinum group element (PGE) deposits have been made in ultramafic intrusions of the Midcontinent Rift Intrusive Supersuite. These include Magma Metals Ltd. Thunder Bay North property in Ontario (9.3 Mt @ 2.44 g/t Pt-Equivalent), Rio Tinto/Kennecott Eagle Minerals Eagle deposit in Michigan (3.6 Mt @ 3.47% Ni, 2.93% Cu) and Rio Tinto's Tamarack property in Minnesota (9 to 11 Mt @ 1.0 – 1.1% Ni, 0.6 – 0.7% Cu).

Orthomagmatic deposits of copper, nickel and PGE are also associated with early ultramafic to mafic intrusive rocks. Stratabound, "reef-style" copper-nickel-PGE mineralization in Ontario occurs within peridotite of the Seagull layered intrusion; within massive, cumulate Ti-Fe-oxide layers in the Eastern border gabbro of the Coldwell Complex; and with Cr-spinel in cyclic anorthosite-gabbro units above the Great Lakes Nickel deposit in the Crystal Lake Gabbro. Vari-textured to pegmatitic gabbro at the base of the Crystal Lake Gabbro hosts the Great Lakes Nickel deposit (~ 41.4 Mt @ 0.334% Cu, 0.183% Ni, 0.69 g/t Pd, 0.21 g/t Pt). Similar rocks of the Two Duck Lake gabbro in the Coldwell Complex host the Marathon deposit (91.45 Mt @ 0.832 g/t Pd, 0.237 g/t Pt, 0.085 g/t Au, 0.247% Cu and 1.44 g/t Ag).

Recent studies of the geochemistry and geochronology of Midcontinent Rift (MCR)-related rocks in and around Thunder Bay have provided a solid framework for explorationists. These studies have shown that mineralized intrusions are typically among the oldest rocks of the MCR and are geochemically distinct from the majority of dikes, sills and volcanic rocks that comprise the bulk of the MCR. The newly discovered deposits are often associated with magma conduits or chonoliths. The relatively small size of the host intrusions makes them a challenging target for exploration. Ongoing research into coeval volcanic and intrusive rocks related to mineralized intrusions allows for the development of new models for Rift paragenesis that can be utilized to develop new models for the genesis of mineralized intrusions.

#### **AN INTEGRATED APPROACH TO VMS EXPLORATION IN ANCIENT COLLISION ZONES: BUCHANS-STYLE MINERALIZATION IN NORTHERN IRELAND?**

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Although most, if not all, volcanogenic massive sulfide (VMS) deposits form within extensional environments, most are preserved within oceanic and ensialic tracts accreted to continental margins prior to continent-continent collision. Within Newfoundland, a complex tectonic collage of peri-Laurentian, Cambro-Ordovician tracts is preserved, which were accreted to the Laurentian margin during the Taconic phase of the Caledonian-Appalachian orogen. Many of these are sequentially divisible into a series of ophiolitic, arc and back-arc assemblages, which host significant VMS mineralization (e.g. Buchans Camp, 16.1 Mt of ore at 14.51 % Zn, 7.56 % Pb, 1.33 % Cu and 1.37 g/t Au). Within the British and Irish Caledonides, peri-Laurentian-hosted VMS deposits remain to be discovered.

New mapping across the Tyrone Igneous Complex of Northern Ireland, supported by extensive major-, trace-element and Nd-isotope geochemistry, and nine new U-Pb zircon dates, suggests a correlation to the VMS-rich Annieopsquitch Accretionary Tract of Newfoundland. Synthesis of more than 30 years of exploration data in Co. Tyrone, coupled with new lithogeochemistry and high-resolution geophysics, has defined stratigraphic horizons favourable for VMS mineralization, coincident with (i) extensive sericitic alteration, (ii) mineralized float, (iii) bedrock silica-iron exhalites, (iv) strike parallel km-scale deep overburden anomalies and (v) geophysical anomalies (EM, magnetic and IP). For example, talc and chloritic altered felsic tuffs at Greencastle contain bands of pyrite-galena-sphalerite-chalcopryrite mineralization assaying up to 10% Zn, 2.8% Pb and 1.2% Cu coincident with a 3 km strike length Zn deep overburden anomaly and a series of EM anomalies. Silicified and chloritic altered felsic tuffs around Tullybrick and Broughderg are coincident with a series of EM anomalies and a 5km strike length Zn (with Cu and minor Pb) deep overburden anomaly. This revised and detailed correlation between the two terranes, integrated with encouraging exploration data has defined exploration fairways in Co. Tyrone with potential to host VMS deposits.

## EVOLUTION OF AN EARLY ORDOVICIAN PERI-LAURENTIAN ARC-OPIHOLITE COMPLEX WITHIN THE CALEDONIAN-APPALACHIAN OROGEN: NEW CONSTRAINTS FROM NORTHERN IRELAND

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The Tyrone Igneous Complex of Northern Ireland is an integral part of the Caledonian–Appalachian orogen recording early-Ordovician arc-ophiolite emplacement onto an outboard segment of Laurentia, the Tyrone Central Inlier, during the Grampian–Taconic event. We present results of new field mapping, high-resolution geophysics and over 200 whole-rock geochemical analyses, integrated with new and existing U–Pb zircon geochronology.

The Tyrone Plutonic Group represents the uppermost portion of a ca. 484–480 Ma dismembered supra-subduction zone ophiolite, characterized by tholeiitic and LREE-depleted layered, isotopic and pegmatitic gabbros, sheeted diabase dykes and rare pillow lavas. Obduction onto the Tyrone Central Inlier must have occurred prior to ca. 470 Ma, due to the presence of xenocrystic Proterozoic zircons within a stitching tonalite, but may have been initiated as early as ca. 480–478 Ma.

The structurally overlying Tyrone Volcanic Group (ca. >475–470 Ma) is characterized by basic to intermediate pillowed and sheeted lavas, volcanoclastic tuffs, rhyolite, banded chert, silica-iron exhalite (ironstone) and argillaceous sediment. Elevated LILE and LREE-enrichment, transitional to calc-alkaline geochemical signatures and primitive to strongly-negative  $\epsilon\text{Nd}(t)$  whole-rock values indicate the Tyrone Volcanic Group formed within an evolving peri-Laurentian island-arc close to Laurentia. The occurrence of primitive within-plate basalt at several stratigraphic levels and the presence of rhyolite with flat to U-shaped REE profiles and rare tholeiitic LREE-depleted basalt suggest a history of intra-arc rifting prior to arc-continent collision. Proterozoic xenocrystic zircons within a late suite of stitching I-type, calc-alkalic, tonalitic to hornblende- and biotite-bearing granitic plutons (till ca. 464 Ma) constrain arc-continent collision prior to ca. 470 Ma. Implications for correlations along the Caledonian–Appalachian orogen are discussed.

## GRAIN BOUNDARY DIFFUSION OF SOME TRANSITION METALS

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Grain boundaries provide one of the most important transport pathways for chemical equilibration of metamorphic rocks. In ‘dry’ rocks, the equilibration length scale of a particular element may be dependent upon its grain boundary diffusivity (GBD), so knowledge of these quantities is essential for the interpretation of metamorphic rock geochemistry. GBDs for Cr, Mn, and Ni were investigated experimentally, in a Type C grain boundary regime, using the ‘detector particle’ technique. ‘Dry’ experiments involved juxtaposing a pre-synthesized quartzite matrix containing 1 wt.% dispersed enstatite with either chromel metal (Cr–Ni alloy), chromium oxide, or Ni metal containing trace amounts of Mn. ‘Wet’ experiments additionally contained pyrophyllite, which was separated from the quartzite matrix by a thin Ni disk. Experiments

were run in a piston cylinder apparatus at 1250°C and 1 GPa for durations of 9.25–92 hours. Post-experiment analyses of the enstatite sink particles for the grain-boundary diffusants (Cr, Mn, Ni) were performed with a Cameca SX100 microprobe. BSE images show that ‘dry’ experiments produced a quartzite matrix with almost no porosity. ‘Wet’ experiments produced a matrix with some evidence for porosity at triple junctions and grain edges, yet we believe that the porosity does not form an interconnected network. Microprobe analysis show that Cr, Mn and Ni concentrations correlate with Mg concentrations within the enstatite sinks. Experiments which utilized a chromel metal source show Cr GB diffusion length scales that vary from 200 to 275 microns for experimental durations ranging from 18 and 92 hours, respectively; interestingly, the chromium oxide source yielded only a 125 micron length scale for a 48 hour experimental duration. Mn GB diffusion length scales reach 175 microns in 9.25 hours in ‘dry’ experiments yet increase by sevenfold in the ‘wet’ experiments. Since Ni is relatively incompatible in enstatite, length scales of Ni GB diffusion often exceed the length of the quartzite/sink matrix or, are in excess of 1600 microns. Ni competes with Mn for site occupancy within the enstatite sink particles and so, Ni concentrations as a function of distance from the source reach a maximum value before declining again. In the ‘wet’ experiments, however, this maximum is not observed and Ni GB diffusion length scales increase by fourfold when compared to ‘dry’ experiments.

## APPLICATIONS AND LIMITATIONS OF SYNCHROTRON X-RAY RADIATION METHODS IN THE STUDY OF JAROSITE IN MARTIAN METEORITES

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The recent discovery of the mineral jarosite ( $\text{KFe}_3(\text{OH})_6(\text{SO}_4)_2$ ) in the Miller Range (MIL) 03346 martian meteorite has provided an opportunity for us to study aqueous alteration minerals in the laboratory. Jarosite is a hydrous sulfate mineral that forms from acidic, oxidizing water; assuming it formed on Mars, this discovery is strong evidence for surface water on Mars at one time in the past. Here we use synchrotron radiation to characterize the chemical and structural properties of the jarosite in order to determine the depositional environment and conditions of its formation. This technique offers a non-destructive way to study this mineral in situ, and allows for an opportunity to see whether such analyses can provide insights into the origin of the jarosite. We have conducted synchrotron XRF and XRD analyses on the MIL 03346 specimens to determine the limitations of these methods in the study of martian meteorites and analogue type investigations. Two MIL 03346 specimens (sections 165 and 190) and two terrestrial jarosite samples (Peña Blanca and Baranco del Jaroso) were analyzed using micro-XRF and –XRD techniques at the Advanced Photon Source (APS) and the Canadian Light Source (CLS). The results revealed areas of alteration that vary from a few microns in width in the veins to larger spots nearly 100 microns wide within the mesostasis. The distribution of the jarosite precipitate suggests that the K and S were mobilized by outside waters flowing through the host rock during jarosite formation. Elemental oxide abundances of the jarosite in the MIL 03346 meteorite are similar to the terrestrial samples. XRF results showed that the multivalent elements V, Ce, and Eu, which are able to trace changes in pH and fluid chemistry, either fall below the limits of the detector or are lost in the noise of the abundant Fe signal. XRD mapping provided minimal diffraction peak images of the jarosite. Possible reasons for difficulties with XRD analyses could be that



the beam was too large to generate a clear signal on the small areas of alteration or that the jarosite itself is not sufficiently crystalline. The results of this study show that even with the recent advancements in modern synchrotron capabilities, the application of these techniques to analyze jarosite within the martian meteorites is limited and requires further experimentation.

**DEFORMATIONAL STRUCTURES AND  
METALLOGENETIC MODEL OF SEDIMENT-HOSTED  
Pb-Zn DEPOSITS IN NORTHERN SEGMENT OF THE  
SANJIANG OROGENIC BELT, SOUTHWEST CHINA**

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**SPECTRUM OF VOLCANIC-SUBVOLCANIC SETTINGS  
FOR KOMATIITE-ASSOCIATED Ni-Cu-(PGE)  
MINERALIZATION IN THE ABITIBI GREENSTONE  
BELT: IMPLICATIONS FOR THE CANADIAN SHIELD**

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Komatiitic rocks and associated Ni-Cu-(PGE) mineralization occur sporadically throughout most geological provinces of the Canadian Shield, including the 2.7 Ga Abitibi-Wawa greenstone belt, the 2.7 Ga Rankin Inlet area, the 1.9 Ga Thompson Nickel Belt, and the 1.9 Ga Raglan horizons of the Cape Smith Belt. Although it has been known for a very long time that this type of mineralization occurs in volcanic (e.g. Alexo), deeply invasive (e.g. Raglan), and intrusive (e.g. Thompson, Dumont) settings, most camps have been interpreted to occur in one setting (volcanic or subvolcanic) or the other.

Recent work in the Abitibi greenstone belt (AGB), however, indicates that Ni-Cu-(PGE) mineralization may occur at multiple levels of single komatiitic volcanic-subvolcanic edifices. Although most of the komatiites in the AGB have been previously considered to be extrusive, an increasing number of units have been shown to be intrusive and it now appears that komatiite-associated Ni-Cu-(PGE) mineralization occurs within a spectrum of environments ranging from intrusive (e.g. Dumont, Sothman) through subvolcanic (e.g. Kelex-Dundead-Dundonald South, McWatters-Galata) to extrusive (e.g. Alexo, Hart-Langmuir #1-Langmuir #2-Redstone-Langmuir W4, Texmont, Marbridge). Thus, komatiite-associated Ni-Cu-(PGE) mineralization in both the Kidd-Munro and Tisdale assemblages of the AGB is not restricted to specific stratigraphic contacts, as previously believed, but may occur in any environment (intrusive, subvolcanic, or volcanic) throughout the stratigraphy wherever lava pathways had access to external S. The differences in the physical volcanology, stratigraphy, and volcanic-subvolcanic architecture of komatiitic rocks in the AGB compared to those in the better-known Western Australian deposits requires modifications of the exploration model for the Abitibi geological context.

The more complex volcanic-subvolcanic architecture commonly present within the AGB makes it more difficult to predict the location of mineralized lava channels and channelized sheet flows/sills within different komatiitic-bearing successions. However, increased understanding of the volcanology and stratigraphy of komatiites coupled with recent discoveries (e.g. C Zone-Bannockburn, Langmuir W4) highlights the potential of finding new Ni-Cu-(PGE) deposits associated with komatiites in both less explored and also more explored camps within the AGB. The more complex komatiitic volcanic-subvolcanic architecture also occurs in other parts of the Superior Province (e.g. Vénus and North Spirit greenstone belts) and may be present in other komatiite-bearing greenstone belts of the Canadian Shield where their economic potential should be assessed in the lights of this new knowledge gained on the komatiitic volcanic-subvolcanic in the AGB.

**MULTIPLE SULPHUR ISOTOPES OF THE  
NEOPROTEROZOIC FRANKLIN SILLS AND HOST  
SEDIMENTARY ROCKS**

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The Neoproterozoic Franklin Sills are located on Victoria Island in the Northwest Territories. These diabasic to gabbroic sills are part of a large igneous province that also includes the Natkusiak flood basalts of Victoria Island, the Coronation sills and Brock In-

WITHDRAWN

lier on the mainland, and dyke swarms extending to Baffin Island and western Greenland. The Franklin sills are between several to 100 meters thick. They pass through a variety of host sedimentary rocks within the Shaler Supergroup including black shales, carbonates, sandstones and evaporites.

The Franklin Sills have been macroscopically compared to those in the Noril'sk region of Russia, which contain large basal deposits of Ni, Cu and PGE. These deposits are interpreted to have formed from the assimilation of crustal sulphur from black shales and evaporites. However the Franklin sills are difficult to study through petrographic analyses alone because textural and mineralogical variability within them is subtle. Multiple sulphur isotopes are therefore critical in gaining an understanding of the extent of fractional crystallization, assimilation and diffusion. Quantifying these processes leads to better modelling of sulphide immiscibility and transport and therefore better exploration strategies.

Samples collected from four different sills have  $\delta^{34}\text{S}$  values between  $-4.6$  and  $+8.1\%$ , while initial results show negligible  $\Delta^{33}\text{S}$  and  $\Delta^{36}\text{S}$  values, a reasonable result for Neoproterozoic rocks. Variability within each individual sill ranges from 1.1 to 6.7‰ and some sills have  $\delta^{34}\text{S}$  values that are distinctly isotopically heavier than others. This suggests that crustal contamination is an important but non-uniform process. While this is a favourable result for Ni-Cu-PGE deposition, this also means that it is difficult to pinpoint factors and lithologies leading to assimilation. A more systematic analysis of samples from sill sections and their host sedimentary rocks collected in 2010 will help quantify these relationships.

#### **PALEOZOIC STRATIGRAPHY AND PETROLEUM RESERVOIR POTENTIAL IN THE HUDSON BAY BASIN, NORTHERN CANADA**

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The Paleozoic Hudson Bay Basin underlies Hudson Bay and adjacent onshore areas in northern Manitoba and Ontario and southern Nunavut. The sedimentary succession in the Hudson Bay Basin includes Upper Ordovician to Devonian strata, unconformably overlain by erosional remnants of Mesozoic strata, with a total (known) maximum thickness of about 2500 m. New lithostratigraphic analyses of the five offshore wells drilled in the Hudson Bay Basin (Netsiq N-01, Beluga O-23, Walrus A-71, Polar Bear C-11 and Narwhal O-58) provide insights into basin depositional and erosional features, including a major regional unconformity in Lower Devonian strata and a Lower Devonian evaporite section of highly variable thickness. Petrophysical analyses of the five wells, integrated with core data, provide information on porosity, permeability, and water saturation in Paleozoic strata. The petrophysical data indicate that many limestone, dolomite and sandstone units within the succession have sufficient porosity and permeability to form good quality reservoirs, with possible hydrocarbon-bearing zones identified in some intervals. This stratigraphic and reservoir framework provides a foundation for ongoing petroleum-system and resource studies in the frontier Hudson Bay Basin and Hudson Platform.

#### **MODELING THE EFFECT OF WEATHERING OF THE DECCAN TRAPS ON THE CRETACEOUS-TERTIARY CLIMATE**

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The Maastrichtian-early Eocene transition (65 to 52 Ma) is marked by deep ocean warming of  $\sim 4^\circ\text{C}$ , followed by a downward trend in temperatures, indicating significant climate change during this time interval. The GEOCLIM climate model have been used to estimate the influence of paleogeography on the observed warming between 65 and 52 Ma, as well as the effect of weathering of the Deccan traps from their formation in an arid zone during the Maastrichtian until their drift into the tropical equatorial zone during the Eocene.

$\text{P}_{\text{CO}_2}$  is estimated to have increased by  $\sim 165$  ppm from 65 to 52 Ma, accompanied by an increase in the global temperature of  $\sim 0.58^\circ\text{C}$  and a warming of sea surface temperatures of  $\sim 1.15^\circ\text{C}$ . Our simulations highlight a mean cooling of the continental surface of  $-1.7^\circ\text{C}$ , due to the drift of continental masses toward northern paleolatitudes at this time. These results lead us to conclude that even if the change in the position of the continents could induce seemingly counterintuitive results (i.e. continents getting cooler when  $\text{P}_{\text{CO}_2}$  rises), other factors compensate for the decrease in mean continental temperatures (such as an increase in the continental surface area and locally more intense runoff) such that, according to our model, Earth's climate warms during the Maastrichtian-Eocene. Moreover, we find paleogeography influences the carbon cycle and thus climate, accounting for 30% of the warming between the late Cretaceous and Eocene.

The influence of weathering of the Deccan traps on the carbon cycle was modeled, with an assumed initial surface area equal to  $0.5 \times 10^6 \text{ km}^2$ . No climate effect was apparent at 65 Ma nor at 52 Ma, due to the location of the Deccan traps in an arid zone. However, sensitivity tests of traps size and distribution showed that the Eocene weathering of the Deccan traps may be responsible for continental temperatures cooling by more than  $3^\circ\text{C}$ , testifying to a significant role of these traps on global climate after 52 Ma.

#### **CAMECO'S EXPLORATION FOR BASEMENT-HOSTED UNCONFORMITY URANIUM MINERALIZATION IN THE NORTHEAST THELON BASIN**

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Cameco Corporation's 100% owned Turqavik & Aberdeen Projects have been undergoing exploration in the northeast Thelon Basin since 2005. The project area spans approximately 230,000 ha north and south of the Thelon River near Aberdeen Lake. Since the project's inception the exploration focus has been primarily for Kiggavik/Andrew Lake-style basement-hosted unconformity uranium mineralization. During the first three years the exploration techniques focused on detailed project-wide geological mapping, boulder sampling and prospecting in concert with airborne and ground geophysical surveys. The mapping and sampling provided the baseline lithological, structural, geochemical, and clay signatures unique to the project area. The most important geophysical surveys to augment our exploration are regional airborne magnetic and radiometric surveys, ground gravity and airborne RESOLVE<sup>®</sup> EM. Detailed (100 m station spacing) gravity surveys were conducted over areas considered to be high priority drill targets. The last three years have been dominated by diamond drilling over areas of prospective structure within the Woodburn Lake Group, and near large Hudson-age granitoid intrusions. Honing into favourable alteration systems and anomalous geochemistry

has been an important factor to drill target selection in the area. The use of molar ratio techniques with our multi-element geochemical data has been crucial to our understanding of the unique pathfinder elements related to basement-hosted uranium mineralization in the Thelon Basin area. Lastly, a strong structural understanding of reactivated brittle fault systems has been a key factor to drilling areas that demonstrate the likelihood of having undergone uranium mineralizing processes.

#### **GEM-ENERGY: PRELIMINARY SURFICIAL GEOLOGY, GEOMORPHOLOGY, RESOURCE EVALUATION AND GEOHAZARD ASSESSMENT FOR THE MAXHAMISH LAKE MAP AREA (NTS 94O), NORTHEASTERN BRITISH COLUMBIA**

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As part of the Geo-mapping for Energy and Minerals Program (GEM-Energy) Yukon Basins Project, the Geological Survey of Canada (GSC) and British Columbia Ministry of Energy (BC MENR) are collaborating to produce digital surficial geology and landform maps and geodatabases of terrain, landforms and geomorphic processes in the Maxhamish Lake map area (NTS 94O), British Columbia. Our work is providing government agencies, industry, communities and the public access to reliable geoscience information on surficial earth materials, geohazards and resource potential for granular aggregate and frac sand. In this paper we present the provisional distribution of surficial deposits and landforms; and describe the sedimentology, surface morphology and facies associations of major terrain units and landforms. This terrain inventory is evaluated to a) better define the regional potential for granular aggregate and frac sand resources in the map area; b) identify key geohazards that could impact surface infrastructure (e.g. road design, well pad locations, pipeline routing); c) provide baseline information useful for future land management decisions on resource development in northeastern British Columbia. The intent of this work is to attract new investment and reduce risks for exploration and development of natural resources in northern British Columbia.

#### **CLIMATE CHANGE: A GEOLOGICAL PERSPECTIVE**

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Based on James Hansen's work the IPCC have postulated increases of 6.4°C (IPCC 2001) and most recently 4.5°C (IPCC 2007) for a doubling of atmospheric CO<sub>2</sub>. Based on these temperature projections, and continuing CO<sub>2</sub> output, we have been confronted by predictions of runaway climate, melting ice caps, catastrophic sea level rise, species extinction, tropical disease outbreaks, more extreme weather and other catastrophes.

There is a serious problem with such predictions since: a) climate has always been non-linear and cyclical, b) it assumes that the preindustrial levels of 280 ppmv of CO<sub>2</sub> are normative, c) it ignores the planetary history provided by the earth sciences. Well documented and repeated analysis of CO<sub>2</sub> proxies show that Cambrian atmospheric CO<sub>2</sub> levels were up to 18 times the preindustrial levels (280 ppmv.) Thus 5,040 ppmv in the Cambrian would result in global average temperature increases of 76-108 degrees C rendering the planet lifeless.

The IPCC projections are inconsistent with geological evidence. Aside from considerations of the technical merits of the methodology used to develop the proxies there are other compelling reasons to accept high levels of CO<sub>2</sub> in the early history of the planet. First the Proterozoic atmosphere is believed to have developed with only three components nitrogen, water vapour and

carbon dioxide with traces methane and sulphur compounds. Secondly the volumes of fixed carbon occurring in ancient sediments require much greater atmospheric exchange than could be provided by current atmospheric CO<sub>2</sub> levels. In the Cambrian the atmosphere contained approximately 10,345GT of Carbon (2.05 GT/ppmv), about 13 times the modern level of 780 GT. Furthermore the Cambrian was characterized by extensive carbonate platforms rimming all of the Continents, Laurasia, Baltica, Siberia, as well as the super continent of Gondwana. Laurasia alone has approximately 710 trillion m<sup>3</sup> of Cambrian carbonate, about one eighth of the total Cambrian carbonate mass, of 5,680 trillion m<sup>3</sup>. This mass of carbonate requires natural sequestration of 1,900,936GT of carbon, approximately 2,500 times the entire mass of carbon in the present atmosphere.

In the Devonian there is a significant draw down of atmospheric CO<sub>2</sub> levels as land plants appear, culminating in the Carboniferous where CO<sub>2</sub> levels reach a low of about 400 ppmv. The requirement for atmospheric carbon in the massive Mississippian carbonate platforms as well as the thousands of Gigatons required for the development of massive Pennsylvanian coal deposits naturally accounts for this change.

#### **THE TEACHERS' MINING TOUR-A NEW PROFESSIONAL DEVELOPMENT PROGRAM**

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The Teachers' Mining Tour, an educator professional development program, was held August 9-13, 2010 at the Canadian Ecology Centre (CEC) located in the Samuel de Champlain Provincial Park, near Mattawa Ontario.

The objectives of the Tour were to present modern mining techniques and technologies, to demonstrate that the mining sector is environmentally responsible and a safe workplace, to promote a wide range of mining careers, to create and develop activities and applications for teachers and students in the classroom, to distribute resources and create a network of teachers utilizing mining as a theme in their classrooms, and to facilitate informed decisions about the economic, social and environmental aspects of the mining industry.

The five day Tour program exposed teachers to all phases of the mining cycle, mining industry professionals, Earth science and mineral education professionals, Earth science and mineral industry themed presentations, educational resource workshops and field trips, and the educational resources available to support their efforts. The program also provided participants with the opportunity to earn part of their Environmental Science Additional Qualification through Nipissing University and the Ontario College of Teachers.

Thirty Ontario teachers participated in the program that included presentations by mineral industry professionals, experts and consultants and site visits to mines and mining manufacturing operations in Sudbury and North Bay. The program received favourable reviews from participating teachers, industry participants and representatives from the organizations that sponsored the Tour.

During the academic year feedback was gathered from the teachers who participated in the program. A formal survey was circulated onto them to gauge how the tour experience informed their teaching. The results of this survey will be discussed.

## WHAT CAN WE LEARN ABOUT THE APPALACHIAN AND OTHER OROGENIC BELTS FROM MODERN SUBDUCTION AND COLLISIONS ZONES

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New understanding of continental subduction zone processes and modern continental/terrane collision zones provides an opportunity to improve our understanding of the processes that formed the Appalachian and other ancient orogenic belts. Although complex in detail, there are some important general points:

(1) The nature and state of two margins prior to collision is very important. One side was a subduction zone with a backarc that can be very wide, 200-1000 km, the other usually is a rifted continent (intervening terranes are usually incorporated in backarc). Crustal scale deformation happens mainly on the subduction zone side in the uniformly hot and weak former backarc.

(2) Backarcs are uniformly hot across their width (even if no extension) so they are very weak and represent long-lived "mobile mountain belts"; there is strength only in the upper crust. The rifted margin side is cold and strong.

(3) There are uniform high metamorphic gradients ('Barrovian'), within the backarc prior to collision (800-900°C at Moho); 'orogenic heat' is not a consequence of collision. There are usually low gradients in the rifted margin side prior to collision; 400-500°C at Moho.

(4) The high temperatures result in a weak lower crust detachment across the whole backarc. The backarc upper crust is commonly thrust landward over strong stable adjacent lithosphere. Two current examples are the present backarc upper crust of the South America Andes overthrusting the Brazilian craton (note this example backarc deformation where there is no collision), and the current Yakutat collision in the Gulf of Alaska is resulting in the whole northern Canadian Cordillera upper crust being driven to the northeast over the Canadian shield. The result is foreland thrusting and earthquakes in the Mackenzie Mountains.

Simplified Appalachian example in Newfoundland: The Humber (and Appalachian Fold and Thrust Belt) represents the strong cold foreland that was overthrust by the mainly crystalline backarc upper crust. The Central Mobile Belt (and Blue Ridge Belt) represents the former hot weak backarc with lower crust detachment. The Avalon (and Piedmont) represents the former rifted margin.

## DIAMONDS FROM THE SEA FLOOR: SIMS OXYGEN ISOTOPE DATA FROM ECLOGITIC GARNET INCLUSIONS IN DIAMONDS FROM THE DAMTSHAA KIMBERLITES (BOTSWANA) AND ARGYLE LAMPROITE (AUSTRALIA)

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The origin of eclogite xenoliths from the cratonic mantle is an enduring problem in models of lithosphere formation and diamond genesis. Whether eclogite represents subducted oceanic crust or melts that crystallised deep within the mantle, is a crucial question that must be answered in any model for the origin of cratonic lithosphere. Understanding eclogite is also important to our knowledge of diamond formation, for despite a low abundance of eclogite in the lithospheric mantle (<4%), diamond with an eclogitic association is disproportionately abundant (~1/3 of world diamond production).

Oxygen isotope ratios have provided some of the best evidence for the origin of eclogite. Oxygen isotope compositions can only be significantly perturbed from primordial values ( $\delta^{18}\text{O}$ [VSMOW] of approximately +5.5‰) through interaction

with Earth's hydrosphere. Cratonic eclogites are commonly observed to have oxygen isotope ratios substantially above, and slightly below, +5.5‰, which is persuasive evidence for a crustal origin of these rocks. Due to their small size and scarcity, isotopic analyses of diamond inclusions are difficult, which hampers our understanding of diamond source areas and the relationship of xenoliths to inclusions within diamonds.

Here we report precise and accurate  $\delta^{18}\text{O}$  SIMS measurements (with total uncertainties of approximately 0.2-0.4‰ at  $2\sigma$ ) of garnet inclusions from the Mesozoic Damtshaa kimberlites (part of the Orapa cluster in Botswana) and the Proterozoic Argyle lamproite, Western Australia. Results from Damtshaa yield  $\delta^{18}\text{O}$  values from +4.7‰ to +8.8‰ with a median value of +5.6‰ ( $n=15$ ). These data are consistent with previously determined bulk  $\delta^{18}\text{O}$  data on garnet from eclogitic xenoliths at the related Orapa kimberlite, and consistent with the hypothesis that these eclogitic rocks represent subducted oceanic crust. Results from garnet inclusions from Argyle range from +5.8‰ to +10.6‰, with a median of +7.4‰ ( $n=29$ ). As there are no eclogite xenoliths at Argyle, these represent the first  $^{18}\text{O}$  measurements of presumed eclogite source rocks at this locality. The high  $\delta^{18}\text{O}$  values require that the eclogite oxygen had some interaction with the hydrosphere, the distribution of  $\delta^{18}\text{O}$  values is, however, unlike that of the total oceanic crust, which has a wider range, and a mode at +5.5‰. Possibly, the eclogite encapsulated in the diamonds is derived from a small part of subducted oceanic lithosphere, such as altered pillow basalts from the sea floor.

## ENSTATITE CHONDRITES AND ENSTATITE CHONDRITE MELT ROCKS: A PETROGRAPHIC, MINERAL AND GEOCHEMICAL STUDY

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Enstatite (E) chondrites are highly reduced primitive meteorites, likely formed near the proto-sun, that have numerous elemental and isotopic characteristics which indicate that they were fundamental building blocks in the formation of Earth and the terrestrial planets. E-chondrites are divided into two classes, EH and EL based on their elemental and mineralogical characteristics. Most E chondrites have undergone varying degrees of textural equilibration, likely due to thermal metamorphism (possibly driven by a mixture of endogenous and exogenous heat sources). Progressive textural equilibration is denoted by petrographic grade, ranging from 3-6, with 3 being the least equilibrated and 6 the most equilibrated (e.g. Brearley and Jones, 1998). Not all E-chondrites fit neatly within this scheme, however: Some are impact melts or impact melt-bearing breccias, and others have experienced partial melting and melt migration in addition to textural equilibration. We present results of a multi-technique characterization of E-chondrites including a range of petrographic types, and contrast the characteristics of type 3-6 EL and EH chondrites with the impact melt La Paz Icefield (LAP) 02225, the EH impact melt-bearing breccia Abee, and the enigmatic enstatite meteorite Queen Alexandra Range (QUE) 94204, which may be a residue of partial melting and complex melt migration of E-chondrite parentage.

The Si content of the Fe,Ni metal increases, while the Fe (and minor element) content of enstatite decreases, with petrographic grade in both EH and EL chondrites (likely corresponding to thermal metamorphism); orthoenstatite which has crystallized from impact melt is also very low in Fe. Clinoenstatite and olivine are lost in favour of orthoenstatite with increasing petrographic grade and also in impact melts. Equigranular, anhedral textures with interstitial melts (plagioclase-silica and FeS-Fe,Ni) are observed in the probable melt residue in QUE 94204. In contrast, LAP 02225

contains elongate orthoenstatite crystals, commonly with inclusion-rich cores, in a fine-grained groundmass of enstatite, metal, troilite and plagioclase. Melt-rich areas of Abee contain euhedral enstatite laths that likely crystallized in local equilibrium with metal  $\pm$  sulfide melts. Terrestrial weathering has affected most of the samples, producing a variety of secondary mineral assemblages including Fe-oxyhydroxides, carbonates and sulfates.

References: Brearley, A.J., and Jones, R.H. (1998) Chondritic Meteorites. In J.J. Papike, Ed. Planetary Materials, 36, p. 398. Mineralogical Society of America, Washington, D.C.

## **SEISMIC HAZARDS TO FUEL TANK FARMS AND GROUNDWATER CONTAMINATION**

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Fuel storage facilities – often referred to as ‘tank farms’ – are critical components of municipal infrastructure. They store and dispense fuels for automotive, aircraft and water-born transportation. In the event of an earthquake, their importance cannot be underestimated in providing automotive fuels for rescue and recovery. Therefore seismically-induced damage to such facilities requires consideration by emergency managers. Most tank farms in California were constructed before the 1980s and their siting was based on seismic data that has since been much improved, thus their siting is a legacy of an earlier, less informed time.

The tank farm serving San Diego, California is known as the Mission Valley Terminal (MVT) and is situated at the foot of Murphy Canyon where it enters Mission Valley, which is in middle of the metropolitan area. It is very likely that the site of the tank farm was chosen in the early 1960s to be remote (6 km) from the Rose Canyon fault, an active fault, which runs from downtown along the trace of Interstate 5 to La Jolla. However, many of the valleys of California follow the traces of active or inactive faults and Murphy Canyon is one such fault-controlled valley. Kennedy and Peterson (2001) pointed out that the west side of Murphy Canyon was displaced upwards relative to the east side of the Canyon sometime during the Quaternary period, i.e., the last 2 million years. The maximum credible seismic event of an earthquake involving the Rose Canyon fault (M7.4, Grant and Shearer, 2004 or MW7.3, Rockwell, 2010) would result in damage in Mission Valley corresponding to a Modified Mercalli Intensity scale of IX, i.e., conspicuous ground rupturing and breakage of underground pipes (Sangines et al., 1991). Therefore, the seismic risk to the MVT is from faults that are both nearby and active, i.e., the Rose Canyon fault, and immediately proximate but of unknown activity, i.e., the Murphy Canyon fault. In addition, there is also concern that earthquakes in metropolitan areas will trigger liquefaction in water-saturated alluvium such as occurs in Mission Valley.

The particular concern considered here is that of the contamination of adjacent groundwater supplies from damage to the pipelines and storage tanks of MVT by surface rupturing, liquefaction or other seismically-induced ground motion. Some idea of the consequences of pipe rupture may be appreciated from the history of contamination of the Mission Valley alluvial aquifer by approximately 200,000 gallons of gasoline that escaped from the MVT during 1986-1991 from a corroded pipeline.

## **CHARACTERIZATION OF SAN DIEGO'S MISSION VALLEY AQUIFER**

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The 1914 annual report of the Department of Water of the City of San Diego (California) expressed with great satisfaction the completion of 13 12-inch water-supply wells in Mission Valley, San

Diego, California. This aquifer delivered a maximum of 2.5 million gallons per day (MGD) to the City and was a major component of the City's water supply prior to the development of the aqueduct to the Colorado River in the late 1930s, after which the aquifer fell into disuse. Today the City of San Diego has a real need to recover use of this aquifer as a water supply given the constraints on Colorado River and Northern Californian sources.

The Mission Valley aquifer is principally a product of erosion of sediments from Murphy Canyon and their deposition as an alluvial fan within Mission Valley and overlying deeper basinal sediments. The paleochannel of the alluvial fan provides the basal gravel layer that was tapped by the City in its pre-World War II aquifer. This gravel is interpreted to be the eroded Stadium Conglomerate present in Murphy Canyon. It is similar to other deep gravel layers found throughout Southern California that are associated with the late Pleistocene lowstand of sea level during the Last Glacial Maximum (LGM). It is overlain by the middle sand layer that appears to represent the erosion of sandy facies of the Friars sandstone within Murphy Canyon, as the Friars lies below the Stadium Conglomerate in the canyon. Finally, the upper gravel deposits identified in the logs may represent erosion of conglomeratic layers in the Friars, as well as continued transport and deposition of conglomeratic sediments from the Stadium Conglomerate falling into Murphy Creek from the canyon walls in the vicinity of Shepard Canyon, approximately four km north of the mouth of Murphy Canyon.

The deeper basin sediments are largely undefined but have recently been investigated by the US Geological Survey. Their deep multi-level well SDAQ (total depth of 289 m) provides some insight into the deeper formations beneath the Mission Valley alluvium and the underlying Friars formation. These interbedded sand, silt and clay sediments are under artesian head, with tritium concentrations < 1 TU and have measureable modern radiocarbon. The age of the deep groundwater appears to be ~19,000 years, i.e., the time of the LGM.

## **PROGRESS IN QUANTITATIVE DETERMINATION AND MAPPING OF TRACE ELEMENTS IN SULFIDE MINERALS USING LA-ICP-MS**

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Quantitative sub-ppm determination of sub-microscopic gold and other elements in sulfide minerals has a number of important potential applications, including: empirical indication of deposit setting, geo-thermometry and -barometry, paragenetic determination and indicator mineral studies. The distribution of precious metals within and between grains is also important in deportment studies for refractory gold sulfide deposits. However, compared to our knowledge of the behavior of trace elements in silicate minerals, our understanding of trace elements in sulfides remains remarkably poor. The main impediment to progress in this area has been the lack of well characterized, multi-element sulfide standards for application to calibration of trace-element microbeam techniques.

This study describes progress in development of calibration and element mapping techniques for Au and trace elements in sulfide minerals using LA-ICP-MS. Element concentration maps have been constructed from time-resolved signal intensity data acquired during multiple, parallel line-ablations across selected areas of petrographic sections. The data were deconvoluted, calibrated and digitally combined to generate elemental signal intensity and concentrations maps, which provide detailed information on spatial variations of gold and other elements within and between grains.

Determining concentrations in mono-mineralic sampling areas has been achieved using conventional calibration protocols involving external standardization and normalization using an internal standard, performed on a (mass) scan by scan basis. For complex mineralogy, calibration has been achieved either using (1) normalization of concentrations to 100% total element abundance, or, (2) internal normalization using different internal standard elements and/or concentrations for different minerals and algorithms that automatically detected the mineral phase being analyzed. Standardization was performed using homogeneous multi-element synthetic pyrrhotite standards that were prepared at CANMET by reaction in evacuated quartz tubes of elemental iron and sulfur doped with metallic or multi-element aqueous standards. Pyrrhotite was used because its structure can include up to 20% vacancies which allow efficient incorporation of trace elements with widely different ionic radius by omission substitution.

The effect of different sampling strategies (continuous vs. episodic sample stage translation), different data smoothing and interpolation algorithms, and different protocols for assigning colors to signal intensity and element concentration maps will be demonstrated with specific examples.

#### **CHARACTERIZATION OF TAILINGS AND RESPIRABLE DUST FROM LEAD-RICH MINE WASTE AND ITS POTENTIAL EFFECTS ON HUMAN BIOACCESSIBILITY FROM THE NEW CALUMET MINE, ILE DU GRAND CALUMET, QUEBEC**

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One of the main risks that exposed and unvegetated tailings pose to the environment and human health is airborne dust that may be inhaled or ingested. The particle size of airborne dust is one of the most important parameters used when describing their properties and behaviour. Finer dusts (<5 µm diameter) have a higher potential of being ingested deeper into the human lung causing possible tissue damage and toxic effects. Lead-hosted particles of tailings dust have become an increasing concern.

The New Calumet Pb-Zn-Ag Mine, located 90 km NW of Ottawa, is located in an accreted arc terrane of the Grenville Province. Lead mineralization occurs primarily as galena hosted within massive sulphide lenses associated with amphibolite and biotite gneisses. From 1944 to 1968 New Calumet Mines Ltd. extracted 3.8 million tonnes of massive sulphide ore averaging 5.8% Zn, 1.6% Pb, and 2.16 oz Ag/tonne. Three million tonnes of tailings remain exposed on the property.

We have collected size-fractionated airborne dust and near-surface tailings at New Calumet Mine to study the correlation between Pb mineralogy and bioaccessibility. Bioaccessibility describes how much of a substance, or mineral, can be dissolved by body fluids and become available for absorption by the body. Different Pb compounds have different solubilities, which in turn affect bioaccessibility. The most bioaccessible Pb compounds are lead carbonates (PbCO<sub>3</sub>, cerussite) and lead oxides (PbO), followed closely by lead sulphates (PbSO<sub>4</sub>, anglesite) and lead sulphides (PbS, galena).

Airborne dust samples were collected by cascade impactor filters and bulk tailings samples were collected directly from the surface and used to make thin sections. Both types of samples underwent synchrotron microanalysis including microXRD for identification of microcrystalline compounds and microXRF for element mapping and metal ratio evaluation. The cascade impactor filters were further analysed by PIXE to obtain elemental concentrations. The bulk samples taken of the tailings were analysed for total metal content, grain size distribution, and Pb speciation using ESEM techniques. In vitro bioaccessibility tests will be carried

out in collaboration with the USGS to examine gastric and pulmonary leaching of metals by simulated body fluids.

Preliminary data shows galena persisting as the most abundant Pb-bearing phase. However, rims of cerussite forming alteration rims on some galena grains have been identified by ESEM, microXRD and microXRF. Element mapping also indicates a correlation of Pb with Cl and Fe suggesting that additional Pb may be hosted in Fe oxyhydroxides and possibly pyromorphite (Pb<sub>5</sub>(PO<sub>4</sub>)<sub>3</sub>Cl).

#### **REGULATION OF HYDROUS FERRIC OXIDE FORMATION BY NEUTROPHILIC Fe(II)-OXIDIZING BACTERIA**

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Neutrophilic iron oxidizing bacteria (FeOB) are microorganisms that oxidize Fe(II) to generate energy for growth at near neutral pH values under generally low *p*O<sub>2</sub> values and elevated levels of Fe(II). These conditions occur in a wide range of environments including the rhizosphere of plants, groundwater discharge zones in wetlands, water flowing from hydraulically conductive fractures in underground excavations, and deep-ocean hydrothermal vents. In this study, FeOB samples were obtained from three contrasting field sites: Loihi Seamount (Southern Hawaii); Äspö Hard Rock Laboratory (Eastern Sweden); and Ogilvie Creek (Northern Canada), to evaluate *in situ* formation of hydrous ferric oxides (HFO) by FeOB. Specifically, the investigation involved an assessment of HFO particle size distributions on extracellular materials associated with different species of FeOB. Three morphologically distinct species of FeOB were distinguished in the samples including *Gallionella ferruginea* (G) *Mariprofundus ferrooxydans* (M) (both with distinctive helical fibrous stalks), and *Leptothrix spp.* (L) (with filamentous sheaths). In all samples, mean HFO particle sizes on G-M stalks were found to be similar to those of particles physically and spatially isolated from bacterial cells; however, the mean HFO particle size on L sheaths were consistently smaller than those on G-M stalks. Considering how mineral solubility varies with particle size and mean interfacial energy  $\gamma$ , values for  $\gamma$  of 1510 mJ/m<sup>2</sup> and 958 mJ/m<sup>2</sup> were calculated for G-M stalks and L sheaths, respectively. This means that HFO particles on L sheaths will be about two times less soluble (i.e. more stable) than equivalent sized particles on G-M stalks. Furthermore, since nucleation rates vary with the negative cube of  $\gamma$  in the argument of an exponential, the heterogeneous nucleation rate of HFO particles on L sheaths is apt to be greater than concurrent rates of heterogeneous nucleation on G-M stalks or homogeneous nucleation in solution. These data indicate that different species of FeOB not only exert a strong influence on mean interfacial energies of cell-associated HFO particles, but also regulate HFO nucleation rates and solubility.

#### **THE INFLUENCE OF ORE PROCESSING ON THE GEOCHEMICAL PATH OF ORE DEPOSITS FROM CRADLE TO GRAVE**

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Geoenvironmental ore deposit models attempt to explain how the geological characteristics of an ore body and its host rocks can define the nature of mine waste. The success of this approach results, in part, because waste rock and mill tailings typically represent 90 to 99% of the rock mined, and two of the most important factors governing the quality of mine drainage leached from these solid

wastes are the sulfide to carbonate ratio, and the trace element suite accompanying the ore, both features inherited from the original ore and host rock. However, in some cases ore processing may have a strong influence on mine drainage by chemically and mineralogically transforming the solids prior to disposal. This is particularly true for gold deposits where ore tends to be both concentrated and processed on the mine site. There are many options for gold ore processing, each of which has different consequences for mine waste.

For example, at Giant mine near Yellowknife, NWT, refractory gold ore was roasted which destroyed a significant fraction of the sulfide, increasing the net neutralization potential of the mine waste. However, roasting typically produces arsenic trioxide in a separate waste stream. This compound is considered highly toxic and soluble. The legacy of past practices in handling arsenic trioxide waste at Giant has resulted in costly and complex remediation of the site although there is no acid mine drainage.

Heap leaching of gold ore at Landusky, MT resulted in the exposure of hydrothermally altered syenite to both alkaline leach solution and acidic drainage, producing elevated dissolved Al concentrations.

Understanding the role that on-site ore processing has on the environmental impact of mine waste can provide guidance on the remediation of legacy sites and the planning of new mines.

#### APPLICATION OF SYNCHROTRON MICROANALYSIS TO GEOCHEMICAL PROBLEMS

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Synchrotron microprobes provide extremely intense X-ray beams with a small spot size and can be easily tuned to a wide range of incident beam energies. One of the major advantages of synchrotron-based X-ray microprobes over instruments utilizing conventional X-ray sources is that the high brightness and tunability allow geological materials mounted as thin sections and grain mounts to be investigated at the level of individual grains using several analytical techniques simultaneously. These include X-ray absorption (XAS) which provides fine-scale molecular speciation information, X-ray fluorescence (SXRF) which can be used for microfocused element analysis and mapping with detection sensitivities at the femtogram level, and X-ray diffraction (microXRD) which can be used to identify phases in a spatially resolved manner that would not be detected using conventional XRD. Another advantage of the technique is that samples require little or no preparation, and can be analyzed under ambient conditions that closely match environmental conditions in the field.

Over the last decade, we have applied synchrotron microanalysis to a range of geological materials representing potential risk to human or ecosystem health including mine tailings, contaminated soils, airborne tailings dust, lake sediments and household dust. There has been an emphasis on identifying the mineral forms of arsenic and antimony to further understand their environmental mobility. Examples from the Giant Mine near Yellowknife and abandoned gold mines in Nova Scotia will be provided. Recent advances in synchrotron microanalysis including rapid element mapping and quantitative SXRF analysis will be discussed.

#### RADIOMETRIC AGE-DATING OF SEAFLOOR HYDROTHERMAL SULFIDES FROM THE ENDEAVOUR SEGMENT, JUAN DE FUCA RIDGE

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Hydrothermal sulfides that precipitate on the seafloor record the spatial, thermal and geochemical history of high-temperature venting from black smokers along ocean spreading centers, arcs and back-arcs. The temporal evolution of these processes, however, is poorly constrained. Venting can be episodic, and simple mass accumulation rates cannot be used to determine the age of a hydrothermal system. Previous radioisotope age-dating of hydrothermal sulfides have focused on rates of chimney growth and sulfide accumulation using short-lived isotopes (e.g.  $^{210}\text{Pb}$ ,  $^{228}\text{Ra}$ ,  $^{228}\text{Th}$ ). These studies represent snapshots of venting activity over short timescales (<10 years). The examinations of processes that occur over the lifespan of an entire vent field require the use of radioisotopes with longer half-lives. Radium-226 (half-life of 1,600 years) occurs in high abundances in hydrothermal barite, and has a half-life suitable for the determination of ages of materials between ~300 to 20,000 years old. A novel age-dating method, using  $^{226}\text{Ra}/\text{Ba}$  ratios in hydrothermal barite has been developed in order to determine the absolute ages of hydrothermal sulfides. We present new radiometric ages of hydrothermal sulfides from vent fields along the Endeavour segment, part of the intermediate spreading-rate Juan de Fuca Ridge. Previous attempts to determine the age of a hydrothermal vent field have often relied on absolute ages of the underlying basalt flows to provide a maximum age of venting. At Endeavour, no new extrusive volcanic activity is thought to have occurred in >10,000 years. Tectonic extension has been accommodated by normal faulting resulting in a <1 km wide axial valley. High-temperature (>300°C) venting occurs in five discrete vent fields along the floor of the axial valley. Inactive or extinct vent sites also occur between the active fields.

Results from  $^{226}\text{Ra}/\text{Ba}$  geochronology in sulfide-associated barite indicate that high-temperature venting within the current axial valley was likely initiated <5,000 years ago. Barite age dates of 63 sulfides from the Mothra, Main Endeavour, High-Rise, Salty Dawg and Sasquatch fields, as well as several extinct or inactive sites outside the active fields show a range of ages from 0 (i.e. actively forming) to a maximum of 3,022 years. This maximum age, from the Main Endeavour Field represents a minimum age of venting at Endeavour. The age spectrum of the Main Endeavour Field indicates continuous venting over 3,000 years. Combined with sulfide tonnage estimates for this field, mass accumulation rates of sulfide and the efficiency of sulfide precipitation can be determined.

#### THE GEOCHEMICAL FOOTPRINT OF THE CENTRAL ZONE ALKALIC COPPER-GOLD PORPHYRY DEPOSIT, GALORE CREEK DISTRICT, NORTHWESTERN BRITISH COLUMBIA, CANADA

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The Central Zone alkaline copper-gold porphyry deposit is located in the Late Triassic Galore Creek district of northwestern British Columbia. Galore Creek represents the end-member of the silica-



undersaturated class of alkalic porphyry systems. The Central Zone deposit is hosted by volcano-sedimentary rocks of the Middle to Upper Triassic Stuhini Group that were intruded by a syenite to monzonite complex and hydrothermal breccias. Post-mineral tilting 45 to 60° W-SW of the Central Zone has provided an opportunity to examine a significant vertical extent of the hydrothermal system, allowing us to define the geological architecture and study the impact of the host rock geochemistry and redox controls on the precipitation of sulfide and silicate alteration minerals.

In the Central Zone early mineralization occurred during potassic alteration and introduced gold-bearing chalcopryrite+ bornite (Cu:Au ~ 2:1). A second gold-poor mineralization event was associated with calc-potassic alteration and dramatically changed the Cu:Au ratio (5:1) in the core of the Central Zone. In general, the highest Cu-Au grades occur at lithological contacts where there are significant changes in the abundances of ferromagnesian minerals, which are interpreted to have been abrupt redox gradients.

Sulfur isotopic compositions emphasize the importance of  $f_{O_2}$  conditions in ore deposition. Sulfides in highly mineralized centers are characterized by moderately negative  $\delta^{34}S_{\text{sulfide}}$  values (-10.66‰ to -7.84‰), whereas sulfides deposited distally show highly negative  $\delta^{34}S_{\text{sulfide}}$  values (-17.13‰ to -4.03‰). These data suggest that the interaction of sulfate-rich ( $SO_4^{2-}$ (aq)) fluids with varying amounts of  $Fe^{2+}$ -bearing minerals in host rocks increased  $H_2S/SO_4^{2-}$  leading to formation of reduced S, and precipitation of sulfide minerals.

The abundances of trace elements such as V and As in the altered host rocks and  $Eu^{2+}$  in hydrothermal garnets are inferred to reflect the same redox influence. Vanadium and As are soluble under highly oxidizing conditions. The shift in oxidation state facilitates their incorporation in alteration minerals. Thus, highest V (>700ppm) and As (>40ppm) concentrations form halos distally to the redox gradients and orebodies. Hydrothermal garnets near lithologic contacts contain excess  $Eu^{2+}$ . In contrast to V and As,  $Eu^{2+}$  is soluble in reduced  $f_{O_2}$  conditions and precipitates close to the redox gradient.

This study demonstrates that redox is the dominant control on ore deposition in the Central Zone. Recognizing redox changes via application of whole rock geochemistry and inexpensive sulfur isotopic studies may provide a valuable guide for future exploration in the Galore Creek district and other alkalic Cu-Au porphyry systems worldwide.

#### **NORTHEAST THELON REGION GEOSCIENCE FRAMEWORK-MAPS FOR URANIUM IN NUNAVUT**

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Improving knowledge of uranium settings under GSC's Geomapping for Energy and Minerals Program aims to sustain development in Nunavut. Shared Industry-GSC geophysical data and field

work provide new constraints to test hypotheses herein. Six Neoproterozoic sequences are distinguished from four early Paleoproterozoic siliciclastic sequences with porphyritic basalt and carbonate markers, all newly correlated between the Amer and Whitehills belts. Five geographically separate sequences of the Neoproterozoic Woodburn Group contain iron formation and felsic tuff, and were stitched by 2.6 Ga rhyolite and granite. The first three sequences include komatiite. The "Halfway" (2.734 Ga) belt is dominated by aphyric pillow basalt; "North Meadowbank" (2.72 Ga) is dominantly felsic; "Pipedream" (2.711 Ga) is diverse, hosting the producing Meadowbank gold mine and Kiggavik uranium deposits; "Wading Lake" (undated) is mafic-intermediate and amygdaloidal; and "Amarulik wacke" (<2.68 Ga) unconformably overlies "Halfway" and "Pipedream".

Paleoproterozoic sequences Ps1 (conglomerate-quartzite), Ps2 (graphitic pelite-basalt-carbonate) and Ps3 (feldsarenite-siltite) form enigmatic ESE-vergent, basement-cored nappes and thrusts. Major basement uplift southeast of the Snowbird -Chesterfield fault zones (STZ) drove mainly NW-vergent to upright D<sub>2</sub> refolding. Orogenic denudation shed Ps4 melange and polymict feldspathic molasse NW into foreland basins, first folded during late D<sub>2</sub>. Subhorizontal D<sub>3</sub> folds record extensional orogenic collapse. Late Mid-crustal ~1.83 Ga Hudson granite sheets, laccoliths and plutons respectively were offset by and stitched dextral mylonite zones. Open D<sub>4</sub> folds, ENE dextral shears and mafic dykes transect the above. Straddling the STZ, the transextensional Baker Lake Basin accommodated terrestrial feldspathic siliciclastic rocks intercalated with ca. 1.83 Ga minette lavas linked to a much broader contemporaneous minette dyke province.

Bimodal basalt-rhyolite volcanism with aeolian quartzarenite (1.75 Ga Wharton Group), and mafic-triggered rapakivi granite within restricted areas overlapped and intruded the eroded minette province. Further erosion and intense weathering preceded transextensional basin accommodation of 3 red bed sequences comprising conglomerate – feldspathic quartzarenite – mudstone (Thelon Formation). Uraniferous fluorapatite cemented syn-sedimentary faults at about 1.67 Ga. The Kiggavik trend of exhumed unconformity uranium deposits spatially coincides with geophysically identifiable, prepared settings: 1.75 Ga Nuelin porphyritic granite intruding "Halfway" sequence, infolded 2.6 Ga rhyolite and Ps1 quartzite; and intersecting right lateral ENE and NNE, re-activated and hydrothermally altered fault zones. The olivine minette 1.54 Ga Kuungmi lavas and Lookout Point dolostone capped Thelon Basin. Tectonic and uranium attributes compare with, but differ in age and the granite factor from Saskatchewan's world class Athabasca basin, which developed along a sister, west-flowing "big river" system to the south.

#### **OROCLINES, A TECTONIC STRING THEORY, AND IMPLICATIONS FOR SUBDUCTION INITIATION AND BASIN FORMATION**

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Oroclines present a challenge to plate tectonic theory. Plates are defined as being internally rigid, and two points within a single plate are assumed to be fixed with respect to one another. Oroclines, however, are interpreted to develop by bending of plates about a vertical axis of rotation. Large oroclines, such as those mapped in Alaska, Iberia and Bohemia, require thousands of kilometers of relative movement between points that are geologically located within single plates.

Here I develop, by an examination of two young (post-10 Ma) basins, the North Fiji basin and the Tyrhennian Sea, a tectonic string theory that reconciles plates with oroclines. Opening of the Melanesian North Fiji basin was accompanied by coeval opening

of the Lau basin, the initiation of subduction beneath and subsequent 60° clockwise rotation of the New Hebridean arc, formation of the d'Entrecasteaux orocline, and the 135° counterclockwise rotation of Fiji. Opening of the Tyrhennian Sea was accompanied by the development of the Calabrian orocline in the south, and bending of the French Alps in the north, the initiation of the Calabrian subduction zone, formation of the Jura fold and thrust belt, and rifting of the Austrian Alps forming the Little Hungarian Plain. In Melanesia, North Fiji basin formation and all related rotations and orocline formation can be attributed to bending of an E-W trending transform fault (the Vitiaz) trapped between the Pacific plate to the east and the Papua collision zone to the west. In the Mediterranean, Tyrhennian Sea opening and related Alpine deformation is all related to bending of a ribbon continent trapped between Africa to the south and Europe to the north. In both cases orocline formation is attributable to bending of plate bounding tectonic 'strings'-highly elongate two dimensional features (a transform fault and a ribbon continent). Bending of these strings is accommodated in the adjacent plates by subduction of oceanic lithosphere in front of, and production of oceanic lithosphere behind an advancing bend. Continental lithosphere bends through crustal separation from, and probable subduction of the underpinning lithospheric mantle. Angular relationships are preserved during bending, allowing for simple palinspastic restoration of the bends. Orocline formation requires subduction; major oroclines are predicted to be bound by cryptic sutures and to have syn-kinematic magmatic suites.

#### **DISTRIBUTION OF DISTINCTIVE GLACIAL ERRATICS IN WESTERN CANADA**

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Information on the transport of glaciogenic sediment is potentially the most important to understanding the glacial history of a region and to mineral prospecting. In mineral exploration, models that guide design and interpretation of drift geochemical and indicator mineral surveys benefit from insights into the history and process of pathfinder dispersion. From 1990 to 1997, fieldwork included locating and collecting trace erratic pebbles and boulders on the surface across western Canada, from Manitoba to BC and the NWT into the northern USA. The information is presented in the form of digital files and a series of digital maps showing the distribution and patterns of dispersion of the unique erratics. The interpretation of the dynamics and mechanisms of dispersion are postulated, however, the advancement of this understanding requires a scientific discussion to test various hypotheses.

A series of digital maps show the distribution of the different erratic/unique rock types. There are eight significant rock types which can be traced from specific, unique point sources. They show highly dynamic patterns of glacial distribution from broad fans to very narrow winding pathways. These patterns will be presented and discussed with respect to currently developed inferences on glacial history and process. These patterns can be interpreted as created by single and multiple events of ice and/or water transport and is a significant contribution to understanding glacial ice and meltwater transport/dynamics.

The application of geochemical, indicator mineral and boulder tracing methods for mineral exploration in glaciated landscapes of Canada and in particular Saskatchewan, has been done for many years with various levels of success especially for gold and uranium. Simple to complex transport directions as well as mechanisms of dispersion from eroded mineral deposits can be found across the Precambrian Shield. Current exploration models need a more specific understanding of the processes involved in

glacial and water transport for the interpretation of pathfinder dispersion to be more effective.

The information presented here advances and improves the understanding of glacial hydrologic systems, glacial dynamics and sub-glacial processes, in western Canada. The further scientific discussion and interpretation of this information will improve the understanding of processes related to the analysis of geochemical and indicator mineral signatures for mineral exploration in glaciated terrain. This is relevant to mineral exploration in western Canada, regional baseline geological surveys nationally, and to understanding glaciated landscapes worldwide.

#### **GLOBAL TEMPERATURE AND THE NUMBER 5.35**

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The "global temperature" is the theoretical equilibrium temperature at which "outgoing energy" in the form of the thermal radiation from the planet balances off the "incoming energy" added to the "Earth system".

Changes to either the "incoming energy" or the "outgoing energy" will shift this equilibrium.

The 150 year global temperature record determined from thermometer based measurements demonstrates two identifiable shifts of this equilibrium; a longer period warming trend since the Little Ice Age, and a superimposed shorter period cyclic trend showing cooling to 1910, warming to 1942, cooling to 1975, and definitive warming from 1975 to 1998.

Since atmospheric CO<sub>2</sub> concentration has not increased in a cyclic fashion, it is highly unlikely that the steady increase in atmospheric CO<sub>2</sub> concentration over the past 150 years has been the primary driver of the observed cyclic global temperature change. Contrary to this observation, output from climate models provides evidence that the 0.4°C increase in global temperature from 1975 to 1998 matches the increases in both CO<sub>2</sub> emissions from fossil fuels as well as a 35.4ppmv increase in atmospheric CO<sub>2</sub> concentration creating a hypothesis of Anthropogenic Global Warming (AGW).

AGW is not actually supported by physical data, but because no fault can be found with either the physics or the mathematics of the General Circulation Models (GCM); AGW is still assumed by many to be a valid hypothesis.

The failings of the AGW hypothesis, while clearly not in the shortcomings of GCMs that support the hypothesis, are easily identified in the faulty CO<sub>2</sub> forcing parameter input into the GCMs to relate increases in atmospheric CO<sub>2</sub> concentration to increases in global temperature. The IPCC literature states this forcing parameter to be  $5.35 \ln(2) = 3.71$  watts/m<sup>2</sup> producing 2.78°C for a doubling of CO<sub>2</sub> through a relationship of 0.75°C for each watt/m<sup>2</sup>.

A 1981 paper shows an output of 2.78°C for a doubling of CO<sub>2</sub> and 3.71watts/m<sup>2</sup> appears in the 2007 IPCC Fourth Assessment Report for the same doubling, demonstrating that this 5.35 value has been used since 1981 and is still being input into IPCC climate models.

My investigation into the validity and genesis of this 5.35 value demonstrates that it is errors in the derivation of this CO<sub>2</sub> forcing parameter that are responsible for the failings of the climate models to properly predict global temperature.

## **A MINERALOGICAL AND GEOMETALLURGICAL STUDY OF THE LUCE IRON ORE DEPOSIT, LABRADOR CITY, NEWFOUNDLAND AND LABRADOR**

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Banded Iron Formations (BIFs) are the main sources of iron ore today with the Paleoproterozoic Labrador Trough being host to one of the largest reserves in the world. With a significant reserve and resource base, the Iron Ore Company of Canada (IOC) located in Labrador City, Labrador) is one of the largest iron producers on the planet. The Luce Iron Ore Deposit is one of IOC's main assets. This deposit is subdivided into three open pits: Luce South, Luce Main and Luce Basin.

The main stratigraphic unit mined by IOC within the Luce Deposit is the Wabush Iron Formation. It is subdivided into three units: The Lower, the Middle and the Upper Wabush Iron Formation, with the middle unit being the main source of iron ore. This formation has been extensively folded and metamorphosed to epidote-amphibolite facies during the Hudsonian and Grenvillian orogenies. In the Luce Deposit, the iron formation forms two plunging synclines and one plunging anticline. The average stratigraphic thickness of the middle iron formation is roughly 200 m. The main minerals in the Wabush Iron Formation are hematite, magnetite and quartz. Minor amounts of carbonates are also present in certain localities.

Based on optical microscopy and Scanning Electron Microscopy-Mineral Liberation Analysis, magnetite, hematite, goethite, limonite, Fe-dolomite and siderite were identified as the main iron-bearing minerals. Minor Ti-bearing minerals (Ti-magnetite, ilmenite and rutile) were also found. The main Fe-minerals are magnetite and hematite, which are coarsest in Luce Main and Basin and finer grained in Luce South. Backscattered electron imaging revealed zoning of iron in Fe-dolomite partially replaced by magnetite. Both martitization (hematite replacing magnetite, reflecting oxidation) and mushketovitization (magnetite replacing hematite, reflecting reduction) are also present. Thus the ores consist of several different generations of magnetite and hematite that likely formed during regional metamorphism, contact metamorphism (associated with intrusion of dykes and sills of the Mesoproterozoic Shabogamo Gabbro) and perhaps recent, groundwater alteration.

Total rare earth element concentrations of the BIFs are typically less than 10 ppm, but increase in some samples to approximately 50 ppm. Chondrite normalized REE patterns are light REE enriched ([La/Sm]<sub>n</sub> typically 2 to 5), with small positive europium anomalies (Eu/Eu\* commonly 1.1 to 1.4) and small negative cerium anomalies (Ce/Ce\* commonly 0.7 to 0.9).

## **TOTNES ROAD VOLCANIC ROCKS: A FRAGMENTAL, TI-ENRICHED KOMATIITE SEQUENCE ON CUMBERLAND PENINSULA, BAFFIN ISLAND**

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During the summers of 2009 and 2010, field work was conducted as part of the Cumberland Peninsula Integrated Geoscience (CPIG) project, a mapping project undertaken as part of the federal government's Geo-mapping for Energy and Minerals (GEM) initiative. During the project, distinctive fragmental ultramafic vol-

canic rocks were recognized on the shores of Totnes Road Fiord and elsewhere across eastern Cumberland Peninsula. The sequence is dominated by fragmental rocks and also contains massive, bedded, pillowed and variolitic volcanic units. Geochemical analyses confirm the ultramafic nature of the volcanic rocks resulting in their classification as komatiite and komatiitic basalt.

CaO/Al<sub>2</sub>O<sub>3</sub> and Al<sub>2</sub>O<sub>3</sub>/TiO<sub>2</sub> ratios indicate that the Totnes Road komatiite (TRK) is an aluminum-depleted komatiite (ADK). Thus, the magma was likely generated by melting at depths >250 km in the presence of majorite garnet which retained Al and HREE in the residuum. Furthermore, the TRK is enriched in TiO<sub>2</sub> with concentrations ranging from 0.83-1.80% compared to 0.3-0.4% in typical komatiites. In addition, the TRK has high concentrations of Hf, Sr, Zr, and the LREE relative to Yb, Al, Y, Sc, and the HREE. This enrichment combined with the TRK's distinctive fragmental nature suggests that it is similar to the rare Karasjok-type komatiites, named after their type location in the Paleoproterozoic Karasjok Greenstone Belt, Finland.

The unique chemical characteristics of the Karasjok-type komatiites have been explained by melting of metasomatised mantle beneath ancient continental crust. The TRK is found associated with semi-pelitic schist, quartzite, and chemical metasedimentary rocks in the form of sulphidic black shale and iron formation. This association of rocks is currently thought to represent part of a Paleoproterozoic cover sequence (Hoare Bay group). The TRK is interpreted to have erupted through extended stable continental crust, represented by a newly recognized 3.0-2.77 Ga plutonic basement complex, which likely had underlying mantle lithosphere that had been metasomatised, potentially as a result of subduction processes. The development of the basin into which the TRK erupted may be linked to the heat provided by the mantle plume. Clastic sedimentation dominated the basin in its early development but was replaced by chemical sedimentation after volcanism due to high heat flow allowing hydrothermal fluid circulation. The fragmental nature of the komatiitic rocks resulted from steam explosivity as the hot magma interacted with the colder basinal waters, this process may have been aided by slight hydration of the magma as it rose through the continental lithosphere.

## **Re-Os GEOCHRONOLOGICAL DATA FOR Zn-Pb DEPOSITS IN THE HOWARDS PASS AREA, YUKON AND NORTHWEST TERRITORIES, CANADA**

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The Howards Pass district straddles the Yukon Territory-Northwest Territories border and consists of stratabound Zn-Pb deposits hosted in unmetamorphosed carbonaceous and siliceous mudstones of the Duo Lake Formation (the informal stratigraphic name in the district is the Howards Pass Formation). Fossil ages (graptolite and conodont) indicate that the host rock unit was deposited in Early Silurian (Llandoveryan) time, but the absolute timing of sulphide mineralization has been unclear. Sulphides occur (a) as fine laminations interbedded with carbonaceous sedimentary rocks with pyrite and sphalerite being the dominant sulphide minerals; (b) as coarse laminations and layers with galena, pyrite, and sphalerite that are structurally controlled by microfolds; and (c) in veins that clearly cut bedding and sulphide laminations. Microtexturally, pyrite within the laminated ores is framboidal to cubic, consisting of irregular masses intergrown with mudstone and other sulphide minerals. New Re-Os isotopic data were obtained for pyrite from two deposits. Four separates from drill core through

the HC West deposit (DON-137) and eight separates from core (XYC-127) and ore pile samples at the XY Central deposit were analyzed. The pyrite separates, obtained largely from textural types (a) and (b) above, have variable Re and Os abundances; samples from the XYC deposit contain 2.2 to 5.4 ppb and 93 to 177 ppt Re and Os, respectively, whereas pyrite from the HC West deposit has 21 to 35 ppb Re and 600 to 695 ppt Os. The  $^{187}\text{Re}/^{188}\text{Os}$  and  $^{187}\text{Os}/^{188}\text{Os}$  ratios positively correlate and range between  $\sim 123$ –694 and  $\sim 1.72$ –3.52, respectively. The Re–Os isotope data yield an isochron age of  $442 \pm 14$  Ma (MSWD = 7.4), with an initial  $^{187}\text{Os}/^{188}\text{Os}$  of  $0.71 \pm 0.07$ . These data show that the early phase of pyrite precipitation (and by inference, associated sphalerite) occurred during the earliest Silurian ( $\sim 442$  Ma), which is consistent with the biostratigraphy of the host rocks. The initial  $^{187}\text{Os}/^{188}\text{Os}$  ( $\sim 0.71$ ) ratio is similar to that of earliest Silurian seawater recorded from the Ordovician/Silurian Type section (Dobs Linn, Scotland), suggesting a hydrogenous source for Os. Owing to the  $\sim 442$  Ma age that indicates syn-sedimentary sulphide precipitation, two possible sources of Os are (1) the zinc- and lead-bearing hydrothermal fluid leached Os from footwall sedimentary rocks that were deposited in seawater, or (2) Os was derived directly from seawater during precipitation of the pyrite, which suggests that the Os content of the hydrothermal fluid was minor relative to that of seawater.

#### THE CARIBBEAN CONTROVERSY: EVALUATING THE PIRATE MODEL

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The Caribbean Plate has migrated eastwards relative to the North and South American Plates since the Late Cretaceous. In principle, as the Caribbean Plate exits the western Caribbean region to the east, replacement lithosphere can enter from the west, from depth, or from the north or south. These end-member possibilities correspond to the Pacific, in situ, and pirate models, respectively, for the tectonic evolution of the Caribbean Plate. Most previous studies have favoured a Pacific model for Caribbean Plate evolution during late Cretaceous and Cenozoic time, but the issue remains controversial. Important for this discussion is evaluation of the pirate model, for which a possible role in the tectonic evolution of the western Caribbean has only been recently proposed.

Main predictions for the pirate model are as follows. At the northwest Caribbean Plate corner, counter-clockwise rotation and microplate escape from the southern margin of the North American Plate is predicted. Microplate escape requires synchronous extension, dextral shear conjugate to the sinistral northern Caribbean Plate boundary, and possibly shortening also, at the trailing, western, and leading edges of the microplate escape channel, respectively. Similarly, at the southwest Caribbean Plate corner, clockwise rotation of the main South American Plate, or microplate escape from the northern margin of the South American Plate, is predicted. Zones of synchronous extension, sinistral shear conjugate to the dextral southern Caribbean Plate boundary, and shortening are required at the trailing, western, and leading margins of rotating lithosphere. Preliminary analysis indicates possible roles for pirate mode tectonics across both corners. At the northwest Caribbean Plate corner, the Corsair rift zone, the dextral Sierra Madre Orientals deformation front, and the Colon fold belt may have accommodated the counter-clockwise escape of the Chortis Block from the Gulf of Mexico, prior to the Oligocene. At the southwest Caribbean Plate corner, the Mid-Atlantic Ridge, the sinistral Romeral fault zone, and the Leeward Antilles Trench may have accommodated the clockwise rotation of the South American Plate into the western Caribbean region, since ca. 55.9 Ma.

#### ITERATIVE MAPPING PROTOCOLS: GANFELD SOFTWARE REFACTORED FOR INTENTIONAL FLEXIBILITY

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During the past decade, the Geological Survey of Canada (GSC) has progressively developed the software called Ganfeld, an Arc-Pad plugin written in VBScript, to support the electronic collection of geological data in the field using handheld devices. During this time, both federal and provincial surveys have used Ganfeld to support their mapping programs. At the Department of Natural Resources, Nova Scotia, it has been useful to modify the stock functionality of Ganfeld, developed and shared by the GSC, to meet the particular requirements of provincial mapping protocols and programs. Repeated periods of customization of Ganfeld led to the recognition that incorporating more explicit design elements directly into the codebase that support such changes would be advantageous.

In the past year, the Department of Natural Resources, Nova Scotia, has refactored a Ganfeld codebase to support a greater degree of customization and evolution. For example, the modular design has been extended, a configuration file has been added, and rudimentary support for adding new data fields on-the-fly has been incorporated for earth materials and structures. The modular design means the Ganfeld interface can either be changed interactively or customized for particular projects. The configuration file means that much of the functionality, such as id schemes, data fields, and data values, can be changed to suit the mapping protocols and data schemes of different surveys, departments, or projects without changing any code. Finally, the support for adding new data fields on-the-fly, removes some of the artificial limitations of software that has not anticipated all use cases, while retaining the advantages of software for maintaining consistency in data entry. The vision for this refactored version of Ganfeld is to serve as both working software and as a prototype for developing an ever improved set of user requirements for field data acquisition software, in general. In collaboration with the GSC and other provincial surveys, elements identified in this process may be incorporated into future versions of Ganfeld.

#### RARE-EARTH ELEMENT (REE) PATTERNS IN THE STRANGE LAKE DEPOSIT, NORTHERN LABRADOR-QUÉBEC: INDICATIONS OF MAGMATIC, MINERALOGICAL AND HYDROTHERMAL CONTROLS

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The Strange Lake Deposit contains an historic total resource of some 56 million tonnes at 2.99%  $\text{ZrO}_2$ , 0.38%  $\text{Y}_2\text{O}_3$ , 0.31%  $\text{Nb}_2\text{O}_5$  and 0.54% total REE oxides; however, the REE estimates from the 1980s were to a large extent based on extrapolation from other data. The deposit is now closed to exploration pending finalization of land-use plans with the Nunatsiavut (Inuit) Government, but its REE potential is under assessment in the context of global interest in the REE, and new discoveries in adjacent Québec. New REE data acquired from archived exploration core samples held by the Department of Natural Resources offer some insight into the behaviour of the REE, their mineralogical deportment, and controls upon their behaviour.

The heavy REE (Gd to Lu) show excellent correlations with Y ( $R=0.85$  to  $0.98$ ) with the strongest association between Y and Ho, consistent with their similarity in ionic radius. Similar correlations exist between individual heavy REE, indicating that historical Y data can reliably be used to estimate grades and resources for these valuable elements. This association is also consistent

with historical observations that many REE and Y are hosted by a still-unnamed Ca-Y-REE silicate. The light REE (Ce to Sm) also exhibit strong interelement correlations, but their association with Y is looser ( $R=0.48$  to  $0.67$ ). Europium (Eu) offers a possible “bridge” between the two REE groups for grade and resource estimation. The REE as a whole (aside from Tm, Yb and Lu) exhibit little correlation with Zr or with Nb, suggesting that gittinsite (Ca-Zr silicate) and pyrochlore are not significant hosts for most REE. Zirconium and Hf are, as expected, strongly linked. The contrasting behaviour patterns may indicate a specific host mineral for the light REE, but could also be interpreted in terms of hydrothermal redistribution of these more mobile cations. Ongoing mineral geochemistry studies, using LA-ICP-MS, coupled with 3D spatial assessment of the whole-rock data, should assist in resolving such interpretations.

#### **ACTIVITIES UNDER THE MINERAL RESOURCE ASSESSMENT COMPONENT OF THE REMOTE PREDICTIVE MAPPING PROJECT, GEM AND MERA PROGRAMS**

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Mineral resource assessment (MRA) is a component of the activities undertaken as part of the GEM (Geo-mapping for Energy and Minerals) and MERA (Mineral and Energy Resource Assessment) programs of Natural Resources Canada. The principal long-term objectives of the MRA component are to develop viable quantitative methods for the identification of areas prospective for discovery of key deposit types across Canada's North and to provide reasonable estimates of the endowment of the commodities contained within the undiscovered deposits.

Ongoing work by Chung, Franklin and Hillary has resulted in the continued development and testing of a new knowledge-driven method for the identification of areas favourable for the discovery of new deposits (VMS, gold). User-friendly software to support the new methodology is under development.

Recent work by Wright, Kerswill and Kjarsgaard in support of the East Arm MERA demonstrated that knowledge-driven models based on the weighted overlay method can be successfully applied to generate useful mineral potential maps for a spectrum of deposit types. Maps for kimberlitic diamond, volcanogenic massive sulphide, magmatic sulphide, vein gold, polymetallic veins, base metal veins, uranium-bearing veins, uranium in sandstone, IOCG-like, chromitite and Proterozoic rare metals in syenite and pegmatite were produced.

Prior to the 2010 field season, Kerswill expanded previous work directed towards delineation of areas prospective for discovery of IOCG deposits in the Great Bear Magmatic Zone (GBMZ). More than 50 targets have been identified, including many in zones that lack known occurrences. Related work is being carried out under the IOCG-Great Bear Region project by Corriveau and coworkers.

Ongoing experiments with the bedrock geology and fault layers of the 1:5000K IPY map for the Arctic (GSC Open File 5816 and soon to be released A-series map 2159) indicate that both data-driven and knowledge-driven approaches can yield useful mineral potential maps for gold in Western Churchill Province.

Recent work by Bretzlaff has resulted in significant improvements to knowledge regarding the distribution and character of mineral occurrences in the GBMZ, southern Melville Peninsula, Cumberland Peninsula and Victoria Island, four areas covered by projects under GEM Minerals. Such information is critical for the

application of data-driven methods that depend upon a training set of known occurrences, and for the validation of knowledge-driven mineral potential maps that do not require a training set.

#### **A DETAILED ANALYSIS OF OVERBANK SPLAY UNITS IN THE NEOPROTEROZOIC ISAAC FORMATION (WINDERMERE SUPERGROUP), SOUTHERN CANADIAN CORDILLERA**

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WITHDRAWN

#### **SUTTON HOTSPOT: RESOLVING EDIACARAN-CAMBRIAN TECTONICS AND TRUE POLAR WANDER FOR LAURENTIA**

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Hotspot tracks represent plate motions relative to mantle sources, and paleomagnetic data from magmatic units along those tracks can quantify motions of those mantle anomalies relative to the Earth's magnetic field and rotational axis. The Ediacaran Period is notable for rapid and large paleomagnetic apparent polar wander (APW) for many continents. Whereas magmatic units attributed to the “Sutton” mantle plume suggest a practically stationary hotspot track, paleolatitudes of Laurentia for that interval vary dramatically; geologic and paleomagnetic data are at odds unless true polar wander (TPW) is invoked to explain a majority of APW. Here we test the plume-TPW hypothesis by generating the predicted Sutton hotspot track for a stationary plume under a moving plate along the Laurentian margin during 615-530 Ma. Our model is the first to provide a kinematic framework for the extensive large igneous province associated with opening the Iapetus Ocean.

## CONTROLS ON HIGH-SULPHIDATION EPITHERMAL GOLD MINERALIZATION: NEW INSIGHTS FROM THE BAWONE-BINEBASE DEPOSITS, INDONESIA

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High-sulphidation epithermal deposits represent increasingly important sources of gold but are difficult to study because of poor preservation and the intense alteration by acidic fluids that commonly leaves few mineral relicts. Here we use a new technique involving pyrite mineralogy, trace-element geochemistry and crystallography to investigate the mechanism by which gold is incorporated into pyrite, using samples from a relatively young high-sulphidation epithermal gold depositing system.

Bawone and Binebase are related high-sulphidation epithermal Au (Cu-Ag) deposits located 1 km apart on the volcanic island of Sangihe, Northeastern Indonesia. Still undergoing exploration, the deposits have inferred resources of 27.3 million tonnes averaging 0.95 g/t gold and 13.58 g/t silver, i.e., 836,718 ounces gold and 11,927,237 ounces silver distributed in supergene and hypogene zones. This study focuses on the hypogene zones where intense acidic fluxing characteristic of high-sulphidation deposits has produced an advanced argillic alteration assemblage dominated by fine-grained quartz, pyrite and alunite with kaolinite (natroalunite and dickite are also present), but without the vuggy silica common to many other deposits. The mineralization in the hypogene zones is dominated by multiple generations of pyrite, cross-cut by late veins of barite-enargite-pyrite. The highest gold concentrations occur in the PyII generation of subhedral, drusy pyrite, showing complex growth and sector zonation.

Using EMPA, LA-ICPMS and SIMS analysis, we have demonstrated that the gold in the hypogene zones is almost all contained in pyrite, specifically PyII, in which we have measured gold concentrations of up to 15.2 ppm Au. Concentrations of up to 5.3 wt% Cu were also measured, which is among the highest concentration ever recorded. PyII enriched in these metals also commonly contains Se, Te, Co, Ni, Sb, Ag, As, Zn and Pb. Combining element maps and quantitative analysis, we have been able to construct relative changes in physicochemical conditions (predominantly temperature) from the distribution of elements between sector zones, and the change of this distribution in successive growth zones of a single crystal. Using the distribution coefficient (Kd) as a proxy for temperature (and potentially pH) and the variation of gold concentration with Kd, we have identified the physicochemical conditions favouring gold incorporation. Preliminary results indicate that gold up-take by pyrite (through adsorption) is greatest when gradients in physicochemical conditions are weakest, which contrasts strongly with the requirements for native gold deposition, namely a strong physicochemical gradient. This has important implications for models interpreting the genesis of high-sulphidation epithermal deposits.

## THE PULPWOOD HARBOUR INTRUSION-A TERRESTRIAL ANALOGUE FOR MARTIAN FERROPICRITES?

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The finding of Fe-rich picritic rocks by the rover Spirit in the Gusev Crater on Mars has stimulated interest in Fe-rich magmatism on the early Earth. An understanding of the petrogenesis of the Martian ferropicrites is hampered by the paucity of data on their mineralogy and geological context. On Earth however, a significant number of occurrences of ferropicrite magmatism have been identified in Archean terranes and thus a study of their min-

eralogy and setting may provide insights into the petrogenesis of their Martian equivalents. One of the best exposed of these terrestrial ferropicrites occurs as sills in the Pulpwood Harbour sequence of the Heron Bay volcanics (ca. 2.6-2.7 Ga) in the Wawa Greenstone Belt of Superior Province of Canada. Although these sills are metamorphosed and tightly folded, top determinations in their enclosing volcanics indicate that the sills consist of a relatively thin lower unit of hornblendite followed upward by serpentinite, and then a thicker upper unit of hornblendite. The serpentinite ranges in composition from dunite to olivine clinopyroxenite, whereas the hornblendites range in composition from clinopyroxenites to gabbros. The sequence of these cumulate rocks can be explained by progressive crystal fractionation: olivine (Fo 79) crystallized first producing the dunite, followed by clinopyroxene producing olivine pyroxenite to clinopyroxenite, and finally plagioclase and iron oxides producing gabbro. Although this crystallization sequence is relatively common in Archean and Proterozoic mafic intrusive suites, the Pulpwood Harbour cumulate sequence is distinct in that it is shifted to significantly more Fe-rich compositions, with the gabbros containing up to 24 wt.% Fe<sub>2</sub>O<sub>3</sub>. Samples collected along the contact of the Pulpwood Harbour intrusion have compositions approaching that of the magma that produced the cumulate rocks and are interpreted to be chilled margins. The compositions of these chilled margins are strikingly similar to those of Martian lavas and thus the parental magma of Pulpwood Harbour intrusion may represent a terrestrial analogue for Martian ferropicrite magmatism.

## MAJOR- AND TRACE-ELEMENT PARTITIONING DATA FOR IMMISCIBLE SILICATE-CARBONATE LIQUID PAIRS FROM EXPERIMENTS ON ALKALI-POOR BULK COMPOSITIONS

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Partition coefficients for immiscible silicate-carbonate liquid pairs (expressed as Ds/c) were determined by EMPA and LA-ICP-MS for experiments in two systems; i) nephelinite – sövite at 0.5 GPa, 1025 – 900°C; and ii) melilitite – Mg-sövite at 2.0 – 1.2 GPa, 1300 – 1050 °C. The experiments cover a wide range of P-T conditions, and in all cases the REE favour the carbonate liquid, with LREE partitioning greater than HREE (Ds/c for La = 0.03 to 0.6; Yb = 0.1 to 0.99). Furthermore, for all P-T-X conditions, niobium always partitions into the carbonate liquid (Ds/c for Nb = 0.41 to 0.99) whilst zirconium partitions into the silicate liquid (Ds/c for Zr = 1.5 to 20). Hence, during liquid immiscibility in these systems, Nb and Zr are strongly decoupled. Hf and Ta are also decoupled, but both partition into the silicate liquid (Ds/c Hf = 3 to 11; Ta = 1.5 to 4). Thorium and uranium show variable partitioning behaviour with Ds/c ranging from 0.2 – 3, the carbonate liquid being favoured at lower T and/or higher P conditions.

The partitioning behaviour for these particular starting compositions (i.e. nephelinite – sövite), are quite remarkably different from the results previously reported for experiments on more peralkaline nephelinite/phonolite – natrocarbonatite systems. Results from earlier experimental studies on highly alkali systems (Veksler et al., 1998) suggested that both REE and HFSE elements always partition into the silicate liquid. This would appear to preclude liquid immiscibility as a process for generating REE- and Nb-metal rich carbonatites.

We argue that our compositions are a closer match to those more typically observed in nature and cover a wide range of P-T conditions. As a result they strongly supports liquid immiscibility as a viable process to generate REE- and Nb-rich sövite and Mg-sövite magmas. Although experiments on more peralkaline com-

positions would appear in the first instance to exclude an immiscible origin at Oldoinyo Lengai, we note that once separated, the two magmas will develop very different trace element signatures due to fractionation of REE- or HFSE-rich mineral phases. Any attempt to reconstruct the original immiscible liquid compositions and compare trace element distributions will be fraught with difficulty.

#### **AN ASSESSMENT OF THE PRECISION AND ACCURACY OF A PORTABLE XRF ANALYZER COMPARED TO FUSION ICP-EMISSION SPECTROMETRY AND AQUA REGIA ICP-MASS SPECTROMETRY**

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Portable X-ray fluorescence (XRF) analyses provide an efficient, cost-effective, and non-destructive method to measure variations in elemental concentrations in sediment samples. For fine-grained materials analytical wet geochemistry, X-ray diffraction (XRD) analyses, and petrographic and microbeam analyses are commonly used to determine elemental abundances and related mineralogy. These methods can be time consuming and expensive especially when a large number of analyses are required. Portable XRF analyses are an increasingly common method used to determine high-resolution elemental abundances at a fraction of the cost and time of wet chemistry.

This study assesses the validity of using a NITON XL3t GOLDD hand-held XRF analyzer in Soil Mode to define the chemostratigraphy of a 90 metre borehole through late Pleistocene Champlain Sea sediments near Ottawa, Ontario. Samples analyzed using the portable XRF unit are compared with results obtained by ICP-emission spectrometry following a Lithium metaborate/tetraborate fusion and by an ICP-mass spectrometry following an aqua-regia digestion. Seventeen elements (K, Ca, Mn, Fe, As, Rb, Sr, Ba, Ni, Cu, Zn, Cr, Ti, V, Sc, S, and Zr) were in sufficient quantities to be detected by the XRF analyser. Quadruplicate analyses for each sample were compared using the R statistical computing and graphics software package. For all detected elements excluding Mo, Ni and S the probability that the differences between the results are due to instrument variability is close to zero therefore the difference between samples at different stratigraphic depths reflects a real change in elemental abundance. For Mo, Ni, and S many of the analyses are near or below the detection limit. Although the values detected by all three methods often varied, the trends of either increasing or decreasing elemental abundances between each method is remarkably similar.

This study demonstrates that portable XRF tools, particularly the NITON XL3t can be used with confidence in chemostratigraphic analyses of fine grained sediment with a Canadian Shield provenance. Comparison of results with a dataset analyzed by conventional means indicates that some differences occur between absolute values between the two methods. This difference however is relatively minor, and for the most part is no greater analytical variability observed between many methods.

Data resulting from this method has applications in pre-screening samples for further often destructive analyses, identification of parent source rocks, changes in depositional conditions, and augments classical core logging techniques including, micro palaeontology, downhole geophysics and wet geochemistry.

#### **THE 380 Ma EAST KEMPTVILLE TIN DEPOSIT, NOVA SCOTIA, CANADA: PETROLOGICAL RECORD OF THE MAGMATIC-HYDROTHERMAL TRANSITION IN A F-RICH FELSIC MAGMATIC SETTING**

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The magmatic-hydrothermal transition in felsic systems represents a sudden change in the physical and chemical properties of magmas, often manifested both chemically and texturally. Importantly, this transition often culminates in the formation of a variety of mineral deposits types, such as veins, greisens, pegmatites and skarns, hence these features are relevant and may provide vectors towards mineralized zones. The East Kemptville Sn-(Cu-Zn-Ag) deposit, hosted by the 380 Ma peraluminous South Mountain Batholith, Nova Scotia, represents such an example of the magmatic-hydrothermal transition which culminated in mineral deposit formation. This transition is recorded on both regional- and local scales by chemical and textural features. The deposit occurs within an evolved topaz-muscovite leucogranite formed as from the extreme crystal  $\pm$  fluid fractionation of the chemically zoned Davis Lake Pluton. This zonation is recorded some major elements (e.g. SiO<sub>2</sub>), incompatible trace elements (e.g. Rb, Li, U, Ta, and Sn), elemental ratios (e.g. K/Rb) and isotopes (Sr, Pb). The increasing role of fluids is recorded by decreasing  $\Sigma$ REE and Eu\*/Eu with a concomitant increase in F, decrease in K/Rb (200 to  $\leq$ 50), development of tetrad REE profiles and departure of Nb/Ta ratios from chondritic values. Increasing involvement of fluids is also reflected by the alteration of magmatic phases and development of local pegmatite pods. At the deposit site the evolved leucogranite has a chilled contact, but it is observed to coarsen downwards through a zone characterized by coarse (m-scale) K-feldspar-rich pegmatite, layered aplite-pegmatite, UST textures, presence of aphanitic dyke rocks and miaroles before a homogeneous, medium-grained phase dominates. These features suggest pressure cycling and periodic fluid saturation during the terminal stages of crystallization, which occurred at a  $T \leq 500^\circ\text{C}$  and  $P_{\text{fluid}} = 3.5$  kbars. The high pressure inferred for this setting is unusual for the textures observed, which are more typical of higher-level environments, but their development may relate to periodic depressurization due to the localization of the leucogranite within a brittle-ductile fault zone.

#### **THE SIGNIFICANCE OF SODIC METASOMATISM IN RARE-ELEMENT PEGMATITES: A PETROLOGICAL AND FLUID INCLUSION STUDY OF THE BRAZIL LAKE LCT-TYPE PEGMATITE, NOVA SCOTIA**

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That evolved, rare-metal enriched pegmatites owe their origin to extreme fractionation of a felsic melt is not disputed, but the role of magmatic versus metasomatic processes in rare-metal enriched settings remains controversial. The 395 Ma Brazil Lake pegmatite (BLP) of Nova Scotia provides convincing evidence that in some cases sodic metasomatism can be implicated in rare-metal mineralization (Ta, Nb, Sn). The BLP consists of a primary Qtz-Kfs-Spd-Ms assemblage, lacks a Qtz-rich core zone and, in some areas, displays textural evidence for syn-emplacement deformation. Blocky Kfs is overprinted by secondary Ab and Ms, with albitization coincident with porosity development. Whole-rock (N=250) geochemical data indicate a strong correlation between



rare metal enrichment and albite formation. The nature and origin of the metasomatism were examined using stable isotopes and fluid inclusions. Oxygen isotope data indicates most albite has a magmatic signature ( $\delta^{18}\text{O}_{\text{Ab}} = +9 \pm 0.5\text{‰}$ ,  $N=6$ ), but that Ms equilibrated in part with an external reservoir. Studies of Qtz- and Spd-hosted fluid inclusions indicate two fluids are present, both of secondary origin; (1) an aqueous fluid having 2-10 wt. % equiv. NaCl with  $T_h = 165$  to  $225^\circ\text{C}$ , and (2) an aqueous-carbonic fluid ( $X_{\text{CO}_2}=0.15$ ) having 3 to 10 wt.% equiv. NaCl and  $T_h = 180$  to  $235^\circ\text{C}$ . Thermometric data and isochoric projections are consistent with petrographic observations suggesting the fluids are not primary and were trapped during the subsolidus history of the pegmatite. An external origin for the  $\text{CO}_2$  is suggested based on  $\delta^{13}\text{C}$  values of  $-22 \pm 2\text{‰}$  ( $N=8$ ). Solute chemistry of the inclusions is constrained from SEM-EDS analysis of evaporate mounds, which indicates Na dominates ( $\text{Na}/\Sigma\text{cations} \geq 90\%$ ), and LA ICP-MS analysis that provide the following average elemental concentrations (in ppm): Na (29300), Al (2865), Li (840), K (620), B (670), Fe (330), Cs (230), Ca (57), Rb (40), and Sr (6) with Ta and Nb below detection. These data suggest the rare metal mineralization coincided with albitization of primary Kfs at ca.  $400\text{--}500^\circ\text{C}$  due to interaction with a residual sodic-rich melt derived from depth, but that a distinct fluid phase was not important until later with some of it externally derived.

#### **GEOLOGICAL, PETROLOGICAL AND GEOCHEMICAL OBSERVATIONS OF AN ARCHEAN SYENITE-ASSOCIATED Cu-Au DEPOSIT, KIRKLAND LAKE, ONTARIO: A TEMPORAL OR GENETIC RELATIONSHIP**

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The Upper Beaver Au-Cu deposit of the Kirkland Lake gold camp, northern Ontario, produced 136,650 oz Au from 0.5 Mt grading 7.9 g/t and 1% Cu (1912-1972). Recent work has delineated a resource of over 0.64 M oz Au, which is increasing with continued exploration. The region is underlain by mafic to felsic volcanic rock sequences with intercalated sedimentary rocks of the Tisdale and Blake River groups with younger sedimentary rocks of the Timiskaming Group; all units are cut by syenitic intrusions. At Upper Beaver, located on a splay off the main, regional E-W trending and metallogenetically significant Kirkland-Larder Lake break, mineralization is spatially related to a 2679 Ma multi-phase syenite complex, which includes magmatic and hydrothermal breccias. The Cu-Au mineralization, which is structurally controlled, is centred on the syenite complex, but also occurs in adjacent metavolcanic rocks. Unusual compared to the stockwork ore of the Kirkland Lake gold domain is the association of mineralization with abundant hydrothermal Fe oxide ( $\text{Mt} \gg \text{Hmt}$ ) and variably pervasive epidote-albite  $\pm$  sericite  $\pm$  actinolite  $\pm$  tourmaline alteration; rare anhydrite also occurs. Petrological and geochemical studies indicate (1) fractionation of the syenite from an Amph-bearing phase to Qtz-Kfs dykes associated with ore zones. The absence of a Eu anomaly suggests an oxidized magma; (2) F-enrichment in both magmatic (i.e. Amph) and hydrothermal (i.e. Apt) stages; (3) Au shows an association with potassic enrichment; and (4) although free Au dominates, silver, bismuth telluride phases (Bi-Hg-Te-Se-Pb-Ag) occur and  $\leq 30$  ppm Au occur in chalcopyrite. Stable isotopic analysis indicate: (1)  $\delta^{34}\text{S}_{\text{H}_2\text{S}} = 0 \pm 2\text{‰}$  and that vein formation occurred at  $450\text{--}400^\circ\text{C}$ ; (2)  $\delta^{18}\text{O}_{\text{H}_2\text{O}} = +10 \pm 2\text{‰}$  based on Qtz and Mt and  $\delta^{18}\text{O}_{\text{H}_2\text{O}} = +8 \pm 2\text{‰}$  for carbonate; and (3)  $\delta^{13}\text{C}_{\text{CO}_2} = 0\text{‰}$ . Limited fluid inclusion studies

have identified both aqueous and aqueous-carbonic fluids, the latter being typical of fluids in Archean vein systems. The data are permissible with a model for the Upper Beaver Cu-Au deposit that involves focusing of mineralizing fluids of mixed parentage involving both that magmatic and metamorphic reservoirs, as supported by a Re-Os age of 2685 Ma for moly from a mineralized zone.

#### **GEOCHEMICAL AND MINERALOGICAL SIGNATURES OF THE DEUTERIC KIMBERLITE FLUID**

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Volatile-rich kimberlite melt may expel large volumes of deuterite fluids. They percolate through the freshly deposited pyroclastic kimberlites and cement pyroclasts with the colloform carbonate like that found in Fort à la Corn and Buffalo Head Hills. Deuterite minerals also grow in late veins adjacent to kimberlite intrusions, like en echelon veins that pervasively cross-cut the Snap Lake dyke and the surrounding country rocks. The carbonatitic affinity of the fluid expelled by the residual kimberlite magma is suggested not only by the predominance of carbonate among the deuterite minerals, but also by the geochemical changes imprinted by the fluid onto mantle minerals.

We studied hypabyssal serpentine monticellite kimberlite of Snap Lake to document effects of removal of the residual deuterite fluid and its interaction with kimberlite minerals. The Snap Lake dyke is comprised of a Group-I kimberlite characterized by the absence of perovskite, low modal carbonate, and low contents of Ca, P, K, Rb, Sr, Zr and Hf. The Ca- and P-poor character of the Snap Lake kimberlite may have resulted from separation of the residual carbonatitic fluid. Furthermore, there is evidence that the fluid locally invaded some domains of partly crystallized kimberlite dyke. The fluid was oxidized and this led to crystallization of rutile enriched in  $\text{Fe}^{3+}$ . The Mn- and Sr-rich character of the fluid is inferred from the formation of Sr-rich apatite (1 wt.% SrO) and Mn-rich ilmenite (3-5 wt.% MnO). All these minerals are present in one highly localized part of the dyke, where they accompany zoned Ba-rich phlogopite. The reverse zoning of the phlogopite from the kinoshitalite core (up to 15 wt.% BaO) to Ba-poor rim is rare in kimberlites, but was previously found in some hypabyssal kimberlites with a distinctly high bulk  $\text{Fe}_2\text{O}_3$  content and high  $\text{Fe}_2\text{O}_3/\text{FeO}$  ratios. The kinoshitalite cores formed from the Snap Lake kimberlite early on, when the melt had barely crystallized 10-20% of its volume. Such low degree of crystallization cannot cause the observed Ba enrichment of kinoshitalite. The residual fluid-rich melt which crystallized 90% of its volume, however, may bring the required high Ba. We therefore suggest that the oxidized residual kimberlite fluids charged with Ba, Mn, Sr and  $\text{Fe}^{3+}$  flushed parts of the Snap Lake dyke and caused the deviating kimberlite mineralogy highly localized in time and space. The geochemical affinity of the fluid confirms its carbonatitic nature, as Ba, Mn and Sr concentrate in carbonatites and are commonly enriched in stockworks of late veins around carbonatites. We also suggest that enrichment in Mn reported in some kimberlite megacrysts and diamond inclusion oxides could be a sign of interaction with deuterite kimberlite fluids.

#### **POPULATION HEALTH RISKS OF ENVIRONMENTAL RADON**

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Radon-222 is a natural radioactive gas formed during the decay series of uranium-238, which is present in rocks and soils in the

earth's crust. Cohort studies of underground miners exposed to high levels of radon gas in the past have consistently demonstrated an increased risk of lung cancer. Although exposures to environmental radon are much lower, case-control studies have also demonstrated increased lung cancer risks in residential settings. Elevated lung cancer risks have recently been demonstrated in a large prospective cohort maintained by the American Cancer Society.

These findings have led the International Agency for Research on Cancer to designate radon as a known cause of cancer in humans in 1988; this designation was confirmed in the Agency's recent review and update of the approximately 100 known human carcinogens. The recent demonstration that residential radon exposure increases lung cancer risk led to a reduction in the Canadian national residential radon exposure guideline from 800 to 200 Bq/m<sup>3</sup>. Analyses of the ACS cohort suggest that individuals exposed to radon levels about the current U.S. Environmental Protection Agency (EPA) radon guideline of 148 Bq/m<sup>3</sup> (equivalent to 4 pCi/L) experienced a lung cancer risk 34% higher than those whose exposures were below the EPA guideline; the U.S. National Research Council's Committee on the Biological Effects of Ionizing Radiation (BEIR VI) has estimated that one-third of the lung cancer burden associated with residential radon is due to exposures below the EPA guideline. The World Health Organization, as part of its recently completed Global Radon Project, has suggested an international residential radon guideline of 100 Bq/m<sup>3</sup>.

This presentation will provide an overview of the current scientific evidence on the population health risks associated with residential radon, including the epidemiological methods used to characterize the lung cancer risks associated with radon exposure. The sources of data on radon exposure used in these studies are discussed, along with factors affecting temporal and spatial variation in residential radon levels. Other issues involved in radon risk assessment and risk management, including those relating to risk communication, are also noted. Opportunities for collaboration between the population health risk assessment and geosciences communities in assessing residential radon exposures and concomitant population health risks are explored.

#### **QUANTIFICATION OF DEFORMATION MICROFABRICS AS A TOOL IN GEOTHERMOMETRY**

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The effect of temperature on the development of microfabrics in crystalline material during and after deformation is significant. Vice versa, under certain conditions, the quantitative aspects of specific microfabrics, such as skeletons of crystallographic preferred orientations, sizes of recrystallized grains, geometries or crystallographic orientations of grain-boundary segments, may serve as indicators of temperatures. Data created by polarizing microscopy, universal stage, fabric analyser, or electron backscatter diffraction, can be quantified by classical methods or by modified new methods of fractal geometry.

Different types of temperatures may be determined. (i) Discontinuous thermometers, such as the occurrence of recrystallization or subgrain boundaries of specific orientation, show if temperature has exceeded or fallen below a specific value. (ii) Continuous thermometers are based on quantified microfabrics and provide temperature values that were reached in the material during different stages of development. These values represent temperatures during or at the decline of deformation, or at the temperature peak. Some of the thermometers are strain-rate dependent and others not. A prominent example of a deformation-related thermometer are the opening angles of quartz-c preferred orienta-

tion skeletons across strain Z. The complex geometry of sutured grain boundaries or their crystallographic orientations indicate temperatures at the decline of deformation. Maximum annealing temperatures can be correlated with the sizes of statically recrystallized and coarsened grains.

Most of these geothermometers work on a statistical basis with range of error of  $\sim \pm 50^\circ\text{C}$  or even less. Because they are mainly empirically established in naturally deformed rocks they may be applied to these rocks without 'scaling' problems. Compared to petrological geothermometers, the microfabric-based ones are advantageous. (i) They can be applied to rocks, such as orthogneisses, which are not or less suitable for petrological geothermometry. (ii) They can be partly directly related to deformation events and, consequently, facilitate linking deformation and temperature-(pressure) histories of rocks. Even if they are affected by additional parameters, such as strain, strain rate or fluids, in general the effects can be taken into account. Microfabrics-related geothermometers and specifically those based on quantified microfabrics are a useful complement to petrological geothermometers, particularly where deformation plays an important part in rock history. They may become even more useful on the basis of increased data sets and new quantification methods.

#### **APPRAISAL OF APPLICABLE DEPTH CONSTRAINTS FOR THE PURPOSE OF ESTABLISHING THE OUTER LIMITS OF THE CONTINENTAL SHELF**

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Among the two constraint criteria in Article 76(5-6) of the United Nations Convention on the Law of the Sea only the distance constraint may be applied on submarine ridges while on submarine elevations that are natural components of the continental margin, the two constraints may be combined. In its Scientific and Technical Guidelines the Commission on the Limits of the Continental Shelf recommends a number of criteria regarding the selection of points along the 2,500 m isobath with regard to the construction of applicable depth constraint lines. In its considerations of the proposed outer limits that coastal States have submitted to the Commission there are clear inconsistencies between the principles adopted by the Commission and the Guidelines governing the determination of valid 2,500 m isobaths for the purposes of delineating the outer limits of the continental shelf. Further, the Commission appears to disregard the distinctive criteria applicable to the parts of the continental margin that are natural components and those that are not natural components, yet integral parts of the continental margin.

#### **GEOENVIRONMENTAL ORE DEPOSIT MODELLING-RECENT DEVELOPMENTS IN CANADA AND POTENTIAL APPLICATIONS**

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The correlation of environmental behaviour with mineral deposit type has been recognized since the early 1990s through independent research by the United States Geological Survey and Natural Resources Canada (through the Mine Environment Neutral Drainage Program). Early geoenvironmental ore deposit models are descriptive in nature, composed essentially of compilations of pertinent geologic, geochemical, geophysical, hydrologic and engineering information that sheds light on the environmental behaviour of geologically similar deposits, both prior to mining and as a consequence of mining, mineral processing and smelting. Recent research efforts branch out to include such topics as developing indicators for quantitative prediction and exploring the links

of geoenvironmental ore deposit models to human health. Current work at the CANMET Mining and Mineral Sciences Laboratories, on the other hand, focuses on clarifying the relationship between deposit geology and mining, mineral processing and mine waste management methods in identifying the environmental challenges associated with mining a particular type of ore deposit. Choosing the right combination of methods at an appropriate stage of the mining life cycle can significantly reduce the environmental impacts and risks and the overall cost of a mining project. Two practical examples will be given, based on observations made at two developing mines at the border of the Yukon and Northwest Territories, to illustrate how taking advantage of the deposit geology and mineralogy to develop a mining strategy may significantly reduce potential acid generation from the prospective sulphidic mine wastes. Prudently applied, environmental ore deposit models can help miners find potential solutions to tackle anticipated challenges during exploration and make development decisions accordingly. Information compiled in a comprehensive model can also help regulators and local communities to decide if a proposed mining project is acceptable from an environmental perspective.

#### **ISOTOPE BIOSIGNATURES PROVIDE EVIDENCE OF MICROBIAL RESPIRATION IN ANCIENT TERRESTRIAL GROUND ICE**

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The study of ancient massive ground ice and sediment-rich ice bodies not only allows an understanding of the stability of permafrost, but also offers the possibility to understand the long-term preservation and viability of microbes within these ice bodies. Although microorganisms have been identified in ancient bodies of ground ice and permafrost, there still is a lack of convincing evidence that the microbes were metabolically active within the ice. In this study, we combine geomicrobiology methods with the measurements of occluded biological and noble gases in four ancient bodies of ground ice to provide evidence of in situ microbial respiration in ancient ground ice bodies. In our samples, abundant cold-adapted heterotroph microorganisms were identified using culture-dependant and -independent methods. The occluded gas measurements, with low  $\delta(\text{O}_2/\text{Ar})$  (less than  $-21.4\%$ ) and  $\delta^{13}\text{C}_{\text{CO}_2}$  (as low as  $-25.2\%$ ) values and high  $\delta^{18}\text{O}_{\text{O}_2}$  (up to  $+16.3\%$ ) values are highly suggestive of in situ consumption of  $\text{O}_2$  by heterotrophic psychrophilic bacteria living within the ice matrix. Overall, the multi-disciplinary approach provides a strong set of tools from which to detect metabolic activity within bodies of ground ice preserved in permafrost, and to derive isotope biosignatures from occluded gases that could allow detecting evidence of life on other cold planetary bodies without necessitating aseptic drilling.

#### **NEW CONSTRAINTS ON PALEOPROTEROZOIC METAMORPHISM AFFECTING THE REPULSE BAY BLOCK, MELVILLE PENINSULA, NUNAVUT: IN SITU LA-ICPMS FROM TWO GENERATIONS OF MONAZITE GROWTH**

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The Repulse Bay block forms the southern portion of the Melville Peninsula, Nunavut, and occurs south of the Paleoproterozoic-age Penrhyn Group. The block is composed dominantly of Archean polydeformed gneisses and granitic intrusions with less abundant supracrustal sequences, made up of marble and metapelite. The monotonous marble-metapelite sequences differ in nature from

the stratigraphically more complex Penrhyn Group, which overlies the southern edge of the Rae Craton, *sensu stricto* to the north. The Repulse Bay block occurs as a piece of middle to lower crust, recording upper amphibolite- to granulite-facies metamorphic conditions. Presently, there is very little known about either the crustal evolution or the tectono-thermal history of the crustal block. Recent regional scale bedrock mapping, integrated with metamorphic mineral paragenesis, microstructure, and U-Pb geochronology are used to document the multi-stage Paleoproterozoic evolution of the Repulse Bay block. By combining these analytical techniques it is possible to provide insights on its tectono-thermal history and enable comparisons with surrounding blocks.

In situ LA-ICPMS monazite geochronology from a garnet-sillimanite-biotite bearing metapelite records at least two temporally distinct stages of Paleoproterozoic metamorphism. A generation of ca. 1850 Ma monazite grains occurs in stromatic leucosomes composed primarily of quartz + K-feldspar that are interpreted to record the timing of prograde biotite-dehydration melting. The youngest monazite grains occur in cordierite + spinel + biotite coronas surrounding regional metamorphic garnet grains. This texturally and morphologically distinct generation of monazite is interpreted to have grown during garnet resorption as a consequence of high temperature decompression at ca. 1807 Ma.

Thus, the metapelites record at least two stages of Paleoproterozoic metamorphism, highlighting the advantages of in situ isotopic dating combined with observed textural relationships. This approach further constrains the tectono-thermal evolution of the Repulse Bay block and therefore is significant in understanding understanding of the overall crustal evolution history of this part of the western Churchill Province. Similar monazite age clusters and thermal evolution patterns are observed on south-central Baffin Island to the east and in the Committee Bay belt to the west.

#### **TRACKING IOCG AND ALKALI-CALCIC PORPHYRY Cu-Au MINERALIZATIONS IN THE ARCHEAN ABITIBI SUBPROVINCE: A GENETICALLY-RELATED INTRUSION APPROACH**

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Regional scale exploration guides for IOCG and alkali-calcic porphyry types of Cu-Au mineralization can be defined using litho-geochemistry of genetically-related intrusions, as demonstrated in the Archean Abitibi Greenstone Belt in Canada. Most recent classifications allow the distinction between a *sensu stricto* IOCG group (e.g. Olympic Dam, Cloncurry, Carajas, Chile) and other deposits with iron oxides such as alkaline porphyry Cu-Au, carbonatite, Kiruna-type and skarn deposits. This more restrictive system made it possible to observe a greater homogeneity in the characteristics associated with the *sensu stricto* IOCG group. This fact enables the recognition of a particular synchronous genetically, but not spatially related intrusive suite. In order to characterize these intrusions geochemically, a litho-geochemical database from the above mentioned districts was compiled from the available literature. The presence of the monzodiorite – quartz monzodiorite – quartz monzonite – granite suite at the regional scale is thought to be a favourable indication for the presence of *sensu stricto* IOCG deposits. These rocks are high-K calc-alkaline (K-CA) or shoshonitic depending on their potassium content and alkali-calcic to lightly alkaline based on their  $\text{K}_2\text{O}+\text{Na}_2\text{O}-\text{CaO}$  vs  $\text{SiO}_2$  content (Frost et al. diagram). Rocks from the continental arc context of Chile could be calc-alkaline. The already known favorable intracratonic and continental arc context associated with *sensu stricto* IOCG mineralization is confirmed on the Pearce di-

agram. Based on lithogeochemistry, these intrusions are very similar to the alkali-calcic and potassic quartz monzodiorite – quartz monzonite and monzogranite porphyries associated with Cu-Au mineralization (e.g. Bingham, Ok Tedi). Results also show that they are different from the alkaline porphyries of monzonite-syenite composition (e.g. Galore Creek, Skouries). In summary, recognition of intrusions based on a lithogeochemical approach will lead to finding *sensu stricto* IOCG deposits or alkali-calcic porphyry deposits. Differences between these two types of deposit in terms of alteration and mineralization styles seem to be associated with the paleodepth of the intrusion. The deeper *sensu stricto* IOCG associated intrusions are unmineralized or unaltered while the shallower porphyries are internally mineralized and altered. A large lithogeochemical database was used for the Abitibi Subprovince in order to extract samples from intrusions showing a favorable signature. The identified intrusions in conjunction with other *sensu stricto* IOCG related features can be used as a first order vector for regional exploration.

### **STRUCTURAL EVOLUTION OF THE VMS FLIN FLON MINING DISTRICT, SASKATCHEWAN AND MANITOBA**

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The Flin Flon mining district is within the Flin Flon–Glennie complex of the Paleoproterozoic Trans-Hudson Orogen. The district comprises several large VMS deposits hosted by 1890 Ma volcanic rocks of the Flin Flon juvenile arc assemblage. The volcanic rocks and deposits were affected by multiple deformation events. During D<sub>1</sub> and D<sub>2</sub> intraoceanic accretion of the Flin Flon arc to other volcanic terranes, the volcanic rocks were folded and possibly faulted during the development of the F<sub>1</sub> Burley Lake syncline, and were refolded by the NNW-striking, Hidden Lake F<sub>2</sub> fold system prior to the emplacement of 1872 Ma dykes and deposition of fluvial sandstone and conglomerate of the Missi Group as a cover sequence unconformably overlying the basement volcanic rocks. During D<sub>3</sub> collision of the Flin Flon to the Glennie terrane, the basement and cover rocks were imbricated as east-dipping thrust sheets bounded by NNW-striking thrust faults and the thrust sheets were internally folded by west-verging regional folds (Pipeline, Grant Lake). As the timing of D<sub>3</sub> and Missi deposition are both bracketed between 1847 Ma, the age of the youngest Missi detrital zircon, and 1842 Ma, the age of crosscutting Boundary intrusions, the deposition of Missi sediments in fault-bounded basins overlying the basement rocks, and the deformation of these basins, must have occurred during the same event.

D<sub>4</sub> marks the collision of the Flin Flon–Glennie complex with the Archean Sask microcontinent. This D<sub>4</sub> event, which was broadly coeval with and outlasted the emplacement of 1840 Ma Phantom Lake dykes, produced east-trending folds (Flin Flon Creek) and N-directed thrust faults (Club Lake, Railway), which truncate the early west-directed D<sub>3</sub> thrust system. D<sub>4</sub> produced a SE-plunging stretching lineation and regional sheath folds (Pipeline) due to rotation of pre-existing fold axes into parallelism with the lineation. ENE-directed compression during D<sub>5</sub> dextrally reactivated D<sub>3</sub> thrust faults along the limbs of Hidden Lake folds and produced a regional NW- to NNW-striking cleavage (S<sub>5</sub>) that transects the regional F<sub>3</sub> and F<sub>4</sub> folds. The last regional ductile structures in the district formed during D<sub>6</sub> terminal collision of

the Sask craton and Flin Flon–Glennie complex with the Archean Superior craton at 1830 Ma to 1790 Ma. During D<sub>6</sub>, WNW compression produced a second regional cleavage (S<sub>6</sub>) striking NNE and reactivated E-striking D<sub>4</sub> thrust faults as dextral shear zones and NNW-striking D<sub>3</sub> thrust faults and lithological contacts as sinistral shear zones.

### **AFTER THE EARTHQUAKE HIT: HOW SEISMOLOGISTS CAN HELP THE POPULATION RECOVER**

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In the aftermath of a largely felt earthquake, the traditional role of seismologists is to provide factual information on the event and its seismotectonic context. Seismologists can, however, go beyond this role and provide to the population earthquake preparedness and mitigation information that can reduce anxiety and encourage recovery. If the earthquake has caused damage, the message conveyed by seismologists should be adapted to meet the needs of the population in the epicentral region and contact should be maintained. It should also send clear and positive messages that develop and maintain public's trust. A strategy was defined to provide useful advice in the first few hours following an earthquake when seismologists may be the only official voice available to comment on the earthquake. The main goal of this message is to empower the population in the epicentral region by making residents active rather than passive and provide it with sufficient information to filter out unfounded rumours and eliminate misconceptions. The paper will present examples when this post-communications strategy was used following the 2010 Haiti, Chile and Val-des-Bois, Quebec, earthquakes. It will also present some communications challenges that seismologists may be confronted with, such as the possibility of strong aftershocks and conflicting information. This strategy could be used in other emergency periods caused by a geohazard event (landslide, volcanic threat, flood, coastal erosion) when geoscientists can provide useful information to help the public recover.

### **IDENTIFICATION OF BRITTLE GEOLOGICAL STRUCTURES IN THE NORTHERN MELVILLE PENINSULA FROM MAGNETICS, DEM AND LANDSAT IMAGERY**

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The northern Melville Peninsula is an area where brittle faults can be mapped in the field. A methodology is being developed to identify lineaments in aeromagnetic and digital elevation model (DEM) data that will assist in locating brittle faults. The method focuses on magnetic contacts and dykes in magnetic data. Local curvature analysis is used for DEM. The current approach combines several techniques including multi-scale detection, curvature analysis, image thresholding and mathematical morphology. These methods produce numerous lineaments of various natures, some associated with geological events affecting the bedrock (ductile and brittle) and some others related to surface geology. The main challenge is to recognize only those that are associated with brittle faulting of the bedrock. For this, the magnetic field is the primary source of information, supplemented by the DEM. Examples of our approach are as follows. Some normal faults can be recognized when they down fault dykes, providing magnetic sources that become abruptly deeper where the fault is located. In addition, fault zones display linear negative values in the magnetic field that correspond to alteration of magnetite by fluids. We present the methodology being developed and some preliminary results.

## **EPEIROGENIC VS. EUSTATIC CONTROLS ON LOWER CAMBRIAN–ORDOVICIAN DEPOSITION IN THE FAILED ARM OF A TRIPLE JUNCTION: A VIEW FROM THE SOUTH SIDE OF THE OTTAWA-BONNECHERE AULACOGEN**

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Although long known to be the failed arm of a late Precambrian triple junction, the timing and rate of subsidence and sedimentary rock accumulation in the Ottawa-Bonnechere aulacogen (O-Ba) have long been problematical. New bio- and lithostratigraphic data show that epeirogenic and eustatic controls alternated in controlling marine onlaps and offlaps and sediment deposition rates in the O-Ba. A relatively simple Cambrian–Ordovician history of the O-Ba has been made unnecessarily complex by a tradition that coined different lithostratigraphic names for identical units in New York, Ontario, and Quebec and presumed a Waltherian depositional model that showed many stratigraphic units as time-transgressive and lateral equivalents.

The oldest sedimentary rocks in the O-Ba are younger than the late Precambrian opening of Iapetus, and are the unexpectedly young (ca. 510 Ma, late Early Cambrian) lower Altona Formation sandstones in northern NY. This apparent epeirogenic transgression was coeval with syndepositional faulting of the northern Vermont shelf and foundering of the Franklin Basin on a line with the thickest Tibbitt Hill volcanics near the cooling Laurentian margin. Upper Altona dolostone and red shale deposition persisted into the middle Middle Cambrian, and was followed by accumulation of highstand, partly terrestrial(?) Ausable Member sandstone of the lower Potsdam only in the O-Ba. Upper Potsdam (Keeseville Member) marine sandstone is upper Middle Cambrian in its lower part, and this emphasizes rapid subsidence of the O-Ba during Ausable deposition.

Terminal Cambrian–upper Tremadocian (uT), unconformity-bound carbonate formations comprise the lower Beekmantown Group to the south on the New York Promontory. However, a Potsdam–Theresa Formation (uT) unconformity across much of the O-Ba suggests long-term absence of any subsidence. An isolated “Beauharnois” outcrop south of Montreal suggests that the trans-Laurentian eustatic rise responsible for Tribes Hill Formation (lower Tremadocian) deposition reached into the eastern O-Ba.

Eustatic controls dominate O-Ba deposition beginning in the late Early Ordovician. The O-Ba and New York Promontory have a comparable, pre-Taconic orogeny succession beginning with Fort Cassin Formation (Floian) carbonates [= “Oxford,” Ontario; “Ogdensburg,” New York; “Beauharnois,” Quebec], unconformably overlying, middle Whiterockian Providence Island Formation carbonate and mudstone [= “Bridport,” Vermont; “Carillon,” Quebec], and the unconformably overlying Chazy Group. But for Rochdale Formation carbonates on the New York Promontory and the coeval, mixed siliciclastic-carbonate Theresa Formation in the O-Ba, no evidence indicates lateral equivalency of Cambrian–Ordovician formations in this region, and the “layer-cake” stratigraphy likely reflects zero depositional slopes.

## **MINERALOGICAL CHARACTERIZATION OF COPPER AND NICKEL PHASES IN THE COPPER CLIFF SOILS**

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Despite significant reductions in smelter-related emissions since the 1970s, high concentrations of metals still remain in Sudbury soils (e.g. Cu+Ni can be > 2000 ppm in the contaminated areas). As the mobility and bioavailability of any metal is directly related

to the solubility of the primary phase they reside in, a study was undertaken in the Copper Cliff (Sudbury) area, proximal to smelter operations, to examine, identify and characterize Cu- and Ni-bearing phases in the soils. Mineral separates (magnetic and non-magnetic) indicate the presence of spherical particulates (also called prills), ranging in size (10 µm–1 mm), that exhibit quench textures (e.g. skeletal crystals) and mineralogical compositions (e.g. olivine) consistent with a high-temperature origin. These particulates were characterized with Scanning Electron Microscopy (SEM), Micro-Raman spectroscopy and micro-X-ray diffraction. Results indicate that two major types of Cu- and Ni-bearing particulates are present: (1) sulphide-bearing spheres, with fayalite and magnetite rims and (2) sulphide-depleted spheres composed of Fe-Ni oxide and silicate phases. Sulfide-bearing spheres contain cores with varying Fe: Ni: Cu ratios and are X-ray amorphous. Reflected-light microscopy indicates that these phases possess a weak anisotropic character. The majority of cores are Fe- and Ni-rich, with only a few spheres being Cu-rich. However, all three elements were often found together within a single core. Micro-Raman spectroscopy indicates that the Ni-sulfide-rich cores are composed of a phase structurally related to heazlewoodite, Ni<sub>3</sub>S<sub>2</sub>. In order to explain the relatively high concentrations of Cu (up to 21 wt.%) in these cores, Ni matte was analysed by X-ray powder diffraction and SEM. These studies demonstrated the presence of heazlewoodite and chalcocite and their intergrowth on the micrometre scale. This observation suggests that both phases occur as intergrowth on the nano-metre scale in the sulphide-bearing spheres. SEM analyses also indicated lesser amounts of millerite, covellite and pyrrhotite. Sulphide-depleted spheres were generally made up of silicates with Fe-dominated inclusions composed of magnetite and other iron oxides. These spheres contain minor Cu and only up to 10% Ni. Future dissolution studies on Ni-matte and spheres are planned in order to model the annual release of Cu and Ni from these phases within the soil.

## **STREAM SEDIMENT GEOCHEMISTRY OF SOUTH-WESTERN AND CENTRAL NIGERIA: REE, HFSE, Au AND Pt MINERAL POTENTIAL**

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Over the last decade there has been an increasing global awareness of the strategic importance of existing and potential rare earth element (REE) mineral sources. This paper presents new results from geochemical baseline stream sediment surveys in Nigeria completed in 2009. The work was part of the World Bank funded Nigerian Sustainable Management of Mineral Resources Project carried out by the Nigerian Geological Survey Agency in cooperation with the British Geological Survey and the Geological Survey of Finland. A total of 284 stream sediment samples were collected from the South-western Nigeria, with an average sampling density of 1 site every 90 km<sup>2</sup>. A total of 1288 stream sediments were collected from the Central Nigeria, with an average density of 1 sample every 20 km<sup>2</sup>. Geochemical analyses were by ICP-MS technique following sodium peroxide fusion-HCl-HF extractions. Au, Pt and Pt determinations were by Fire Assay-acid dissolution method.

The distribution of REE, selected HFSE, and Au and Pt concentrations in stream sediment samples are presented in relation to the geology, known mineral occurrences, as well as other factors that affect the distribution of elements in the surface environment.

A systematic approach to the interpretation of the elemental concentrations and distributions involved a range of statistical techniques (including correlation, cluster analysis and principal factor analysis) to investigate the structure and trends within the data set, thus providing insights into the underlying geological, physical, geochemical and anthropogenic processes that are important in controlling the stream sediment geochemistry. Zones with known and speculated fields of pegmatites are mapped with notable high anomalies of a range of REE as well as Nb and Ta. Compared to a range of published regional stream sediment studies in Africa, Asia and Europe, these results from Nigeria show comparatively high concentrations, for REE and HFSE, as well as other trace elements. In addition, there are several anomalies for Au and Pt that warrant follow-up investigations to determine the source of alluvial and isolated deposits.

#### **THE PYRITE TO PYRRHOTITE METAMORPHIC TRANSITION; A MECHANISM FOR SOURCING GOLD, SULFUR AND ARSENIC FOR OROGENIC GOLD DEPOSITS**

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Petrographic studies of the sedimentary host rocks at the Bendigo saddle-reef orogenic gold deposit in Central Victoria have revealed the presence of minor disseminated pyrrhotite within folded and metamorphosed carbonaceous shales, that form the tops of sandstone turbidite units in the lowest stratigraphic sequence intersected to date in the Kangaroo Flat mine. Similar sediments, at higher stratigraphic levels in the mine, contain disseminated pyrite rather than pyrrhotite. Textural evidence indicates that the pyrrhotite formed by replacement of diagenetic arsenian pyrite within the carbonaceous shales, during metamorphism at lower to middle greenschist facies. LA-ICPMS analyses of diagenetic pyrites in the sediments indicates they are enriched in As, Au, Ni and Co. This is in marked contrast to the disseminated pyrrhotite, which contains similar levels of Ni and Co, but is depleted in As and Au. These relationships demonstrate that the metamorphic conversion of diagenetic pyrite to metamorphic pyrrhotite, at greenschist grade, releases gold and arsenic to the metamorphic fluid, and becomes a viable source for orogenic gold deposits hosted within or above a package of sulfidic carbonaceous sedimentary rocks. We propose this as a key mechanism for generating orogenic gold deposits in meta-sedimentary basins.

#### **USE OF MULTI-BEAM RADARSAT-2 DUAL-POLARIZATION C-HH AND C-HV SAR IMAGERY FOR SURFICIAL GEOLOGY MAPPING IN NUNAVUT, CANADA**

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Our study presents an assessment of the use of multi-beam RADARSAT-2 dual-polarization C-HH and C-HV SAR imagery for surficial geology mapping in Nunavut, Canada. The study used RADARSAT-2 SAR images acquired using the Standard Beam 1 and 7 (S1 and S7) modes in both ascending (A) and descending (D) orbits. Multispectral LANDSAT-7 ETM+, digital elevation model (DEM) data and aerial photographs were also used. RADARSAT-2 SAR images were speckle-filtered and georeferenced. Representative training areas of distinctive surficial deposits (bedrock, thin till, thick till with sparse vegetation, thick till with dense vegetation, sand and gravel, boulders and organic de-

posits) have been identified by interpreting the aerial photographs, LANDSAT-7 ETM+ images and field information. Maximum likelihood supervised classifications were carried out on the RADARSAT-2 SAR images, alone or combined with either the LANDSAT-7 ETM+ and/or the DEM data. The best classification accuracy occurred when the RADARSAT-2 C-HH and C-HV SAR images were combined with both the LANDSAT-7 ETM+ and the DEM data. Limitations of the study are also presented.

#### **BUBBLE SIZE DISTRIBUTIONS AND PERMEABILITY MEASUREMENTS IN SCORIA SAMPLES FROM EYAFJALLAJOKULL VOLCANO, ICELAND**

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Scoria samples from Eyafjallajökull (EFJ) were collected and analyzed using three dimensional (3-D) tomography at the Elettra Synchrotron Light source, Trieste, Italy, to study bubble size distributions and correlate them with the volcano's explosivity. EFJ volcano is located on a propagating rift outside the main zone of plate spreading in Iceland, where the southern end of the eastern rift zone terminates. EFJ erupted explosively on April 14, 2010 and had a major impact on society, grounding trans-Atlantic flights for days. Prior to this eruption, EFJ was the site of a long magmatic unrest which took place over a period of 18 years. Earlier in March an effusive fissure near the eastern flank of the volcano produced basaltic lava. However, the samples collected by Margherita Polacci (Istituto Nazionale di Geofisica e Vulcanologia, Pisa, Italy) on May 8, 2010 are trachyandesite scoriae and coarse ash. The interaction of magma and ice from the volcano summit produced enhanced explosive activity and contributed to the formation of coarse ash. The 3-D tomographic volumes are processed using ImageJ and Blob3D software. ImageJ is used to normalize, crop, threshold and segment the raw images, and Blob3D is used for vesicle separation and to count the number of vesicles in order to obtain their size distribution in each sample. Various techniques for vesicle separation are being tested in order to discover the one that most faithfully separates vesicles from the crystals and glass in the rocks and to determine the uncertainties in the measured bubble size distributions due to the thresholding and separation processes. Permeability measurements will be taken with a gas permeameter on the EFJ samples and compared against permeability simulations made using the reconstructed tomographic volumes. Relationships between bubble size distributions, permeability, viscosity and explosivity in EFJ will be investigated and compared with previous studies on a basaltic volcano, Stromboli, Italy, to test the hypothesis that bubble size distributions in volcanic ejecta correlate with eruptive intensity. The analysis of bubble size distributions could lead to better predictions of the timing and intensity of eruptive events, which would in turn lead to better preparation and evacuation of areas at risk of being affected by the eruptions.

#### **THE ATLANTIS II DEEP – GEOCHEMICAL INSIGHTS INTO METAL PRECIPITATION IN THE RED SEA**

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The Atlantis II Deep contains a unique volcanic-associated sediment-hosted base metal deposit amounting to ~90 Mt of metalliferous sediment (2% Zn, 0.5% Cu). The deposit is situated in the axial valley of the slowly spreading Red Sea rift. The bottom of the deep has an area of ~50 km<sup>2</sup>, which has been covered by metal-depositing brine for at least 15,000 years. The Atlantis II Deep is underlain by oceanic basalt, on top of which lies 5-25 m of metalliferous mud. The metalliferous sediment has accumulated

at variable but rapid rates of  $>1$  m/1000 years. The conditions in the brine pool are optimal for preserving metals that are carried into the deep by outflowing hydrothermal fluid, which has vented at different times from a number of different locations. The main source of the present metal deposition is well known, but the locations of possible multiple vent sources during the evolution of the basin have not been determined.

In 1979, there was an attempt to mine the metalliferous mud; however, development of the resource did not proceed beyond the pilot mining test. The sediment cores collected during the resource evaluation were archived and have been made available for the present study. These include about 500 gravity cores distributed evenly over the entire 50 km<sup>2</sup> of the deep. Despite more than 30 years in storage, the remarkable state of preservation of the cores allows detailed studies of the structure, stratigraphy and mineralogy. Different depositional units reflect chemical changes within the basin caused by changes in the composition and layering of the brine pool and variation in composition of the inflowing hydrothermal fluid. Detailed logging of 40 cores shows abundant small-scale structures, striking delicate laminations (individual laminae  $<1$  mm), and apparently simultaneous deposition of different minerals in different parts of the deep. Some of these changes correlate with rapid changes (order of 10 years) in the concentration of Cu and Zn in the brine, which may be controlled by episodic introduction of reduced sulphur. In this study we examine a variety of mineralogical, textural, and geochemical characteristics of the sediments to determine the fundamental controlling mechanisms on metal deposition, the spatial and temporal variability in the location of the likely vent sources, and the patterns of element dispersion outwards from the inferred vent sites.

#### **SUBEPITHERMAL Au-Pd MINERALIZATION ASSOCIATED WITH AN ALKALIC PORPHYRY Cu-Au DEPOSIT, MT. MILLIGAN, QUESNEL TERRANE, BRITISH COLUMBIA, CANADA**

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At the Mt. Milligan Cu-Au porphyry deposit, barren and weakly mineralized hydrothermal veins occur in volcanic rocks adjacent to zones of Cu-Au porphyry mineralization, and overprint porphyry-stage veins. The earliest studied veins are barren, and consist of quartz  $\pm$  pyrite  $\pm$  carbonate  $\pm$  chlorite  $\pm$  tourmaline. These early veins are similar to 'transitional' to late-stage hydrothermal veins in other alkaline porphyry Cu-Au deposits, and we consider these to be the equivalent of 'transitional' (post-porphyry, pre-epithermal) quartz-sericite-pyrite veins in calc-alkaline porphyry environments.

Primary fluid inclusions in quartz in the barren and weakly mineralized veins are liquid-vapour, homogenize to liquid over a narrow range in  $T$  ( $\sim 170$ – $270^\circ\text{C}$ ;  $n=96$ ), and show a wide range in salinity (4.2 wt.% NaCl equiv. to 28.7 wt.% CaCl<sub>2</sub> equiv). LA-ICPMS analyses indicate that the fluids were highly enriched in As (to 2260 ppm), Sb (to 230 ppm), B (to 5400 ppm), Au ( $\sim 1$ – $2$  ppm) and Pd ( $\sim 0.5$ – $1$  ppm) but depleted in Cu ( $<740$  ppm; rarely  $>80$  ppm) compared to typical porphyry-stage fluids. Metal ratios in the fluids overlap with bulk rock metal ratios in the mineralized veins.

The inclusions are interpreted to contain a contracted magmatic vapour (produced by boiling) that lost Cu during the formation of porphyry stage veins at depth. Fluids show decreasing B, As, Sb and increasing Sr, Ca and salinity with time. Stable C, O and H isotope analyses suggest that metal precipitation was pos-

sibly the result of mixing of the magmatic-derived fluid with a heated saline groundwater. Fluid inclusion microthermometry and chlorite thermometry constrain the approximate formation conditions of the veins between  $\sim 200$ – $1500$  bars and  $\sim 240$ – $280^\circ\text{C}$ . After mineralized vein formation, circulation of low salinity, metal depleted fluids occurred. These latest stage fluids may have formed by mixing of a saline magmatic fluid-groundwater hybrid with meteoric water.

This study suggests a genetic link between porphyry-stage events and the deposition of Au and PGE in late-stage veins in an alkaline igneous environment. Recognition of hydrothermal processes involving the transport of Au-PGE-As-Sb-Bi-Te-B-rich fluids at depth (i.e. "subepithermal" regime) may indicate that low-sulfidation epithermal Au deposits are present in the shallower parts of the magmatic-hydrothermal complex if uplift and erosion were minimal. Conversely, the formation of high-grade, low-sulfidation epithermal Au deposits may be prohibited if porphyry-epithermal transitional fluids precipitate ore metals through mixing with groundwater, prior to reaching the level where meteoric water mixing and epithermal boiling normally occur.

#### **OROGENIC GOLD DEPOSITS IN THE BOURLAMAQUE PLUTON, VAL D'OR, ABITIBI GREENSTONE BELT: STRUCTURAL CHARACTERISATION AND $^{40}\text{Ar}/^{39}\text{Ar}$ DATING**

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U/Pb and  $^{40}\text{Ar}/^{39}\text{Ar}$  ages from various orogenic gold deposits in the Val d'Or mining district vary between ca. 2630 and ca. 2510 Ma, with ages locally older than 2690 Ma. Controversial genetic interpretations have been proposed for these gold deposits. Two types of orogenic, vein-type gold occurrences are described: (1) «early» quartz-carbonate-chlorite veins ( $>2696$  Ma), and (2) «late» quartz-tourmaline veins ( $<2680$  Ma). These «late» veins are abundant in the  $2700 \pm 1$  Ma (U/Pb zircon age), synvolcanic Bourlamaque pluton in the Val d'Or area, and are exposed in the Sullivan, Dumont, Lac Herbin, Ferderber, Beacon, Wrightbar and Beaufor deposits. They are typically hosted by ductile, EW-trending and south-dipping shear zones that are considered to be the product of faulting and hydrothermal events genetically related to the Cadillac Fault Zone, a 1<sup>st</sup>-order regional structure that may represent the principal channelway for mineralizing fluids towards 2<sup>nd</sup>- and 3<sup>rd</sup>-order structures hosting the auriferous quartz veins. In the Lac Herbin deposit, underground mining exposes the development of Riedel-type structures related to steeply-dipping shear zones. Auriferous quartz veins are hosted by these steeply-dipping shear zones. The Beaufor mine shows a similar network of Riedel shears but gold mineralisation is hosted by moderately-dipping secondary structures, suggesting a more efficient auriferous hydrothermal activity as compared to Lac-Herbin. North-dipping barren structures, such as the Beaufor and Perron faults, have been interpreted as post-mineralization structures and correlated with the «K» Zone, the Beacon and the Lac Herbin-South faults of the Sullivan, Beacon and Lac Herbin deposits, respectively.

Fifty-seven samples have been dated by  $^{40}\text{Ar}/^{39}\text{Ar}$  single-grain step heating method. Dating on amphiboles from the undeformed intrusive facies of the Bourlamaque pluton yield ages as old as ca. 2690 Ma, consistent with the U/Pb crystallisation ages of the intrusion. Muscovite  $^{40}\text{Ar}/^{39}\text{Ar}$  dating from the mylonitic shear zones and related extensional and sheared quartz veins of the Lac Herbin, Beaufor and Beacon deposits yielded ages varying between 2610 and 2420 Ma, which are clearly distinct from the



inferred age of regional peak metamorphism (ca. 2660-2680 Ma).  $^{40}\text{Ar}/^{39}\text{Ar}$  spectra from the Lac Herbin and Beaufor deposits show a systematic and reproducible pattern: muscovite ages from the quartz veins range from ca. 2610 to ca. 2530 Ma whereas muscovites grains from the hosting mylonites yield high-temperature step ages that are consistent with those of the quartz veins but show thermal perturbations as young as 2515-2520 Ma which are attributed to late stages deformation following the main event of auriferous hydrothermalism.

#### **CHALCOPYRITE DISEASED SPHALERITE: ALTERNATE DIAGNOSES**

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Since the introduction of the term chalcopyrite disease in the mid-1980s, the experimentally determined, limited solubility of Cu in sphalerite (cubic) at temperatures less than 500°C (Cu-Fe-Zn-S system) is cited as evidence against the exsolution hypothesis that was generally accepted earlier. The regularity of the radial and concentric inclusion patterns (disease) of chalcopyrite in sphalerite is particularly striking and has been used as evidence for a crystallographically controlled exsolution origin for the occurrence of chalcopyrite inclusions in sphalerite and sphalerite stars in chalcopyrite. This negative evidence for chalcopyrite exsolution in conjunction with descriptive analysis has lead to other hypotheses including the replacement, epitactic growth, coprecipitation, and diffusion-controlled growth models. This communication recognizes that wurtzite is a very common low-temperature phase recognized by its hexaform nature and that some of these natural hexagonal ZnS crystals have chalcopyrite disease as well. However, the solution characteristics of Cu in wurtzite have not been studied.

Wurtzite crystals from the vent wall of a submarine sulfide spire from Axial Seamount, Juan de Fuca Ridge, Pacific Ocean that were formed at temperatures of approximately 250°C were analysed in detail. The ZnS crystals are variably birefringent and translucent in the core, but were opaque to semi-opaque along the rims. Microprobe traverses across the rims (opaque) into the interiors (translucent) of several hexaform and a few other crystals show that Cu contents of the opaque ZnS rims are significantly greater (1 to 2 atomic prop. Cu) than the Cu solubility in sphalerite determined experimentally, whereas the translucent interiors that have chalcopyrite blebs (disease) have Cu contents consistent with the solubility studies on sphalerite (<0.1 atomic prop. Cu). In several cases, the boundary between the opaque and translucent zone in sphalerite has textures that are reminiscent of exsolution. If this is indeed Cu substitution/ solution in wurtzite, polytype and then polymorphic transformations toward the cubic sphalerite structure induced by decreasing temperatures could cause chalcopyrite exsolution. At present the Cu solution stoichiometry in wurtzite is only known to be similar to cubanite or intermediate solid solution with a 1:2 Cu-Fe atomic ratio. Therefore, at least some chalcopyrite disease originates from exsolution of chalcopyrite during the polymorphic transformation of Cu-bearing, Fe-rich wurtzite to sphalerite. There are numerous possible scenarios for the exsolution of chalcopyrite from wurtzite (ZnS), which differ mainly in the coordination of Cu within wurtzite and whether Cu or coupled Fe-Cu ions are diffusing in the ZnS crystal.

#### **OXYGEN BAROMETRY OF KIMBERLITE MAGMAS USING THE Fe CONTENT OF MONTICELLITE**

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We present a new oxygen barometer for kimberlite magmas based on the Fe content of monticellite,  $\text{CaMgSiO}_4$ , a ubiquitous liq-

uidus mineral in kimberlite liquids. We crystallized monticellite (Mo) in equilibrium with kimberlite liquids (liq) in the system Ca-Mg-Al-Si-Ti-Fe-O at 100 kPa from 1225 to 1350°C and at  $f_{\text{O}_2}$  from NNO-4.1 to NNO+5.3 (where NNO is the nickel-nickel oxide buffer). A strong correlation was found between  $\text{XFe-Mo}/\text{XFe-liq}$  and  $f_{\text{O}_2}$ . The  $\text{XFe-Mo}$  also varied with temperature and composition, but these dependencies are small compared to that with  $f_{\text{O}_2}$ . The experimental data were fitted by weighted least square regression to a non-linear relationship used to describe  $\text{Cr}^{2+}$ - $\text{Cr}^{3+}$  equilibria in melts, with three coefficients and  $\text{XFe-Mo}/\text{XFe-liq}$ . The application of this new oxygen barometer to monticellite compositions in kimberlites from the literature reveal a wide  $f_{\text{O}_2}$  range from NNO-5 to NNO+2, (with uncertainties of about 1 log unit). The  $f_{\text{O}_2}$  range of kimberlites is markedly wider than any other igneous rock type. We are currently exploring: the oxygen fugacity of kimberlites between and within cratons, the relationship of this variable to the Fe-in-perovskite oxygen barometer (Bellis and Canil, 2007 J Petrol) and to the diamond content and quality of kimberlites, on both regional and local scales.

#### **GEOCHRONOLOGY, PETROGRAPHY, GEOCHEMICAL CONSTRAINTS, AND FLUID CHARACTERIZATION OF THE BURITICÁ GOLD DEPOSIT, ANTIOQUIA DEPARTMENT, COLOMBIA**

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Gold mineralization at the Buriticá gold deposit, located about 75 km north of Medellín in the Middle Cauca metallogenic belt, is hosted by the Miocene Buriticá Andesite porphyritic intrusion ( $^{40}\text{Ar}/^{39}\text{Ar}$  on hornblende yields  $7.41 \pm 0.40$  Ma). This shallow intrusive rock is characterized by a plagioclase-hornblende-augite-biotite phenocrysts assemblage hosted in 50% to 75% of micro-crystalline groundmass, with occasional trace amounts of apatite as inclusions in mafic minerals. It intrudes Cretaceous back-arc basin pillow basalts and associated mudstones and chert of the Cañasgordas Group, as well as the Cretaceous tonalitic Buriticá Stock ( $>85.93 \pm 2.10$  Ma). Geochronology data are reported at the  $2\sigma$  uncertainty level.

Whole rock geochemical analyses of the Buriticá Andesite plot in the high-K calc-alkaline field. Sericite-altered rocks show significant potassium and silica enrichment relative to their fresher equivalents. Chondrite-normalized trace element compositions show LREE-enrichments over HREE, indicating clinopyroxene and/or hornblende fractionation during emplacement. On primitive mantle-normalized diagrams, the rocks show a strong subduction signature and unusually high Sb concentrations in the deposit host rock. This is consistent with a Miocene subduction-related magmatic arc observed roughly along the Cauca-Patía-Fault-System.

Multiple generations of alteration are observed in the Buriticá area. Moderate to strong chlorite-rich propylitic alteration and fracture controlled magnetite-orthoclase-quartz potassic alteration pre-date mineralization. Gold mineralization is associated with a proximal sericite-adularia-pyrite-quartz-carbonate assemblage and a distal epidote-chlorite-calcite-pyrite propylitic alteration. Disseminated base metal sulfides (sphalerite, galena, chalcopyrite) are also locally seen with the adularia-sericite alteration. Hydrothermal sericite has been dated at  $7.73 \pm 0.12$  Ma, which indicates that within error, it is coeval with the emplacement of the porphyritic andesite.

Gold is hosted in two different sets of veins, striking around N72°/85° and N105°/90°, respectively. Mineralization is mostly structurally controlled, although it also occurs as disseminated

base-metals sulfides within an intrusive breccia called the Yaragua Breccia, and in close proximity to the mineralized veins.

Vein paragenesis is divided into two different gold-bearing stages. Stage 1 is a banded quartz-base metal sulfide event characterized by early pyrite-chalcopyrite-galena-sphalerite associated with fine grained quartz and trace amounts of tetrahedrite-tennantite, gold and silver; this is followed by precipitation of late coarse-grained vuggy quartz with euhedral termination. Stage 2 is a calcite-rich event showing brecciation textures, and characterized by early pyrite-sphalerite-galena-quartz-gold, and late calcite-stibnite.

Sulfur isotope analysis on coeval galena and sphalerite from Stage 1 yields crystallization temperatures from 294°C to 409°C. Sphalerite- and quartz-hosted fluid inclusion analysis is underway to refine these results.

#### **PROCESS CONTROLS ON THE DISPERSAL PATTERNS OF GLACIAL SEDIMENTS UNDER ICE SHEETS: APPLICATIONS TO PROSPECTING IN GLACIATED LANDSCAPES**

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It is generally recognized that dispersal plumes are synthetic expressions of complex interplays between erosion, transport and deposition processes. The quintessential conceptual summary of these processes and their expression in a dispersal plume consists of the diagram of Miller (1984) showing a dispersal plume rising down-ice with a concomitant concentration decrease toward the surface. However, the physical mechanisms underpinning this conceptual model are only loosely defined and generally reflect basic treatment of glacial sediment production mechanisms (abrasion, plucking, etc.) and transport processes. Dispersal mechanisms, reflecting sediment transport pathways and responsible for producing the characteristic plume pattern, also require precision. Consequently, sediment dispersal has been regarded as a product of subglacial sediment deformation in some cases, while others view dispersal as a reflection of englacial processes (mainly shearing) that are later preserved within the till bed. It is likely that these are complimentary processes affecting different portions of the glacier bed. However, the relative importance of each process and the controls on their operation has not been examined within the context of sediment dispersal plumes. Questions also exist regarding the effects of other subglacial processes on dispersal patterns. For example, does comminution (break-down of particles) take place preferentially at the bed or within the ice? If sediments are comminuted at the bed, are they then (re-)entrained within the ice for further dispersal? Beyond large scale shearing and sub-sole deformation, are there additional pathways for sediment transfer between bed sediments and englacial sediments?

Since presentation of Miller's (1984) diagram, field and laboratory studies of subglacial environments, emphasizing the operation of physical processes at the ice-bed interface, have shed light on the flow dynamics and mechanisms of glaciers and large ice sheets. These results bear directly on sediment dispersal mechanisms and patterns. They also have direct applications to the field of prospecting, yet they have only been summarily (if at all) integrated in to existing dispersal models.

This presentation aims to refine understanding of glacial processes underpinning existing dispersal models by evaluating and integrating recent advances in the field of subglacial processes. Of particular interest are i) the importance of deforming beds to sediment dispersal in light of new understandings of bed rheology, ii) the mechanisms and relative importance of englacial sediment transfer, and iii) the contributions of subglacial hydrology to sediment accretion and dispersal.

#### **LOCALIZATION AND PETROGENESIS OF ARCHEAN AND PROTEROZOIC MAGMATIC Ni-Cu-PGE MINERALIZATION**

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Magmatic Ni-Cu-(PGE) deposits formed throughout geological time, mainly in rifted continental tectonic settings. They formed in dynamic lava channels, feeder sills, and magma conduits in a wide range of volcanic-invasive-subvolcanic-plutonic settings, and formed from a wide range of magma types, but there are systematic differences between Archean, early Proterozoic, and younger deposits. Archean deposits formed primarily from high-Mg komatiites (e.g. Kambalda, Mt Keith-Perseverance, Dumont-Alexo-Dundonald-Marbridge, Hart-Langmuir-McWatters-Redstone-Textmont) and only rarely from basaltic magmas (e.g. Montcalm), even though basalts are much more abundant than komatiites in those areas. Similarly, Early Proterozoic deposits formed from low-Mg komatiites (e.g. Namew Lake, Thompson), komatiitic basalts (e.g. Raglan), and ferropicrites (e.g. Pechenga), even though associated basalts are much more abundant. Middle-late Proterozoic and Phanerozoic deposits formed from the most magnesian ferropicritic (e.g. Jinchuan), picritic (e.g. Noril'sk), and basaltic (e.g. Duluth, Voisey's Bay) magmas in those areas. The association with the most magnesian magmas in each area reflects their higher temperatures and greater propensity to incorporate S from country rocks. All sulfide-rich deposits (e.g. Duluth, Kambalda, Noril'sk, Pechenga, Thompson) and many sulfide-poor deposits (e.g. Mt. Keith) exhibit geological, geochemical, and/or isotopic evidence for incorporation of S from crustal rocks. The abrupt change in the maximum Mg content of mantle-derived magmas at ca. 2.4 Ga corresponds to a fundamental and irreversible change in the thermal and compositional structure of the Earth's mantle at the end of the Archean. Archean deposits formed in extrusive (e.g. Kambalda, Alexo, Hart-Langmuir-Redstone-Textmont-Bannockburn C Zone), invasive (e.g. Dundonald South-Sox), and intrusive (e.g. Mt-Keith-Perseverance, Dumont-Dundonald South-Dundeal- Alexo Small Pit-Kelex, McWatters-Galata-Sothman) settings. Proterozoic deposits formed in deeply erosive to very high level subvolcanic (e.g. Raglan), subvolcanic (e.g. Pechenga, Thompson), and plutonic (e.g. Jinchuan, Namew Lake) settings. Known Phanerozoic deposits (e.g. Noril'sk, In-sizwa) formed exclusively in subvolcanic settings. The greater abundance of extrusive settings in the Archean, paucity in the early Proterozoic, and absence in the mid-late Proterozoic and Phanerozoic reflects corresponding changes in magma viscosity (komatiite > komatiitic basalt > picrite > basalt) and differences in the densities and tectonic settings of crustal rocks into which the magmas were emplaced (e.g. Yilgarn vs. Abitibi, Raglan vs. Thompson). Depending on the crustal structure and tectonic stress regime, they formed lava channels (e.g. Kambalda, Raglan), sills (e.g. Jinchuan, Noril'sk, Pechenga, Thompson), or subvertical conduits (e.g. Voisey's Bay). The most important control on ore genesis and localization is therefore tectonic setting, not magma type.

## THE ROLE OF TEMPERATURE AND FLUID CONTENT IN SILLIMANITE DEFORMATION AND RECRYSTALLIZATION MECHANISMS IN FELSIC GRANULITE, ATHABASCA GRANULITE TERRANE, WESTERN CANADIAN SHIELD

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The rheology of deep continental crust plays a fundamental role in large-scale tectonic processes. Current knowledge draws significantly from experimental work because well-characterized examples of naturally deformed lower crustal rocks are rare. The Athabasca granulite terrane, northern Saskatchewan, exposes a large region of high-pressure tectonite ( $>20,000 \text{ km}^2$ ) and thus provides a natural laboratory for studying lower crustal deformation and metamorphic processes. Here, we focus on a lithology characterized by an anhydrous assemblage  $\text{grt} + \text{sil} + \text{kfs} + \text{pl} + \text{qtz}$  that initially developed in the late Archean. This lithology was subsequently affected by multiple crustal-scale shear zones allowing for examination of deformation mechanisms across a range of temperature and fluid conditions. Two general deformation settings are considered: (1) the Cora Lake shear zone, which was likely active during the late Archean but also exhibits a younger ( $\sim 1.9 \text{ Ga}$ ) mylonitic overprint at  $1.0 \text{ GPa}$ ,  $900\text{--}800^\circ\text{C}$ ; and (2)  $1.85\text{--}1.80 \text{ Ga}$  exhumation-related shear zones that involved synkinematic hydration to the new assemblage  $\text{grt} + \text{crd} + \text{bt} + \text{sil} + \text{pl} + \text{qtz}$  at  $0.8\text{--}0.5 \text{ GPa}$ ,  $650\text{--}550^\circ\text{C}$ .

Textural analysis reveals contrasting microstructures for deformation under dry, high-temperature and fluid-infiltrated, moderate-temperature conditions. Garnet deformation in both dry and hydrated granulite is restricted to cataclastic fracturing. In the dry granulite, a mylonitic foliation is defined by quartz, K-feldspar, and plagioclase ribbons and recrystallized grain-sizes ranging from  $<10\text{--}50 \mu\text{m}$ . Boudin-shaped sillimanite prisms ( $\leq 3 \text{ mm}$ ) display extensive internal subgrain structure. Finer-grain recrystallized sillimanite prisms occur adjacent to scalloped margins and primarily within strain shadows of larger sillimanite clasts. In the hydrated granulite, matrix foliation is characterized by recrystallized polygonal quartz and plagioclase ( $\sim 100\text{--}200 \mu\text{m}$ ) and aligned biotite. Prismatic sillimanite fish ( $\leq 1 \text{ cm}$ ) are locally bent and display undulose extinction but subgrain structure is absent. Clasts also have asymmetric tails of fine-grain foliation-parallel sillimanite needles. Textural evidence from sillimanite in dry granulite is consistent with dislocation creep and recovery by subgrain rotation recrystallization. In contrast, sillimanite recrystallization in hydrated granulite appears consistent with dissolution-reprecipitation aided by grain-boundary fluid. The absence of hydrous fluid is inferred to have largely facilitated preservation of dynamic microstructure in dry granulite. Quantitative analysis with electron backscatter diffraction will further elucidate how deformation and recrystallization mechanisms evolved in sillimanite and other phases as a function of varying temperature and fluid conditions. These characteristics may reflect larger scale heterogeneity in the rheology and seismic properties of dry versus hydrated deep-crustal shear zones.

## EVIDENCE FOR HYDROTHERMAL ACTIVITY IN THE WOODLARK BASIN, AN ARC-INFLUENCED OCEANIC SPREADING CENTER

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The Woodlark Basin is an ca. 6 Ma oceanic spreading center that is presently being subducted along the San Cristobal trench. The eastern portion of the Woodlark Spreading Center (WSC) is moderately fast spreading ( $\sim 7.2 \text{ cm/yr}$ ). Recovered young volcanic rocks show increasing arc affinities with proximity to the trench. The moderately fast spreading rate and presence of young volcanic rocks suggest that hydrothermal activity might also be present. We report here the first results of hydrothermal plume surveys in the widest and fastest spreading segment of the WSC (i.e. sub-basin 5b). We found evidence for active hydrothermal venting in basin 5b, with concurrent light scattering ( $\Delta\text{NTU}$  maximum = 0.023), pH ( $\Delta\text{pH}$  maximum = 0.005), total dissolvable Fe and Mn ( $\text{TD}_{\text{Fe}}$  maximum =  $85 \text{ nM}$ ,  $\text{TD}_{\text{Mn}}$  maximum =  $10.2 \text{ nM}$ ) and helium ( $\delta^3\text{He}$  up to 6 ‰ above background) anomalies.  $\text{TD}_{\text{Fe}}/\text{TD}_{\text{Mn}}$  values in the most hydrothermally enriched parts of the plume are elevated (up to 10.2), similar to submarine hydrothermal systems associated with volcanic arcs. The elevated  $\text{TD}_{\text{Fe}}/\text{TD}_{\text{Mn}}$  values for the western end of the segment (Station V00A24) we interpret to indicate arc contamination of the hydrothermal fluid source, consistent with arc-influenced volcanic rocks recovered from the eastern end of the spreading center. The relatively elevated total dissolvable metal concentrations, combined with only weak dissolved gas anomalies, suggest that the plume is from a well-established, albeit relatively weak, hydrothermal system. If the hydrothermal plume originates from the axis of segment 5b of the WSC, this implies a plume rise of  $\sim 800 \text{ m}$ , to around  $3600 \text{ m}$  water depth.

## DEFORMATION HISTORY OF THE GRENVILLE FRONT TECTONIC ZONE AND THE BRITT DOMAIN BETWEEN THE SUDBURY BASIN AND THE FRENCH RIVER IN ONTARIO, CANADA, AND ITS TECTONIC IMPLICATIONS

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The Grenville Front Tectonic Zone (GFTZ) and the Britt domain between the Sudbury Basin and the French River in Ontario, Canada are the NW part of the Grenville Province. Based on detailed mapping, structural analysis, and LA-ICP-MS zircon dating we establish the deformation history of the NW Grenville Province and discuss its tectonic implications.

Our field study unravels three phases of deformation.  $D_1$  deformation is characterized by a transposition foliation ST and isoclinal  $F_1/F_2$  folds in high grade gneissic rocks.  $D_2$  deformation is characterized by NNW-trending tight-to-open  $F_3$  folds with amplitudes ranging from kms to tens of kms. In the GFTZ, the  $F_3$  folds have one limb dipping toward ESE, and the other toward S. Compared to those in the Britt domain,  $F_3$  folds in the GFTZ have

larger interlimb angles due to D<sub>3</sub> overprinting. D<sub>3</sub> deformation is characterized by NE-trending F<sub>4</sub> folds and top-to-the-NW-thrusting mylonite zones. F<sub>4</sub> in the GFTZ are centimeter-to-meter-scale, ENE-trending folds. They are S-folds with fold axes plunging toward NE if occurring on the F<sub>3</sub> ESE-dipping limbs, and Z-folds with axes plunging toward SE if on the F<sub>3</sub> S-dipping limbs. Mylonite zones only occur in the GFTZ and become dominant toward its NW boundary. From the Britt domain to the GFTZ, F<sub>4</sub> folds become tighter and are transposed to the mylonitic foliation at the NW boundary of the GFTZ.

Our zircon dating indicates that the formation of the sub-horizontal ST foliation and development of F<sub>3</sub>, F<sub>4</sub> folds and mylonite occurred during 1050-950 Ma. We suggest that these structures can be correlated with those in the Shawanaga and Parry Sound area where timing of deformation is constrained. We suggest that the sub-horizontal ST developed between 1050-1030 Ma, the F<sub>3</sub> folds occurred between 1028-1018 Ma, and the F<sub>4</sub> folds and the mylonite zones developed between 1000-950 Ma.

If the effects of D<sub>2</sub>-D<sub>3</sub> deformations are removed, the F<sub>1</sub>/F<sub>2</sub> are recumbent folds and the ST is sub-horizontal with NW-trending stretching lineations on it. These fabrics indicate sub-horizontal NW-directed flows in mid-to-lower crust. The flow is similar to crustal flows in younger orogenic belts in the world such as the southern Omineca Belt in Canadian Cordillera and the Dabie Shan orogen in China. The F<sub>3</sub> folds have axial planes perpendicular to the Grenville Front, which indicates that the D<sub>2</sub> deformation occurred in a NW-SE crustal extension in the orogenic collapse. F<sub>4</sub> folds and the top-to-the-NW thrusting mylonite zones indicate that the D<sub>3</sub> deformation occurred in a NW-SE shortening between 1000-950 Ma.

#### **GIS-BASED PREDICTIVE MODEL FOR GOLD AND BASE METAL MINERALIZATION IN THE REMOTE AREAS OF NORTHERN PAKISTAN**

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Mineral exploration in northern Pakistan is challenging due to its mountainous, often glaciated and remote nature. Exploration activities have therefore mainly focussed on stream sediment sampling and analysis. A large geochemical database (~2000 samples for 50 elements) now exists as a result of extensive sampling campaigns by the Australian Aid Program, Pakistan Mineral Development Corporation (PMDC) and Sarhad Development Authority, covering an area of ~80,000 km<sup>2</sup>. To aid in interpretation, catchment basin maps were generated using LANDSAT TM and DTMs and overlain on the available regional geology and structures. Sample geochemical data from each catchment were interrogated in ArcGIS 9.2, with Factor Analysis used to identify elemental associations for different geological zones defined by structures and lithologies.

The GIS models successfully detected the occurrence of known stibnite veins and disseminations in Chitral, porphyry-type skarns in Dommal Nissar and Skardu and Ni-PGEs in the mafic-ultramafic rocks of Chilas. The models also provided information on which to interpret the mode of origin of certain anomalies of previously unknown origin. The majority of anomalies are associated with the Resuhn fault and Shyok Suture Zone, which suggests a dominantly structural, rather than lithological control on the mineralisation. However, some intrusion-related anomalies have also been delineated.

The study demonstrates the strength of a GIS-based approach to the analysis of a stream sediment multi-element geochemical

dataset to develop models for gold and base metal mineralisation in remote and glaciated areas of north Pakistan.

#### **MINERALOGY AND OXYGEN-ISOTOPE GEOCHEMISTRY OF HYDROTHERMAL CLAYS FROM WELL WK244, WAIRAKEI GEOTHERMAL FIELD, NEW ZEALAND**

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Drill cuttings recovered from Production Well WK244 of the Wairakei Geothermal Field, New Zealand, have been analyzed to determine the mineralogy, morphology and oxygen-isotope compositions of the hydrothermal clays present in these samples. These data provide a tool for assessment of the paleo-hydrological conditions and temperature fluctuations that have operated in the subsurface-information that is valuable in development of this geothermal resource. SEM photomicrographs demonstrate a change in clay morphology from micron-scale laths and hairy fibers to pseudo-hexagonal plates as depth and temperature increase. Mixed-layer illite/dioctahedral-smectite (I/S) and chloritic phases are the principal clay minerals present. The chloritic clay occurs as R0 chlorite (>0.9)/trioctahedral-smectite. The I/S exhibit a classical sequence from R1 to R3 interstratification with the illitic component increasing with temperature and depth. The results of methylene blue absorption tests are strongly inversely correlated to the percentage of illite in the I/S, which validates this drill-site technique for estimating I/S composition. Correlation between the percentage of illite interstratification and downhole temperature (67 to 214°C) for Well WK244 yields an illite geothermometer,  $T(^{\circ}\text{C}) = (I - 0.30839)/(0.00296)$ , where I is the ratio of illite in the I/S; this relationship is consistent with the result obtained previously for a nearby Wairakei borehole. The  $\delta^{18}\text{O}$  values of the I/S (<0.5-0.2 ‰) decrease systematically with increasing measured downhole temperatures and depth, from +5.4‰ at 195 m depth (~63°C) to +0.8‰ at 710 m (>224°C). These data have been used to estimate the isotopic composition of the reacting subsurface fluids, assuming that the clays are in isotopic equilibrium with their present subsurface environment. The combined results are suggestive of a clay alteration assemblage developed in a diffuse fluid-flow environment from near-neutral to mildly alkaline fluids, conditions that are known to persist locally within the Wairakei Geothermal System.

#### **MONAZITE AGE CONSTRAINTS ON THE TIMING OF METAMORPHISM AND DEFORMATION IN THE FOXE FOLD BELT, MELVILLE PENINSULA, NUNAVUT; AN ELECTRON MICROPROBE STUDY**

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The Paleoproterozoic Foxe Fold Belt (FFB) formed during the 1880-1865 Ma Foxe Orogeny as part of the Trans-Hudson Orogeny. The FFB consists of interfolded Paleoproterozoic Penrhyn Group metasedimentary rocks and underlying Archean Prince Albert Group basement. An older, separate Archean terrane, the Repulse Bay Block, is exposed ~10-15 km south of the southernmost exposures of the Penrhyn Group and immediately south of the FFB. Collision between the Repulse Bay Block and the Prince Albert Group may have extruded the Penrhyn Group to the NNW, during formation of the NNW-verging FFB. The Penrhyn Group is a passive margin sequence of massive marble, minor amphibolite, and calc-silicate, pelitic, and psammitic gneisses meta-

morphosed at upper amphibolite-facies conditions. The Prince Albert Group contains ca. 2760-2700 Ma supracrustal rocks and granitoid intrusions.

Peak metamorphic conditions for Penrhyn Group units located ~130 km apart at opposite ends of the FFB in Melville Peninsula of ~700°C and ~5 kb in the SW FFB and ~650°C and ~4.5 kb in the NE FFB were established by Henderson (1983) and Mazurski (1980). We collected Penrhyn Group metapelites with the following respective peak assemblages for geochronology from the N, NE, and SE-central FFB: Sil-Bt-Kfs-Pl  $\pm$  leucosome; Bt-Kfs-Pl  $\pm$  Sil, and Sil-Grt-Bt-Kfs-Pl  $\pm$  leucosome. Our assemblages are compatible with Henderson's and Mazurski's interpretation of near-constant metamorphic grade throughout the FFB.

In-situ electron microprobe U-Th-Pb geochronology of sampled units yielded dates between ca. 1857 and ca. 1776 Ma. Petrographic analysis and monazite Y-zonation patterns were used to determine the age and significance of metamorphic events. Two high Y monazite cores from the NE and SE-central FFB yield ca. 1857 Ma dates interpreted as the age of initial monazite growth. A ca. 1843 Ma date on the rim of a monazite inclusion in a K-feldspar porphyroblast yields a lower age constraint on the peak metamorphic assemblage in the SE-central FFB. A ca. 1776 Ma high Y monazite rim is interpreted as the age of garnet breakdown to Bt + Pl in the SE-central FFB. Dates between ca. 1857 and ca. 1843 Ma suggest prograde monazite growth from crustal thickening initiated by the Foxe Orogeny. The ca. 1776 Ma date suggests retrograde monazite growth during uplift after the 1830-1800 Ma collision of the Superior Province to the SE.

#### **INSTRUMENT DEVELOPMENT FOR A LUNAR MICRO-ROVER MISSION**

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A collaborative mission to land a micro-rover carrying a science payload on the Moon has been proposed. Such a potential Canadian-led international robotic mission to the Moon will combine Canada's expertise in robotics, space instrumentation, and planetary science, with the UK's small satellite experience, and lunar orbiter and lander programme, and the USA's existing lunar science and exploration program provides a unique opportunity for demonstrating an innovative low-cost Canadian-led lunar mission. To minimize the mission cost, the spacecraft carrying the rover from the Earth will land directly on the lunar near-side without a lunar orbiter. The possibility of extending the mission past one lunar day will be investigated. In this paper, four types of science and instruments as well as the landing site consideration will be discussed. The potential measurements are (1) Alpha Particle and X-ray Spectrometer for bulk chemical composition, including search for Cl, S, Zn; (2) Thermal IR imager for site panorama as well as thermal inertia measurements to infer physical properties, especially grain size; (3) Microscopic imager for grain sizes, shapes, size distribution of clods; (4) A set of space environment measurements including magnetometers, electric field measurement as well as radiation dosimeter.

#### **ORGANIC CARBON AMENDMENT OF TAILINGS FOR PASSIVE TREATMENT OF MINE DRAINAGE**

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Field and laboratory experiments were conducted to evaluate organic carbon amendment of sulfide-rich tailings for passive treatment of pore water and drainage. Fine-grained mill tailings containing approximately 34% (w/w) pyrite were amended with organic carbon to promote microbially-mediated sulfate reduction,

metal-sulfide precipitation and alkalinity production. Pore water and drainage associated with these tailings commonly contains elevated concentrations of  $\text{SO}_4$ ,  $\text{S}_2\text{O}_3$  and Zn, and trace to moderate Fe, Cu, As, Sb, Tl and Mo concentrations. Field-scale experiments evaluated amendment of tailings with varied mixtures of peat, spent-brewing grain (SBG) and municipal biosolids (MB). The geochemistry, microbiology and mineralogy of five field-scale test cells, amended with 5 or 10 % (v/v) organic carbon, and two control cells were monitored with time. Increases in concentrations of dissolved organic carbon (DOC) to >200 mg L<sup>-1</sup> were observed in cells amended with peat + SBG and peat + SBG + MB. Furthermore, pore-water  $\text{SO}_4$  concentrations in these cells exhibited decreases from > 3000 mg L<sup>-1</sup> to < 500 mg L<sup>-1</sup> as a function of time and depth below the tailings surface. Removal of  $\text{SO}_4$  in these cells was accompanied by  $\text{H}_2\text{S}$  production, large increases in  $\delta^{34}\text{S}_{\text{SO}_4}$  values, undersaturation of pore-water with respect to gypsum [ $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ], and most probable number populations of sulfate-reducing bacteria > 106 cells g<sup>-1</sup>. Large decreases in the mass transport of Zn, Ni, Sb and Tl were observed under sulfate-reducing conditions, and mineralogical investigations indicate that metal attenuation resulted from the precipitation of secondary Fe-S and Zn-S phases. The effect of amendment rate on treatment performance was evaluated in laboratory columns containing tailings amended with peat + SBG at rates of 0, 2 and 5 % (v/v). Decreases in  $\text{S}_2\text{O}_3$  concentrations in column effluent in amended columns, resulting from reduction or disproportionation reactions, generally were accompanied by decreases in mass transport of Cu, Mn, Ni, Pb, Tl and Zn. However, reformation of  $\text{S}_2\text{O}_3$  was observed in amended columns under low Fe and Zn input concentrations. Increases in effluent concentrations of Mo were observed with increasing amendment rate, whereas Sb discharge was generally consistent among all columns. Although the mobility of sulfide-mineral oxidation products in general decreased in the organic-amended tailings, initial increases in dissolved Fe and As concentrations were observed in field and laboratory experiments. Nonetheless, subsequent attenuation of Fe and As was observed after sulfate-reducing conditions were established. These experiments demonstrate the potential for tailings drainage management using organic carbon amendments.

#### **THE ROLE OF FLUORINE ON THE SOLUBILITY OF HIGH FIELD STRENGTH ELEMENT IN SILICATE MELTS**

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Ore deposits of high field strength elements, e.g., Ta, Nb and REE generally are also enriched in fluorine, but the specific role that fluorine plays in ore deposit formation is poorly understood. To address this problem a series of experiments were conducted to determine the solubilities of manganocolumbite ( $\text{MnNb}_2\text{O}_6$ ) and manganotantalite ( $\text{MnTa}_2\text{O}_6$ ) in granitic melts. Three types of fluorine-free starting glasses were first synthesized, two of which are completely synthetic (HPG-1 and HPG-2) and a third was produced by melting a sample of natural granite (NG), from the Hub Stock, Czech Republic. HPG-1 is metaluminous (ASI=0.97), NG is peraluminous (ASI=1.14) and has an initial F content of 0.36 wt. %. HPG-2 contains 1.1 wt. %  $\text{Li}_2\text{O}$ , 1.7 wt. %  $\text{P}_2\text{O}_5$  and 2.02 wt. %  $\text{B}_2\text{O}_3$ . It has an ASI of 1.0, but if Li is included as an alkali, then the glass is peralkaline. In each of the three glasses up to ~11 wt. % F was added as AgF so that the ASI of the melt in each series would be constant.

Experiments were conducted at 800°C and 200 MPa. The log solubility product values of tantalite and columbite for the HPG-

1 melt are -3.36 to -2.92 mol<sup>2</sup>/kg<sup>2</sup> and -3.01 to -2.87 mol<sup>2</sup>/kg<sup>2</sup>, respectively and within error limits solubilities apparently do not vary with fluorine. Similar data was obtained for the NG melts where the log solubility product values range from -3.00 to -2.35 mol<sup>2</sup>/kg<sup>2</sup> and from -2.83 to -2.67 mol<sup>2</sup>/kg<sup>2</sup> at 800°C, respectively. The log solubility products tantalite and columbite values in the highly fluxed HPG-2 composition are higher, -2.34 to -2.41 and -2.72 to -2.79, respectively. The solubilities are also independent of the fluorine content of the melt and it is not clear whether the increased solubility is primarily related to the peralkaline nature of the melt (if Li is included as an alkali element), or whether the other fluxing have an important role. Experimental studies by other authors have shown that rare earth element solubilities behave similarly, and are not affected by the fluorine content of the melt. Thus, although rare-element deposits are associated with F-rich magmatic rocks, there is no experimental evidence that indicates that fluorine plays a direct role in mineralization at the magmatic stage of mineral deposit evolution.

### SYNTHESIS AND STABILITY OF ELBAITE

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Elbaite and other lithium-rich species of tourmaline (rossmanite and liddicoatite) occur solely in the latest-stage primary units and miarolitic cavities of highly fractionated granitic pegmatites. In all three species, Li occupies the octahedral Y site, along with Al. Manganese and F are not essential to most of the end-members, but natural crystals tend to be enriched in both, especially in Mn to several wt.% MnO. The Li-tourmalines occur commonly wherever Li-rich pegmatites contain appreciable "black" tourmaline (schorl-olenite-foitite solid solutions, or SOFTur) in the outer marginal zones.

Though most species of tourmaline (e.g. schorl-dravite, olenite, foitite, uvite, and others) have been readily synthesized over a wide range of pressures, temperatures, and starting compositions, synthesis of elbaite has proven elusive. The three known prior reports of elbaite synthesis are not reliable for different reasons. Our previous attempts to synthesize elbaite at 200 MPa and 350°-800°C have produced tourmaline compositions that lie mostly in the SOFTur ternary space, e.g., NaFe<sub>3</sub>Al<sub>6</sub>(BO<sub>3</sub>)<sub>3</sub>Si<sub>6</sub>O<sub>18</sub>(OH)<sub>3</sub>(OH,F)-[vac]AlFe<sub>2</sub>-Al(FeH)<sub>-1</sub>, with and without Mn, even at saturation in eucryptite. Recent efforts to synthesize elbaite from a starting composition of kaolinite + Li<sub>2</sub>B<sub>4</sub>O<sub>7</sub> + Na<sub>2</sub>B<sub>4</sub>O<sub>7</sub> + H<sub>3</sub>BO<sub>3</sub>, however, have produced tourmaline that contains up to ~39% Elb component based on electron microprobe analyses. The Elb component increases with T from 350°-650°C, and with increasing P from 200 to 260 MPa. An appreciable <sup>IV</sup>B(T) component increases with decreasing T at 200 and 260 MPa.

The preliminary results appear to confirm that the stability of elbaite increases with pressure in excess of 200 MPa. In this regard, the stability field of elbaite may resemble that of spodumene, with which elbaite commonly occurs, and which is restricted to a high pressure (relative to eucryptite and petalite) that is necessary to force Li into octahedral coordination (as opposed to tetrahedral in the other phases). Crystallization of elbaite at approximately 550°C at 250-300 MPa would be consistent with prior estimates of pocket-forming conditions based on fluid inclusion analysis in relation to the quartz-saturated stability fields of the lithium aluminosilicates.

### TECTONIC, SEDIMENTARY AND METALLOGENIC RE-EVALUATION OF BASAL STRATA IN THE MESOPROTEROZOIC BYLOT BASINS (NU): ARE UNCONFORMITY-TYPE U CONCENTRATIONS A REALISTIC EXPECTATION?

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The Mesoproterozoic Borden, Fury and Hecla, Ashton and Hunting, and Thule basins, collectively known as the Bylot basins, were developed in a series of sub-parallel depressions, linked to extension associated with the Mackenzie Igneous event at ca. 1270 Ma.

Within the Borden basin basal strata of the Uluksan Group are dominated by theolitic volcanics and siliciclastic sandstones, much of which has previously been interpreted as terrestrial flows and fluvial sandstones. Thick lava flows in the Nauyat Formation contain cryptic pillow structures and typically have fine-grained fragmental tops. A subaqueous origin for these flows is supported by the presence of stomatolitic carbonate on the top of several flows, and the presence of sand-injectites at the base of flows. Associated quartz arenites are all of marine origin. Although much of the overlying Adams Sound formation has been interpreted as fluvial we found no evidence for this, except locally at the base of the basin near Paquette Sound. Paleocurrents do not indicate a strong unimodal pattern to the NW as recorded earlier, but reflect a more open basin. Most of the formation was deposited on a tide and storm shelf, with local development of large sand-wave complexes. A similar marine dominated setting can be demonstrated in both the Ashton and Hunting and Fury and Hecla basins. The latter containing thin sheets of fluvial deposits within the Nyeobe Fm on the south side of the basin, and in the basal 3 m of the Whyte Inlet Formation on the NE margin of the basin.

Paleocurrent patterns in all three basins do not reflect confinement between the walls of a restricted grabens, suggesting that basin initiation may have been related to transtensional extension rather than aulacogen development associated with opening of the so-called Poseidon ocean.

Although uranium within basement granites north of the Fury and Hecla Straits may have been scavenged by fluids well after lithification of the Mesoproterozoic basin fill, to produce local vein type U deposits, the potential for extensive unconformity type deposits, analogous to those in the Athabasca Basin is exceptionally low, as most of the sandstone have early siliceous cements, and had a low feldspar content, inhibiting development of extensive secondary porosity.

### MODIFIED PLACER GOLD DEPOSITS IN THE PALEOPROTEROZOIC HURONIAN SUPERGROUP, CLEMENT AND PARDO TOWNSHIPS, ONTARIO

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Local gold concentrations of up to 9,442 ppb are found in laterally extensive pyrite-bearing, framework supported, cobble and boulder conglomerates in the basal 30 m of the Huronian Supergroup, about 90 km NNW of Sudbury in the southern part of the Cobalt Embayment. These were deposited as part of a valley-fill succession, in shallow gravel-bed braided rivers with local hyperconcentrated flows. The basal contact with underlying Archean psammites is typically highly irregular and shows no obvious sign of weathering, suggesting that deposition took place during or soon after retreat of the glaciers responsible for deposition of the Ramsey Lake Formation. Highest gold concentrations are associated with moderately well sorted medium to large pebble conglomerate that show some signs of reworking during low flow events. Depositional elements are typically lenticular and of lim-

ited lateral extent. Unlike the pyritic quartz-pebble conglomerates at the base of the Matinenda Formation in the Elliot Lake and Blind River areas, these conglomerates contain no uraninite and are polymict, with material derived from a highly restricted catchment area with marked local and regional topographic relief. Porous detrital allogenic pyrite and euhedral post-depositional pyrite have overlapping, generally positive  $\delta^{34}\text{S}$  values, indicating a closed system during diagenesis and metamorphism. The presence of biotite-enriched rims on many of the metavolcanic and metasedimentary clasts in the conglomerates suggests that gold was partly leached from the allogenic pyrite grains at the peak of the Penokean Orogeny at 1.85-1.5 Ga. The potential source of the Au-bearing detrital allogenic pyrite appears to be an as yet undiscovered Archean VHMS deposit located 1 to 8 km north of the deposit.

## TITAN

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Saturn's giant icy moon Titan has been of considerable interest since the presence of an atmosphere was hinted at one century ago. The NASA-ESA-ASI Cassini-Huygens mission, at Saturn for the last 6 years, has transformed this curious dot in the sky into a remarkably diverse, complex and interesting world, which is in many ways more Earth-like than anywhere in the solar system. This talk will summarize some of Cassini's recent findings with emphasis on the interactions between Titan's surface, atmosphere, and interior.

One major surprise was that Titan's tropics have vast sand seas of linear (longitudinal) dunes, apparently made from organic compounds produced by atmospheric photochemistry. Despite the very different environment (low gravity, air 4x denser than Earth) and materials, the dunes have an apparently identical size and morphology to large linear dunes on Earth, from which we can learn in the field about how dunes interact with wind and topography on Titan.

(Dry) fluvial channels are found at all latitudes and display a range of morphologies, presumably carved by methane rainstorms. Curiously high radar-reflectivities suggest some channels are littered with spheroidal radar-transparent cobbles, raising new questions about fluvial sorting and rounding of sediment. These processes of erosion and deposition make Titan's fairly small impact crater population somewhat degraded, encouraging study of terrestrial analogs. Debate rages about whether Titan is (cryo)volcanically active.

Perhaps most exciting, Titan's polar regions have many lakes and a few large (~500 km) seas of liquid hydrocarbons. One shallow lake in the Titan's south-Ontario Lacus has shrunk by several km as Cassini has watched, and the profound difference in abundance of liquids between hemispheres suggests that Croll-Milankovich cycles may redistribute the liquid over geologically short timescales. Another curiosity is that the seas appear dead flat, without ripples. With the caveat that empirical wind-wave relations do not apply on Titan and oceanography is now no longer just an Earth science!-this may be because observations in the large northern seas have been during winter calm. As we move into Titan's northern summer (a Titan season is 7.5 Earth years long) models predict that winds in Titan's arctic will freshen: Kraken may be about to stir.

Titan's meteorology and geology make it an outstanding object for comparative planetology, and the rich inventory of organics on Titan makes it a particularly appealing target for astrobiology. Future missions might include boats and balloons.

## STRATIGRAPHY AND DEPOSITIONAL SETTING OF POTSDAM GROUP STRATA ALONG THE NORTHWESTERN OTTAWA EMBAYMENT – A PRELIMINARY REPORT

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The Cambrian to Lower Ordovician Potsdam Group is one of the first named rock units in North America. It comprises the earliest Phanerozoic sedimentary cover in the St. Lawrence Lowlands, directly overlying Grenville basement rocks and a 500 my unconformity. In most places in the Ottawa Embayment it consists of undeformed strata that are coeval with sedimentation on the Early Paleozoic passive-margin Laurentian Platform. This study focuses on the stratigraphic relationships and environments of deposition of strata that make up the Potsdam Group, specifically the Nepean Formation, in the northwestern part of the Ottawa Embayment, in and around the city of Ottawa.

Preliminary stratigraphic investigations indicate that a variety of depositional facies are observed in the Nepean Formation around Ottawa. In west Ottawa exposures consist mainly of parallel-bedded and -laminated sandstone with inversely graded laminae, adhesion stratification, and small wave ripple indicating varying aeolian and shallow water deposition. These strata are interbedded with small- and medium-scale trough cross-stratified, medium-grained sandstone that locally form erosionally-based tabular units interpreted to represent the fill of subaqueous (tidal?) channels. To the east of Ottawa, the Nepean comprises stacked medium- to large-scale trough cross-stratified sandstone beds with common robust vertical trace fossils. Paleoflow is generally towards the southeast. These strata are interpreted to represent large-scale subaqueous sand bars overridden by smaller scale dunes in a high-energy tidal setting. Further eastward, the succession immediately overlying the basement consists of at least four sharply bounded units. In one location, the basal unit comprises interbedded mudstone and dolostone that might correlate with one of the known carbonate-bearing stratigraphic outliers in the Potsdam Group, such as the Altona Formation in New York or the Riviere aux Outardes Member in Quebec. In most places, however, the base of the section consists of medium-scale trough cross-stratified, pebbly sandstone, representing shallow channel deposition, overlain sharply by fine-grained tabular and bioturbated sandstone of open marine origin. These strata, in turn, are succeeded by medium-scale trough cross-stratified, coarse-grained sandstone with common scour surfaces, pebble lags and an absence of trace fossils – these strata are interpreted to represent deposition in a high-energy (braided?) fluvial system.

Currently it is unknown how these various depositional facies and stratal units relate in space and time, but some preliminary depositional interpretations and stratigraphic correlations are proposed concerning the local stratigraphy and its relationship with Potsdam Group strata within the larger scale Ottawa Embayment.

## VMS DEPOSITS AND MAGMATIC SULPHIDES: INSIGHTS FROM A THICK THOLEIITIC SILL OF THE MESOPROTEROZOIC BELT-PURCELL BASIN

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One of the characteristics of economic VMS deposits is the "favourable horizon" whereby most ores of a VMS district are restricted to a narrow stratigraphic interval that is just a fraction of the total stratigraphic range occupied by the entire volcanic pile. This distribution is at variance with the seawater convection model which predicts that sulphide deposition should take place over the entire time span of active submarine volcanism. A more appealing explanation is that the ephemerality of VMS formation reflects an



event in the subvolcanic magma chamber (such as magma mixing or decompression) which resulted in the catastrophic upward release of metals and sulphur, similar to the processes envisaged for porphyry copper ore systems in subaerial felsic volcanic environments.

The upward release of metals and sulphur from submarine magmas and also magmas of mafic composition is demonstrated by a 850 metre thick tholeiitic sill that was emplaced into wet sediment of the Aldridge Formation during active rifting of the Mesoproterozoic Belt-Purcell basin. Magmas for these sills were contaminated by assimilation of both Archean basement and Aldridge sediments, resulting in a hydrous magma from which hornblende was the main ferromagnesian phase to crystallize. Chemical analysis of drill cuttings representing 3 metre sample lengths indicate a weak fractionation from Mg# values of 42 in the lower part of the sill to 30 near the top. Over the uppermost 150 metres of the sill, the sulphur content gradually increases from a 0.08% to 4.18%, occurring as 1 to 200 micron intergranular monomineralic grains of pyrrhotite, minor chalcopyrite and rare galena and sphalerite. This upward increasing concentration of sulphides suggests partitioning of metal sulphides into low density phases during magma crystallization.

The major difference between the sill and crustal contaminated mafic intrusions elsewhere that host sulphide melt segregations at their bases, is the high water content of the sill magma. This suggests that the low density phases were aqueous, and likely similar to those that transport metals and sulphur upwards from subaerial felsic magmas. VMS systems in arc and back arc environments can therefore be considered the submarine equivalents of porphyry copper systems, but in which the magmatic hydrothermal metal sulphides are conveyed or redistributed to the sea floor by convected seawater.

#### **GEOLOGICAL, MINERALOGICAL AND FLUID INCLUSION STUDIES OF VEIN-HOSTED Mo-Cu MINERALIZATION AT MOLY BROOK, SOUTHERN NEWFOUNDLAND**

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The Moly Brook deposit is located near Grey River on the south coast of Newfoundland and is hosted within sheared granitoid rocks of the Siluro-Devonian Burgeo Intrusive Suite. It consists of a linear zone (~1200 × 500 m) of generally NS-trending, sub-vertical tensional quartz veinlets defining sub-parallel sheeted structures, and localized stockworks. Sulphide-bearing granitic dykes and veinlets are spatially related to the hydrothermal system. Field relationships and geochronology indicate a genetic and temporal link between evolved granite magmatism and molybdenum-copper mineralization at ca. 380 ± 2 Ma.

A three-stage vein classification has been developed for the area based upon detailed drill core and petrographic studies. Stage I predates sulphide mineralisation and is represented by biotite-actinolite-magnetite veins and later quartz-K-feldspar-magnetite assemblages. Stage II veins represent the main sulphide mineralisation event and comprise assemblages of quartz-molybdenite-magnetite, quartz-molybdenite-sulphide-magnetite and aplite-sulphide-fluorite veinlets. These veins are variably associated with K-feldspar-biotite-magnetite alteration halos. A later quartz-muscovite-molybdenite-magnetite assemblage is associated with muscovite-sericite halos and distinctive comb textures. Molybdenite is typically present as fine-grained, disseminated stringers and rosettes along Stage II vein selvages; paragenetically molybdenite

appears early, relative to other sulphides. Stage III veins postdate sulphide mineralization and consist of thicker, massive, quartz-muscovite veins and calcite-epidote-chlorite veinlets that crosscut all other vein types.

Fluid inclusion (FI) studies (petrography, microthermometry and Raman spectroscopy) of vein quartz from Stage II molybdenite veins reveal the presence of five primary fluid inclusion types: Type I are liquid-rich, and Type II are vapour-rich, aqueous-carbonic FIs with a general composition H<sub>2</sub>O-CO<sub>2</sub>-NaCl-CH<sub>4</sub>±N<sub>2</sub>. Salinities range from 4 to 10 eq. wt. % NaCl and minimum trapping temperatures are between 330°C and 490°C. Type III are liquid-rich, and Type IV are vapour-rich, aqueous FIs with salinities ranging from 1 to 14 eq. wt% NaCl, whereas Type V are liquid-rich, high salinity (>26 eq. wt% NaCl) aqueous FIs of the general composition H<sub>2</sub>O-NaCl-KCl, with traces of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>. Minimum trapping temperatures of the aqueous FIs range from 240 to 350°C. These data reflect the variable composition of mineralising fluids associated with the main Stage II sulphide mineralisation event. Furthermore, Type I and II represent relatively early, high temperature magmatic-hydrothermal fluids that evolved towards the lower temperature fluid represented by Types III, IV and V.

#### **MICROSTRUCTURAL ANALYSIS OF THE BOROSILICATES GRANDIDIERITE, PRISMATINE AND TOURMALINE IN GRANULITE-FACIES PARAGNEISSES FROM THE LARSEMANN HILLS, PRYDZ BAY, EAST ANTARCTICA**

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Granulite-facies (6-7 kbar and 800-860°C) paragneisses of late Neoproterozoic age in the Larsemann Hills include several units unusually enriched in B. Tourmaline, (Na,Ca)(Mg,Fe)<sub>3</sub>Al<sub>6</sub>Si<sub>6</sub>O<sub>18</sub>(BO<sub>3</sub>)<sub>3</sub>(OH,F,O), and two high-temperature borosilicate minerals, grandidierite, (Mg,Fe)Al<sub>3</sub>BSiO<sub>9</sub>, and prismaticine, (vac,Mg,Fe)(Al,Mg,Fe)<sub>9</sub>(Si,B,Al)<sub>5</sub>O<sub>21</sub>(OH,F), are associated with orthopyroxene, garnet, cordierite, biotite, sillimanite, quartz, K-feldspar and plagioclase. The following B-rich lithological types are recognized: (1) blocky tourmaline-quartz granulites, (2) well-foliated grandidierite-sillimanite±prismaticine gneisses, (3) biotite gneisses with segregations of coarse-grained prismaticine, (4) prismaticine-sillimanite-cordierite gneisses, and (5) plagioclase-quartz-prismaticine gneisses.

Petrographic analysis of these units reveals a variety of microstructures associated with each of the borosilicates. All three borosilicates are found together in some samples, but complex microstructures make it difficult to determine whether they are in equilibrium. Grandidierite forms both medium-grained subhedral crystals that are commonly aligned, and very fine fibrous aggregates in biotite and orthopyroxene. Rare quartz halos around grandidierite are also present. Tourmaline microstructures include aggregates of rounded grains; color zoning, e.g., olive cores with bluish rims; overgrowths on prismaticine and grandidierite. Microstructures associated with prismaticine include coarse prisms in biotite and cordierite-rich segregations in biotite gneisses, overgrowths around grandidierite, and embayment by cordierite and tourmaline. Prismaticine locally contains tourmaline inclusions. The borosilicates are also commonly isolated by other minerals, such as prismaticine in cordierite, or are enclosed in one another, e.g., grandidierite enclosed in prismaticine. In some cases, the three borosilicates are found in one section, but in separate layers. Locally, prisms of grandidierite and prismaticine are aligned roughly parallel, and occur with trace amounts of fine-grained tourmaline;

this may represent an equilibrium assemblage of the three borosilicates.

Microstructural relationships suggest a three-stage evolution with early, peak, and post-peak metamorphic growth for tourmaline and grandidierite, and prismatic growth at the peak. Prismatic-grandidierite-sillimanite, grandidierite-tourmaline assemblages appear to have been stable at the metamorphic peak, but there is little evidence for a stable prismatic orthopyroxene-garnet assemblage. Biotite and cordierite tend to be later formed phases. The precursor to the B-rich rocks could have been tourmaline-rich metapelites; and quartzites ("tourmalinites"). Boron released from tourmaline breakdown is normally lost to fluid or anatectic melt in paragneisses subjected to granulite-facies metamorphism. However, retention of B in the Larsemann Hills paragneisses could be due to its high concentration in the precursors, which resulted in partial tourmaline preservation, as well as in formation of the high-temperature borosilicates grandidierite and prismatic as products of tourmaline break down reactions.

#### **CRYSTAL SIZE DISTRIBUTION OF FELDSPAR CRYSTALS FROM GRANITIC ROCKS OF EURAJOKI (FINLAND) AND THE SOUTH MOUNTAIN BATHOLITH (NOVA SCOTIA, CANADA)**

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Crystal size distributions (CSD) studies of granitic rocks allow the quantification of sizes of crystals and contribute to a better understanding of crystallization conditions. They are a useful complement to other techniques, such as petrography and geochemistry, and help to decipher the processes that occurred during rock formation. The majority of CSD studies have been done on igneous rocks have been performed on volcanic rocks and mafic plutonic rocks, but here the technique is used in order to better understand crystallization conditions of two well-studied granitic bodies; the Eurajoki stock in Finland and the South Mountain Batholith (SMB) in Nova Scotia.

The Eurajoki stock is part of the Laitila rapakivi granite and is composed of two petrographically distinct granite types. SMB was emplaced in the Meguma Terrane of the Appalachian Orogen and is composed of six different granite types. CSDs of potassic feldspars from Eurajoki and of plagioclase and potassic feldspars from the South Mountain Batholith are curved upwards, except for one member composed of muscovite leucogranite where the CSDs are straight. Characteristic lengths indicate three populations of crystals sizes for the former and two populations for the latter. Based on CSDs and other observations, it is proposed that potassic feldspar crystals from Eurajoki have been texturally coarsened likely because it was emplaced into a hot environment. In the South Mountain Batholith, textural coarsening formed megacrysts because constant ascent of new magma into the plutons slowed undercooling and buffered the temperature producing the right conditions for coarsening.

Textural coarsening, as revealed by CSDs, is an important process in the formation of the granites from Eurajoki and the SMB, and more generally, may be an important process in the formation of other plutonic felsic rocks.

#### **VOLCANOLOGY AND STRATIGRAPHY OF A SUPRACRUSTAL SUCCESSION OF THE PRINCE ALBERT GREENSTONE BELT, WESTERN MELVILLE PENINSULA, NUNAVUT**

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The Prince Albert Group (PAG) and correlative rocks of the western Churchill Province outcrop as semi-continuous, northeast-trending, komatiite-bearing greenstone belts for over a thousand kilometres of strike-length between Baker Lake and Melville Peninsula. Ongoing geological mapping and U-Pb age dating, at the PAG type locality, in the Prince Albert Hills of western Melville Peninsula reveal that these rocks are significantly older (ca. 2970) than those of otherwise lithologically comparable sequences of the western Churchill Province (2770-2760 Ma). To single it out, the greenstone belt at the type locality is hereafter referred as the Prince Albert Greenstone Belt (PAGB).

The southern part of the PAGB comprises a NNE-SSW trending volcano-sedimentary succession metamorphosed to upper greenschist up to amphibolite facies that has undergone at least two phases of deformation. The succession can be subdivided into three packages based on field relationships, lithological association, mineralogy and relict primary textures. Package A is composed of ultramafic flows and related intrusions, chiefly mafic subaqueous flows intercalated locally with thin layers of mafic volcanoclastic and clastic sediments; spinifex and cumulate textures are locally recognisable in ultramafic rocks, pillows in mafic volcanics and bedding in volcanoclastic and sedimentary rocks.

Package B is composed of intermediate to felsic volcanic rocks with intercalated thin beds of felsic volcanoclastic and clastic metasediments. Volcanic rocks of this package are commonly massive to locally brecciated, with bedding and cross-bedding only discernable in volcanoclastic rocks. Package C is dominated by basaltic and andesitic flows. It includes at least two distinct silicate-facies banded-iron-formations signalling pauses and time gaps during the volcanic history. Package C also includes subordinate felsic to intermediate volcanoclastic and clastic metasediments, locally with alternating thin mafic and felsic flows.

Except for long-known iron deposits, no other major mineral occurrences were historically inventoried in PAGB. This is no longer the case since the discovery of a new nickel showing that testifies to the prospectivity and potential of this greenstone belt. Grab samples of massive sulphides from a gossan zone occurring along the irregular basal contact of ultramafic rocks with underlying mafic volcanic and gabbroic rocks yielded up to 7.4% Ni. This discovery, in combination with rocks types encountered and numerous gossans, highlights the mineral potential of PAGB.

#### **MAINLAND CANADA, NORTH OF 60: AN AREA OF POTENTIAL AND CHALLENGE FOR PETROLEUM EXPLORATION**

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A probabilistic assessment of total conventional oil and gas potential (produced and remaining) for northern mainland Canada show that approximately 70% of the oil and 60% of the gas has yet to be discovered. This assessment, which included a number of plays that extend well into British Columbia and Alberta, estimated a potential of 1053\*10<sup>6</sup> m<sup>3</sup> (6.6 BBO) of oil and 2189\*10<sup>9</sup> m<sup>3</sup> (77 Tcf) of gas (mean volumes). Restricting the area of interest to 'north of 60' increases the ratio of undiscovered to discovered resources but reduces the potentials to 4.8 BBO and 32.6 TCF gas.

North of 60, the Interior Platform is predicted to contain  $388.5 \times 10^6$  m<sup>3</sup> (2.4 BBO) of oil and  $600.5 \times 10^9$  m<sup>3</sup> (21 Tcf) of gas and the Foreland Belt,  $375 \times 10^6$  m<sup>3</sup> (3.8 BBO) of oil and  $322.2 \times 10^9$  m<sup>3</sup> (11.3 Tcf) of gas.

Areas with the greatest potential are Great Slave Plain and its adjoining foreland, Colville Hills and the Norman Wells area of Mackenzie Plain. The top three plays in terms of oil potential are Kee Scarp Reefs in the foreland belt (1.3 BBO), Cambrian clastics of the Interior Platform (0.95 BBO) and Arnica-Landry platform in the foreland belt (0.85 BBO). The top three gas plays are Cambrian Clastics of the Interior Platform (10.7 Tcf), Manetoe facies in the foreland belt (8.6 Tcf) and Slave Point Reef Edge in the Interior Platform (3.2 Tcf).

Reflection seismic and potential field data provide insights into structural and stratigraphic aspects of these plays and some of the challenges inherent in searching out the undiscovered resources. Kee Scarp reefs, the reservoir at Norman Wells oil field, are readily identified on seismic but their relatively small size make them difficult to find. Cambrian thickness maps, when combined with bouger gravity, show the influence of continental breakup tectonics on the development of depocentres and depositional patterns and may assist in building a predictive model for finding basal Cambrian (Mt Clark Fm) sandstone, an important potential gas and oil reservoir. Reservoirs in the generally tight Arnica-Landry require secondary porosity development by fracturing, leaching or Manetoe diagenesis. One can identify locations favourable for such development, such as at the Summit Creek discovery, but direct recognition of porosity on seismic is only possible with broad-band data carefully processed to preserve subtle amplitude and phase characteristics. This requires a far better understanding of the geophysical parameters than is typical for a frontier region.

#### **MOLECULAR-SCALE CHARACTERIZATION OF THE MERCURY BINDING ENVIRONMENT ON BROMINATED BIOMASS ASH USING X-RAY ABSORPTION FINE STRUCTURE SPECTROSCOPY**

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Mercury is a toxic substance emitted to the atmosphere through many sources, including coal-fired power plants. Upon deposition, the mercury is bio-accumulated up the food-chain, leading to significant neurological disorders in humans. While current approaches for mercury removal have focused on the injection of powdered activated carbon sorbents into the flue gas stream, the cost of activated carbon has led to a search for alternative sorbent materials. Recent lab and field-scale experiments have demonstrated the potential for brominated industrial solid waste from biomass combustion to be an efficient, cost-effective alternative to activated carbon. However, little is known about how the mercury is bound to the biomass during capture. Understanding the binding environment of mercury in the biomass system may improve the capture efficiency and lead to the development of more efficient, low cost sorbents.

To better understand the mechanisms involved in mercury capture by the brominated biomass ash, X-ray absorption fine-structure (XAFS) spectroscopy data was collected at the Hg LIII edge, Br K-edge, and S K-edge and analyzed to determine the local bonding environment around the mercury atoms. The coordination environment of mercury was compared between mercury bound to a commercial brominated activated carbon and the brominated biomass ash.

Our results indicate that in both the commercial and biomass ash sorbents, the mercury was captured by chemisorption; however, the mercury binding environment was different for each material. Mercury was found to bind to reduced sulphur during capture by the commercial brominated activated carbon while mercury was surrounded by carbon and bromine in the brominated biomass ash.

#### **THE SOFT X-RAY MICRO-CHARACTERIZATION BEAMLINE (SXRMB) AT THE CANADIAN LIGHT SOURCE: A VERSATILE NEW TOOL FOR EARTH SCIENTISTS**

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The Soft X-ray Micro-characterization Beamline (SXRMB) is a medium energy, bending magnet-based beamline at the Canadian Light Source, Saskatoon, SK. The main focus of SXRMB is research in the 'intermediate energy range' (between 1700 and ~5000 eV, capable of reaching 10000 eV) which covers the K-, L-, and M-edges of many main group and transition metal elements. This energy range provides access to important elements such as silica, sulphur, phosphorus, calcium, titanium and chromium and has wide applications in such fields as geology, mineralogy, soil science, biogeochemistry and environmental science.

When fully operational, the SXRMB beamline will have three distinct capabilities. The standard X-ray absorption fine-structure (XAFS) endstation is operational and is capable of measuring total electron, fluorescence and transmission yields. A microprobe endstation is currently being commissioned (tested) and will be available to users in the near future. The microprobe will provide a focused X-ray beam ( $10 \times 10 \mu\text{m}^2$ ) that will enable micro-XAFS and micro-X-ray fluorescence (XRF) spectroscopy data to be collected on a small spot size in order to reduce the heterogeneity often present in natural samples. The third capability, currently under construction, is hard X-ray photoelectron spectroscopy (XPS). Hard X-ray XPS provides a higher kinetic energy than traditional XPS instruments allowing for deeper penetration into a material, bringing more chemical information from below the surface and reducing the problem of surface contamination.

In this presentation we summarize the techniques that are available at this beamline along with information on sample preparation. Finally, a few research highlights in the area of geological and environmental applications will be presented to demonstrate the capabilities of the SXRMB beamline.

#### **HIGH RESOLUTION MULTIPROXY STUDY OF LACUSTRINE SEDIMENTS FROM WAITE LAKE, TIBBITT TO CONTWOYT TO WINTER ROAD, NT**

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Waite Lake (62.84°N, 113.33°W) is located near the southern end of the Tibbitt to Contwoyto Winter Road (TCWR). The TCWR is the sole means of ground transportation of goods and services to mines located north of Yellowknife with more than \$500 million per year transported along this strategically important route. Since 87% of the route traverses frozen lakes the TCWR is very sensitive to warmer weather, which shortens the annual transportation window. This was the case in 2006 when abnormally warm conditions, associated with a strong El Niño event, resulted in significant financial losses.

A freeze core 2 m in length was collected and was sliced at mm intervals using a freeze core microtome custom designed by our group. Radiometric dating and modelling suggests a basal date of ~4000 cal. years and that 1mm represents 2-4 yr of accumulation, the highest sampling resolution yet achieved in any paleolimnological analysis in the southern Northwest Territories. Proxies under examination include magnetic susceptibility, loss on ignition, particle size analysis, and thecamoebian assemblages.

A multiproxy approach was utilized to reconstruct the paleoclimate of the southern Northwest Territories over the past 3000 years. Particle size analysis, a proxy for dynamics in catchment energy and precipitation, was carried out at mm-scale and coupled with time series analysis permitted recognition of trends and cycles at decadal resolution. Thecamoebians are agglutinated, primarily benthic protists that have been previously demonstrated to respond to climatically induced environmental changes. Three thecamoebian species dominate the core assemblages: *Diffugia amphoralis*, *Centropyxis constricta* "aerophila" and *Cucurbitella tricuspidis*. The stratigraphic distribution of both *C. constricta* "aerophila" and *C. tricuspidis* are characterized by sawtooth abundance patterns throughout the core, but in opposite phase, with *C. constricta* "aerophila" characterized by an increase in abundance toward the top of the core and *C. tricuspidis*, a species often linked to eutrophication, decreasing in abundance. These preliminary results indicate that the region has undergone significant climate variability. When the results were calibrated and combined with the other proxies under examination a detailed reconstruction of late Holocene climate change was generated.

#### THE ROLE OF ALBITISATION IN THE EVOLUTION OF THE NECHALACHO REE DEPOSIT, THOR LAKE, NWT

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The Nechalacho nepheline-syenite (NNS), which hosts the Nechalacho REE deposit, underwent multiple alteration events, including a major episode of late albitisation. The margins of the NNS record intense alteration in which most of the syenite was altered to fleshy pink albite, present either as euhedral blades (cleavelandite) or stubby crystals. Albite is accompanied by relict pegmatitic K-feldspar, which occurs as anhedral masses, and by interstitial and vein fluorite. Owing to the intensity of albitisation, primary textures are rarely preserved.

The paragenesis of the albitised rocks can be divided into three distinct stages. Early replacement of K-feldspar by stubby albite and infilling of void space by bladed albite following dissolution of other primary minerals (stage 1) characterizes the bulk of the alteration. Albite and K-feldspar then underwent brittle deformation and were locally cross-cut by microbreccias, the matrices of which consist dominantly of an intergrowth of quartz and fluorite (stage 2). Vugs interstitial to albite and K-feldspar are also filled by fluorite and quartz. Later chlorite and carbonate minerals partially replaced fluorite, albite and K-feldspar (stage 3). These three alteration stages resulted in extensive losses in K, Fe, Mg, Ca, Mn, HREE and Y, and gains in Na, Al, Si and the LREE. Quantifying metasomatism remains difficult as typically immobile elements have been extensively remobilised in the NNS, including the REE, Zr, Nb, Ta, Ti and Al.

Albitisation can be explained by the cation-exchange reaction  $(\text{Na}^+)_{\text{aq}} + \text{K-Feldspar} = (\text{K}^+)_{\text{aq}} + \text{Albite}$ , which is favoured by increasing temperature. Moreover, the required increase in temperature could have resulted from the intrusion of the NSS into the Grace Lake Granite and Thor Lake Syenite. This would have caused waters from the latter units to be drawn into the NSS thereby heating them and promoting albitisation. A sudden de-

crease in temperature produced by the adiabatic expansion accompanying brecciation would have prompted crystallisation of quartz and fluorite, as well as the replacement of albite by K-feldspar.

Fluorite is commonly intergrown with acicular (Ce)-bastnäsite and monazite, suggesting that these minerals are genetically associated. Rapid crystallisation of fluorite likely resulted from super-saturation of a fluid produced by mixing of a F-bearing fluid, exsolved from the NSS, with the external Ca-bearing and albitising fluid. We propose that the LREE were transported as fluoride complexes in the magmatic hydrothermal fluid and that deposition of fluorite sharply lowered fluoride activity, thereby destabilising the REE-fluoride complexes, causing deposition of (Ce)-bastnäsite and monazite.

#### INTEGRATED PLANETARY OPERATIONS AT THE MISTASTIN LAKE LUNAR ANALOGUE SITE, LABRADOR, CANADA: RECOMMENDATIONS FOR FUTURE LUNAR MISSIONS

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Canada is well situated to participate in future lunar missions (e.g. MoonRise – a NASA New Frontiers mission (<http://moonrise.jpl.nasa.gov>). In order to prepare and test scientific protocols, our research group carried out a three week, Canadian Space Agency-funded, robotic "analogue mission" at the Mistastin Lake impact structure. The mission included two teams: 1) mission control, which was based at the University of Western Ontario and 2) a rover team based in Labrador. No mechanical robot was used in this deployment. Instead, four geologists acted collectively as a rover—they made traverses with the instruments, collected data as requested by mission control, and sent the data to mission control using a remote satellite terminal. All science decisions were made by the mission control team based on data obtained from the field.

Lessons learned and recommendations for future lunar missions fall into three categories:

**Logistics:** During the deployment, communication schemes were optimized and data management was streamlined.

**Key recommendations:**

- Determine a realistic data budget that will help define the upper limit of digital data uploaded per session;
- Improve the wireless network in the field to allow real-time communication between mission control and the field team;
- Increase human resources.

**Operations:** Prior to and during the mission, mapping, sample site selection and analysis protocols were developed, and the scientific decision making processes regarding outcrop mapping and sample site selection was characterized.

**Key recommendations:**

- Increase cross training between different members of the entire team (e.g. engineers, scientists, mission control, field operators);
- Design operational schedule with understanding that science operations only accounts for 20% of field time.

**Technical:** Determined science requirements and limitations of existing off-the-shelf-instrumentation.

**Key recommendations:**

- Increase the resolution of 1) light detection and ranging (LIDAR) measurements used for making 3-D intensity models of the surrounding area (range: up to 1 km); and 2)

the mobile scene modeller (mSM) used for making 3-D colour models at outcrop scale (range 2-5 m);

- Obtain stereo imagery from multiple angles to increase situational awareness;
- Establish minimal data resolution needed for digital camera imagery, at different scales (e.g. panoramic, outcrop, macro);
- Improve visualization software that would allow seamless data integration of different data sets.

Lessons learned and recommendations will be carried forward to the next analogue mission at the Mistastin Lake lunar analogue site in 2011, which will include a mechanical rover and a human sortie element.

#### **THE LATE FEMIC MELT IN THE GESHERE SYENITE – PERALKALINE GRANITE PLUTON, NIGERIA: A RESERVOIR OF INCOMPATIBLE ELEMENTS**

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Of the fifty-two or so intrusive centers in which the classic Nigerian Younger Granites (Jurassic) are exposed, Geshere is one of two that are only now receiving attention. The pluton is composite and elongate, approximately 10 km in length, and exposes the association hypersolvus syenite, peralkaline granite, and subsolvus annite granite. The syenitic magma crystallized massive amounts of sanidine solid-solution, which exsolved completely and ordered partially. The removal of alkali feldspar caused the melt to evolve progressively toward the pseudoternary granite minimum. In this suite, magnesium is virtually a trace element, which means that the mafic minerals are very close to the Fe end members. In such cases, they are the last minerals to crystallize from the magma, at each step of the way from syenite to most evolved granite. A corollary of this statement is that as the magma decreases in amount, it becomes progressively more femic (mafic is etymologically incorrect!). Interstitial pools of this femic magma crystallize dominantly as ferro-richterite and annite, and also to hedenbergite and fayalite. The amphibole, which is close to the femic melt in composition, encloses a host of accessory minerals, including perrierite-(Ce) or chevkinite-(Ce), ilmenite, magnetite, monazite, apatite with vestiges of britholite, zircon, sphalerite, bastnäsite and calcite. There is evidence of early growth of clean ferro-richterite from this late melt, then later growth of the same amphibole charged with myriads of nuclei of these phases. This femic magma is the repository of the overall budget of high-field-strength elements and rare-earth elements. The femic minerals are susceptible to oxidation upon emplacement in the upper crust, and to replacement by low-temperature pseudomorphic assemblages. The alkaline fluid released upon full crystallization of the melt is a potent agent for the late mobilization of these incompatible elements. Although the Geshere pluton is not an appropriate site to illustrate the separation of this femic melt, it does illustrate an important host and mechanism of enrichment, owing to the massive rejection of the rare elements by the early-formed precipitates from the magma, alkali feldspar and quartz, which are formed in massive quantities. We recall that alkaline fluids are also involved at the beginning of the story, in the deeper crust, where the Pan-African basement becomes metasomatized to a slightly alkaline syenitic precursor prior to near-complete anatexis. This fluid involves both CO<sub>2</sub> and H<sub>2</sub>O, which explains the globules of calcite trapped in the mafic fraction.

#### **EXPLORING EARTH'S PRIMORDIAL MANTLE USING OLIVINE-HOSTED MELT INCLUSIONS**

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The magnesium-rich Baffin Island lavas are interpreted to represent primitive magmas that are minimally changed since leaving their mantle source. Lead isotopic evidence indicates that these picrite magmas may be melts of the Earth's primordial mantle reservoir. Silicate melt inclusions trapped within olivine crystals during their crystallization are considered to be aliquots of their parental melts and thus their compositions provide insight into the nature of their primordial mantle source. The olivine phenocrysts from the Baffin Island picrites have a forsterite content ranging from ~Fo<sub>85</sub> to ~Fo<sub>92</sub> with the majority of the phenocrysts at ~Fo<sub>87</sub>. In this study, the ratio of potassium to titanium (K/Ti) in inclusions is used as a proxy for the level of enrichment in light rare earth elements and other incompatible trace elements in the melt, as it is unaffected by the fractionation of the olivine and plagioclase phenocryst phases. The pillow lava margin glasses and silicate melt inclusions exhibit a range of K<sub>2</sub>O/TiO<sub>2</sub> from ~0.05 up to a maximum of ~4.0, with the majority of the compositions falling between 0.05 and ~0.20. Based on the presence of a population minimum at a K<sub>2</sub>O/TiO<sub>2</sub> of 0.08, we define depleted glass compositions (N-type) as those with K<sub>2</sub>O/TiO<sub>2</sub> > 0.08 and enriched glass compositions (E-type) as those with K<sub>2</sub>O/TiO<sub>2</sub> < 0.08. E-type melt inclusions are found in olivine phenocrysts below Fo<sub>87</sub>, whereas N-type inclusions occur in the more magnesian olivine phenocrysts (>Fo<sub>87</sub>). N-type melt inclusions are relatively restricted in composition and occur in olivines in N-type glass margins, whereas E-type melt inclusions are highly variable (K<sub>2</sub>O/TiO<sub>2</sub> ~0.05 to ~4.00) in the olivines in E-type marginal glasses and even within individual olivine phenocrysts. The E-Type Baffin melt inclusions appear to be mixtures of two distinct liquids: one a depleted end-member similar in composition to the N type melt inclusions characterized by low K<sub>2</sub>O/TiO<sub>2</sub>, La/Lu, and low Zr/Y, and the other an enriched end-member characterized by elevated values of the forgoing ratios. The differences between the E- and N-type end-members in the Baffin Island lavas are as large as those observed within modern MORB, suggesting that the Earth's primordial mantle (ca. 4.55 Ga) was as heterogeneous as the asthenospheric mantle is today.

#### **INVESTIGATION OF THE IMPACTS OF THAW SLUMP DISTURBANCES ON WATER QUALITY NEAR FORT MCPHERSON, NWT, CANADA**

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The previously glaciated region of the western NWT hosts a number of thaw slumps that deliver considerable sediment load to surface drainage networks. On the Peel Plateau near Fort McPherson (NWT), large retrogressive thaw slumps have been observed on historical aerial photographs. Several slumps were visited in summer 2010 as part of a program to assess their impact on surface water quality in the Stony Creek drainage basin and the Peel River. Considering that the hamlet of Fort McPherson is located only 30 km north-east of an area undergoing extensive permafrost degradation, investigating the cause of thermokarst and its environmental effects (including water quality of nearby streams) is needed to assess its impact on the fish habitats and water supply of the local community. The development of thaw slumps on the Peel Plateau has led to the formation of large mudlobes extending a few hundred meters downstream from the headwall. In some instances, these mudlobes dam river flow to form lakes whereas others spill into streams, thus directly increasing their sediment load.

In this study, we characterize the chemistry of runoff from thaw slumps and associated mudflows to investigate its impact on the water quality of the Stony Creek watershed and of the Peel River downstream of Stony Creek. Field measurements (pH, electrical conductivity, total suspended sediment) and sampling for inorganic, organic geochemistry and isotopes ( $\delta^{18}\text{O}$ ,  $\delta\text{D}$ ,  $^3\text{H}$ ) were used to characterize the composition of slump runoff (at 3 locations along the mudlobe), unaffected surface waters and surface waters affected by slump runoff. Slump runoff is characterized by high suspended sediments (515 g/L), high conductivity (1326  $\mu\text{S}/\text{cm}$ ), high  $\text{SO}_4^{2-}$  (max. 1800 ppm) and high  $\text{SO}_4^{2-}/\text{Cl}^-$  values. Conductivity measurements are highest halfway down the slump mudflow, and then progressively decrease as the slump runoff receives contributions from unaffected streams further down the mudflow. Since the 1970's, monitoring of the Peel River chemistry has shown an increase in the  $\text{SO}_4^{2-}/\text{Cl}^-$  ratio. With such high  $\text{SO}_4^{2-}$  concentrations in the slump runoff, it is likely that the contributions of slump runoff are playing a role in the increased  $\text{SO}_4^{2-}$  concentrations of the Peel River.

#### THE VARIETIES OF QUARTZ CRYSTALS IN ALPINE-TYPE FISSURES (GREECE)

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Quartz is formed in various geological environments and it is considered one of the most common minerals in the crust. The different conditions, namely the pressure and temperature that characterise each environment, determine which type of  $\text{SiO}_2$  mineral will crystallize. The type and often the habit of the crystals, the accessory minerals, as well as the solid inclusions they contain provide useful information regarding the environment of formation. In Greece, numerous quartz crystals are formed in alpine-type fissures in greenschist phase metamorphic conditions. During the ascent of metamorphic rocks to the surface, extensive fissures are formed in shear zones and several minerals including quartz are deposited due to the decrease in pressure and temperature. These fissures are usually elongated or sigmoidal. They develop perpendicular to the schistosity of the rock and crosscut the major structural elements of the Alpine compressive deformation. Quartz crystals from different areas of the Rhodope-Servomacedonian massif (northern Greece) and the Attico-Cycladic massif (central-southern Greece) are examined and compared. Varieties include colourless and smoky quartz, as well as morion and amethyst. Apart from the usual prismatic crystals, more elaborate habits are encountered such as Tessin and Dauphiné habits, gwindel and faden quartz, phantoms with chlorite or sericite and the incredible variety of sceptres (normal, inverse, double, triple) that often include window structures. As solid inclusions and accessory minerals we can find actinolite, epidote, chlorite, feldspars, muscovite, rutile, tourmaline, hematite and spessartine. Many quartz crystals found in alpine-type fissures in Greece are of gem quality and their potential for use as gemstones should be evaluated. Furthermore, numerous sites contain rare quartz crystals which should be preserved in mineralogical geotopes.

#### ARCTIC COASTAL LANDSCAPE EVOLUTION INFLUENCED BY POLYTHERMAL ICE COVERAGE ON CUMBERLAND PENINSULA, BAFFIN ISLAND

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The uplifted rim of the Eastern Canadian Archipelago has been

shaped during multiple glacial cycles forming a high relief landscape with freshly scoured valleys and fiords juxtaposed to highly weathered interfiord uplands. Cumberland Peninsula on Baffin Island has been a focus for the development of many conceptual models for landscape evolution under polythermal ice coverage. However, due to difficulty in access, previous studies were mostly restricted to the coast and adjacent uplands, leaving the interior relatively unexplored. Therefore, the extent of and interactions between the LIS and local alpine glaciers during the last glacial cycle reside unclear, in particular whether inter-fiord uplands remained ice-free and served as biological refugia. A new 1:100,000-scale map of the glacial deposits and ice flow stratigraphy of Cumberland Peninsula is constrained with terrestrial cosmogenic nuclide (TCN) exposure ages throughout the peninsula and additional radiocarbon ages on mollusc shells from raised marine deposits along the coast. The TCN data reveal a significant inherited concentration of  $^{10}\text{Be}$  and  $^{26}\text{Al}$ , reflective of an insufficient amount of glacial erosion to remove previously exposed regolith indicative for cold-based glaciation, particularly in thin-covered highlands. Using the youngest ages at each sample site we are able to show that valleys and fiords have been filled with glacial ice until around  $12.5 \pm 1.2$ – $12.1 \pm 1.1$  ka (all errors  $1\sigma$ ) with subsequent retreat to the interior until  $8.8 \pm 0.8$ – $8.3 \pm 0.7$  ka. Separation of the LIS and local fiord ice occurred at about the same time ( $12.7 \pm 1.1$  –  $8.6 \pm 0.8$  ka) based on a sequence of moraines damming a lake, whose shoreline sediments have been dated using a  $^{10}\text{Be}$  depth profile. Significantly reduced  $^{26}\text{Al}/^{10}\text{Be}$  ratios measured on interfiord uplands reveal a complex exposure history representing one or more burial events likely due to protective cold-based ice cover. However, the timing of the last ice coverage cannot be estimated leaving the question of biological refugia during the last glacial cycle unanswered. A novel approach for estimating the timing of the last glacial plucking of exhumed pre-Quaternary tors combined with exposure dating with in-situ  $^{14}\text{C}$  to circumvent the problem of inheritance will be applied to improve our knowledge of polythermal ice dynamics on Cumberland Peninsula.

#### RARE EARTH ELEMENT REDISTRIBUTION AND DISPERSION

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Primary Rare Earth Element (REE) concentrations (economic or sub-economic) suffer during secondary hydrothermal or weathering processes which may lead to REE redistribution and/or dispersion.

REE patterns (including Y, Th, U) of various generations of fluorites, iron hydroxides, and manganese oxides precipitated from groundwaters from hydrothermal ore deposits in the Schwarzwald (SW Germany) were analyzed by LA-ICP-MS. REE patterns of secondary fluorites are very similar to those of the primary fluorites they have grown onto, although their overall REE content is much lower. This suggests that dissolution of old fluorites was the essential source of REE for the young ones. The uranium contents in the younger fluorites are much higher (up to 180 ppm) than in the primary fluorites. They are negatively correlated with the overall REE contents and with  $\text{Ce}/\text{Ce}^*$  which suggests that U is transported as U(VI). This is most likely explained by highly oxidizing conditions during formation of the secondary fluorites. The secondary fluorites show variable crystal morphologies and pronounced growth and sector zoning. This indicates strong dependence of REE and U incorporation on surface complexation and composition of the solution. This also points out the necessity to carefully consider crystal shape and zoning effects when cal-

culating apparent fractionation coefficients between fluorite and a fluid phase.

Goethite and manganese oxides which are co-genetic with the fluorites display much more variable REE patterns. They act as sinks for REE along with several distinct REE minerals (e.g. rhabdophane). Differences in Y/Ho ratios between those minerals also point to complexation controlled redistribution behavior. The manganese oxides show pronounced Ce anomalies, which appear to depend on the oxidation state of Mn. This is probably due to catalyzed oxidation of Ce(III) to Ce(VI) on the mineral surface during growth. There is good correlation between La, Gd, and Y anomalies in our goethites and Mn oxides, where REE incorporation is controlled by sorption. La and Gd anomalies can be used as a quantitative expression for the tetrad effect and Y-Ho fractionation is related to the (usually weaker) tetrad effect, as it is known from other geochemical systems. In primary and secondary fluorites these anomalies show no correlation. This suggests that sorption on oxides and hydroxides has large influence on the REE behaviour during low-temperature mineral-water interaction and remobilization even if they are only minor phases. Conversely, secondary fluorites apparently have REE patterns closer to those of the waters they have precipitated from.

#### USING MELT INCLUSIONS TO UNDERSTAND THE MAGMATIC CONTRIBUTIONS OF ORE-METALS INTO SEAFLOOR HYDROTHERMAL SYSTEMS

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Melt inclusions are small portions of melt trapped inside phenocrysts during their growth. We have investigated melt inclusions from basalts of the Menez Gwen (Mid-Atlantic Ridge, Azores) in order to better understand the possible contribution of magmatic ore-metals in this active modern seafloor hydrothermal system. Conventional analytical techniques were used (SEM and EPMA) in conjunction with more advanced approaches (LA-ICP-MS and ToF-SIMS). Two types of highly plagioclase-phyric (HPP) basalts were identified at Menez Gwen. Type I HPP basalts are highly vesicular and extremely enriched in incompatible trace elements (enriched E-MORB) whereas the type II HPP basalts are less vesicular and less enriched in incompatible trace elements (less enriched E-MORB). The variability found in trace element geochemistry of the groundmass and melt inclusions of the type I and II HPP basalts precludes exotic crystal fractionation and favours a system whereby mantle heterogeneities have producing different melts or mixtures of melts that were later mechanically mixed. Melt inclusion data indicates that type II melts were sulfur saturated and more Cu-rich than type I melts. Cu did not necessarily precipitate as immiscible sulfide globules but partitioned preferentially as sulfide sublimates lining vapor bubbles inside the melt inclusions. The presence of an immiscible magmatic volatile phase rich in Cu, combined with the extensive pre- and syn-eruptive degassing of the type I melt, would have enhanced the mobilization of these metal-rich magmatic components. This ore-metal rich magmatic fluid is a suitable precursor of mineralized hydrothermal solutions that carry metals into hydrothermal convection cells above the shallow crustal magma chambers. Melt inclusion data provides new evidence that magmatic degassing at Menez Gwen into the upper level hydrothermal convection cells probably contributed to the formation of the sulfide chimneys and mound seen today on the seafloor. The timing of degassing and enriched geochemistry of lavas seem to be key factors for the pre-eruptive de-

gassing of magmatic ore-metals enabling them to be contributors to the seafloor hydrothermal system at Menez Gwen.

#### THE PETROGENESIS OF THE GARNET MENZERITE-(Y), $\{(Y, REE)(Ca, Fe^{2+})\}[(Mg, Fe^{2+})(Fe^{3+}, Al)(Si_3)O_{12}]$ , AND ITS BEARING ON THE Y+HREE BUDGET IN FELSIC GRANULITES FROM THE GRENVILLE PROVINCE, PARRY SOUND, ONTARIO

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The partitioning of yttrium (Y) and heavy rare earth elements (HREE) between major and accessory phases during metamorphism can provide valuable constraints on petrogenesis and directly link observed reactions with radiometric ages. The recent discovery of menzerite-(Y) in a well-layered sequence of Mesoproterozoic granulites from the Parry Sound domain provides new perspective on the petrogenesis of Y+HREE-bearing phases. The menzerite-(Y)-bearing sample has a rhyodacitic bulk composition and is highly-enriched in Y+HREE compared to chondrite ( $Y_N = 51.2$  and  $Yb_N = 64.7$ ), average bulk continental crust ( $Y_N = 4.0$  and  $Yb_N = 5.0$ ), and average lower continental crust ( $Y_N = 4.2$  and  $Yb_N = 5.0$ ). Samples from adjacent layers range from basaltic andesite to rhyolite in composition – generally following a sub-alkaline, island-arc tholeiite trend, and exhibit moderate to strong Y+HREE enrichment. Bulk-rock contents of most REE are positively correlated with Zr content and negatively correlated with MnO content. Microstructural relations indicate that menzerite crystallized early, and was partially resorbed prior to being armored by euhedral overgrowths of moderately Y+HREE-enriched almandine. Phase-equilibrium modeling indicates that menzerite-(Y) likely formed at  $T = \sim 700^\circ C$ ,  $P = \sim 8$  kbar in equilibrium with oligoclase, ferrosilite, quartz, and iron oxides during prograde heating and was consumed incongruently during partial melting near peak conditions ( $T = \sim 850^\circ C$ ,  $P = \sim 11$  kbar). Zircon from the menzerite-(Y)-bearing sample commonly contain irregularly shaped, inclusion-rich cores ( $1312 \pm 11$  Ma;  $Th/U = 0.33-0.59$ ) mantled by metamorphic rims ( $1146 \pm 12$  Ma;  $Th/U = 0-0.33$ ). Both zones commonly exhibit pronounced positive Ce anomalies, negative Eu anomalies, and HREE enrichment trends typical of igneous/melt-present crystallization. However, zircon cores generally are more enriched in Y+HREE ( $Yb_N = 1370-5322$ ; avg. = 3817) than the rims ( $Yb_N = 345-2659$ ; avg. = 1093). The cores are inferred to be detritus derived from the rhyodacitic precursor, whereas the rims crystallized in contact with the anatectic melt as did almandine. We suggest that because prograde heating occurred outside the stability field of almandine, the Y+HREE liberated by partial dissolution of the igneous zircon was incorporated in a garnet phase, menzerite-(Y), sufficiently enriched in Y + HREE to be stable. Peak conditions stabilized zircon and almandine; the latter inherited Y+HREE released by menzerite-(Y) breakdown. Modest Y+HREE-enrichment in zircon rims is likely the combined result of the relatively small volume fraction of almandine present during zircon growth and partitioning of Y+HREE into zircon relative to the anatectic melt.

#### INTRACRATONIC FAULT SYSTEMS IN THE CONTINENTAL INTERIOR PLATFORM OF THE MIDCONTINENT (USA)

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The Midcontinent region of the United States is a continental-interior platform; its upper crust consists of a veneer of Paleozoic strata overlying Proterozoic crystalline basement. Repeated epeirogenic displacements during the Phanerozoic warped this lithosphere into regional-scale basins, arches, and domes. Because



of these structures, the sedimentary veneer of the region varies from 0 km-thick (at the center of the Ozark Dome, where 1.47 Ga granite and rhyolite crop out), to about 7 km-thick (in the deepest portions of the Illinois Basin). Thus, despite the relative lack of surface topographic relief in the plains of the Midcontinent, structural relief of the Cambrian/Precambrian contact is comparable to that of many contemporary orogens. Midcontinent fault-and-fold zones occur within or bordering epeirogenic structures. Typically, the faults of these zones are basement-penetrating (thick-skinned). Some display relict normal-sense displacement at depth, and several of these bound sediment- and/or volcanic-filled rift basins. At shallower crustal levels, most of the faults divide into smaller splays. While some faults crop out at the ground surface, others die out up-dip into the axial zone of monoclinal folds. In this regard, Midcontinent fault-and-fold zones resemble Laramide-style structures of the Rocky Mountains and Colorado Plateau. The dip-slip component of Midcontinent fault-and-fold zones can be defined by seismic profiles and drilling logs. Strike-slip displacement is more difficult to document, because the structures are not well exposed. Nevertheless, patterns of en echelon fault arrays adjacent to larger fault traces, as well as structural studies in quarry exposures and mines, indicates that some zones do have a strike-slip component of displacement. The timing of movement can be documented by examination of local-scale stratigraphy (shoals; local alluvial fans; unconformities). Such studies indicate that significant displacements took place during Ordovician, Devonian, and Late Paleozoic time. Notably, the fault-and-folds zones display two dominant trends — N to NE, and W to NW. These trends are parallel to well documented rift trends (e.g. the Midcontinent rift, the Reelfoot rift, the Rough Creek graben, etc.). This relation, along with other structural clues, suggest that the Midcontinent fault-and-fold zones initiated during Proterozoic rifting, and were reactivated by transpression during episodes of Paleozoic marginal orogeny. Effectively, the faults delineate upper crustal blocks which jostled with respect to one another when stress was transmitted into the interior of the continent. There are several Midcontinent fold-and-fault zones whose map-view pattern and structural trends closely resemble those of the Ottawa-Bonnechere graben, emphasizing that the OBT is part of the same continental system of brittle deformation.

**PROTEROZOIC MELT INCLUSIONS OF NATIVE SILVER AND NATIVE BISMUTH AT COBALT, ONTARIO: AN EXAMPLE OF NATIVE METAL ENRICHMENTS IN FIVE-ELEMENT DEPOSITS VIA COMBINED PISTON-CYLINDER EXPERIMENTS AND HIGH TEMPERATURE RAMAN STUDIES**

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**GOLD MINERALIZATION AND HYDROTHERMAL ALTERATION AT THE SYENITE-HOSTED YOUNG-DAVIDSON GOLD DEPOSIT, MATACHEWAN, ONTARIO**

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The Young-Davidson (YD) deposit is a syenite-hosted gold deposit located at the western extension of the Cadillac-Larder-Lake-Deformation-Zone (CLLDZ), south west of Kirkland Lake. The YD syenite is a fine to coarse-grained, trachytic and porphyritic polyphase intrusion that was emplaced along the contact between Timiskaming meta-sedimentary rocks to the north and Larder-Lake meta-volcanic rocks to the south and hosts the majority of the gold mineralization. Gold mineralization is best developed in zones of intense potassic alteration, quartz veining, pyritization and decreased magnetic susceptibility.

There are at least three generations of veins: V<sub>1</sub> boudinaged iron-carbonate veins, V<sub>2</sub> folded quartz-pyrite veinlets and V<sub>3</sub> planar quartz-carbonate veins. V<sub>2</sub> and V<sub>3</sub> extensional veins occur as arrays developed during early D<sub>2</sub> deformation along the CLLDZ. The gold mineralization is dominantly hosted by disseminated pyrite and V<sub>2</sub> vein pyrite. Two textural types of pyrite are recognized: Type 1 pyrite is corroded with abundant rutile, hematite and magnetite inclusions and Type 2 pyrite is euhedral and oxide-inclusion-poor. Both types of pyrite host gold but Type 1 pyrite is characteristic of the disseminated and V<sub>2</sub> vein styles of mineralization whereas Type 2 pyrite is dominant in the V<sub>3</sub> vein style mineralization. The Au:Ag ratios of gold inclusions analyzed by electron microprobe also indicate two stages of mineralization. Inclusions in V<sub>3</sub> veins exhibit lower Au:Ag ratios relative to V<sub>2</sub> veins and disseminated pyrite. Rutile grains contain up to 8% WO<sub>3</sub>, up to 3% V<sub>2</sub>O<sub>5</sub> and up to 0.3% Sb<sub>2</sub>O<sub>3</sub>, consistent with other orogenic Au deposits in the Abitibi.

The most important alteration types at YD are K-feldspathization and hematization. Carbonatization is pervasive but does not correlate with the distribution of the mineralization. K-feldspathization is characterized by replacement of albite twinned Na-feldspars by untwinned K-feldspars and is accompanied by carbonate and minor sericite in the groundmass. Chloritization is important at the periphery. Hematization consists of hematite replacement of magnetite and incorporation of fine grained hematite within K-feldspars.

The association of mineralization oxide-bearing pyrite grains indicates that gold precipitation may have been controlled by oxidation of the mineralizing fluids. Based upon textural observations and the presence of a disseminated stage of mineralization, it is possible that remobilization of an early disseminated stage of mineralization occurred at YD; deformation and veining remobilized and deposited gold with sulfides in V<sub>2</sub> and V<sub>3</sub> veins.

#### KASSITE FROM THE PRAIRIE LAKE (ONTARIO) AND IRON MOUNTAIN (WYOMING) AND ITS RELATION TO PEROVSKITE ALTERATION

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Kassite [CaTi<sub>2</sub>O<sub>4</sub>(OH)<sub>2</sub>] is a rare mineral typically found in silica-undersaturated environments. Localities where it was previously recognized include the Afrikanda alkaline-ultrabasic complex in Kola Peninsula (Russia), Magnet Cove alkaline complex (Arkansas) and an ultrabasic Fe-ore deposit in Wuyang (Henan, China). Identification of kassite is not trivial because it is dimorphous with cafetite, and can be easily confused with titanite, perovskite or TiO<sub>2</sub> polymorphs during a routine petrographic examination.

The primary objective of the present study was to determine the nature of Ca-Ti oxide phases commonly observed to replace perovskite in alkaline and carbonate-rich rocks (including carbonatites, kimberlites and nephelinites). For detailed analysis, we selected relatively large (100 µm – 1 mm) grains of hydrous Ca-Ti oxide from silicocarbonatite from the Prairie Lake complex (Ontario) and serpentine-calcite kimberlite from Iron Mountain (Wyoming). Both samples were examined using electron-microprobe analysis, Raman micro-spectroscopy and X-ray micro-diffraction. For comparison, cafetite from Khibiny (Kola, Russia) was investigated using the same techniques. Our data show that the major product of perovskite alteration in a CO<sub>2</sub>-rich environment (prior to the development of anatase and/or ilmenite) is kassite, i.e. a monoclinic (space group P2<sub>1</sub>/a) polymorph of CaTi<sub>2</sub>O<sub>4</sub>(OH)<sub>2</sub>. The refined cell parameters of the Prairie Lake material are: a = 5.285(1) Å, b = 8.990(2) Å, c = 9.549(3) Å, and β: 90.42(2)°. This mineral can be readily distinguished on the basis of its Raman spectrum, which contains well-defined lines at 169, 219, 340, 440, and 695 cm<sup>-1</sup> not observed in its dimorphous cafetite.

In addition to providing constraints on the conditions of perovskite alteration in CO<sub>2</sub>-rich systems, the present study has implications for safe disposal of fission products in perovskite-based ceramics and applicability of radiometric and other isotopic data obtained on perovskite concentrates.

#### POST-OROGENIC CARBONATITES AT PAINT LAKE, MANITOBA, CANADA

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Geological mapping at Paint Lake, Manitoba reveals the area is underlain by mainly Archean orthogneiss, with subordinate metapsammite and metagreywacke. Trace element and Sm-Nd isotope geochemistry suggests these metasediments cannot be correlated with the Proterozoic Ospwagan Group of the Thompson Nickel Belt, being derived instead from an older, more mafic source. A zone of carbonatite magmatism and metasomatism with a strike length of at least 23 kilometres intrudes these gneisses and parallels the regional strike of the Thompson Nickel Belt.

Two modal types of carbonatite were identified in the Paint Lake area: calcite carbonatites and calcite-dolomite carbonatites; both types exhibit textural variations owing to postemplacement grain comminution and segregation. The calcite carbonatites contain subordinate amounts of magnesio-hornblende, diopside, phlogopite, fluorapatite, allanite, titanite, scapolite, barite, bastnasite, monazite, zircon, magnetite and sulfides. The calcite-dolomite carbonatites comprise a texturally complex carbonate matrix, made up of early Mg-rich calcite with exsolved dolomite inclusions and interstitial dolomite, with subordinate olivine, phlogopite, actinolite, fluorapatite and magnetite. The C-O isotopic composition of the carbonatites indicates a mantle carbonate source. This conclusion is consistent with the Sr-isotope and trace-element (Mn, REE, Ba) chemistry of the rock-forming carbonates. The major- and trace-element composition of calcite and amphiboles indicates that both carbonatite types may have been derived from the same magma by fractionation. The whole-rock compositions of the Paint Lake carbonatites show depletion in high-field-strength elements typical of post-orogenic carbonatites.

Detail mapping of two calcite carbonatite outcrops suggests the carbonatites intruded late in the tectono-magmatic history of the Paint Lake area. The dykes crosscut all phases but the latest pegmatite dikes. Given the extraordinary strike length of the carbonatite magmatism and metasomatism, the potential for rare element mineralization is significant. Post-orogenic carbonatites similar to those at Paint Lake host some of the largest rare-earth deposits in the world (e.g. Maoniuping in China) and several targets of potential economic interest (e.g. Eden Lake in Manitoba). Our current efforts are focused on the rare-earth mineralization in the Paint Lake carbonatites.

#### MERCURY ISOTOPE COMPOSITIONS OF THE KUROKO DEPOSITS IN JAPAN

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Mercury isotopes of sulfide ores from the middle Miocene volcanogenic massive sulfide deposits (Kuroko) were analyzed by a high resolution multicollector inductively coupled plasma mass spectrometer (MC-ICP-MS, Neptune), for estimating the origin of mercury for mineralization.

Because <sup>202</sup>Hg/<sup>198</sup>Hg has the best balance between precision of measurement and mass difference among isotope ratios for seven mercury stable isotopes (<sup>196</sup>Hg, <sup>198</sup>Hg, <sup>199</sup>Hg, <sup>200</sup>Hg, <sup>202</sup>Hg, <sup>203</sup>Hg and <sup>204</sup>Hg), we used the *f*δ notation of <sup>202</sup>Hg/<sup>198</sup>Hg ratio of the sample relative to the <sup>202</sup>Hg/<sup>198</sup>Hg ratio of the standard (S-HG02027, Inorganic Ventures, Inc). Although, there is no available standard material for Hg isotope analysis, it should be noted that this problem does not preclude reporting data using the *f*δ notation.

The  $f\delta^{202}\text{Hg}/^{198}\text{Hg}$  values of the sulfide ores of large (over  $10,000 \times 10^3$  metric tons) Kuroko deposits (e.g. Kosaka), range from +2.8‰ to +8.5‰, while the  $f\delta^{202}\text{Hg}/^{198}\text{Hg}$  values (+0.4‰ to +3.6‰) of smaller Kuroko deposits (e.g. Nurukawa) are lower than those of large Kuroko deposits. The  $f\delta^{202}\text{Hg}/^{198}\text{Hg}$  values of large Kuroko sulfide ores increase with increasing concentrations of As (<4,000 ppm), Se (<106 ppm), Sb (<2,090 ppm), Hg (<96 ppm) and Au (<23 ppm), suggesting a large input of these elements from magmatic fluids including isotopically heavy Hg for large Kuroko deposits.

The  $f\delta^{202}\text{Hg}/^{198}\text{Hg}$  values of the M3 mudstone of pre-Kuroko mineralization stage and the M1 mudstone of post-Kuroko mineralization stage range from -0.5‰ to +0.9‰ and -0.5‰ to +0.2‰, respectively. Their As, Sb and Hg concentrations are <45 ppm, <5 ppm and <773 ppb, respectively. We compare these Hg isotope data and As, Sb, and Hg concentrations with those of marine sediments containing high As (<4,100 ppm), Sb (1,190 ppm) and Hg (<35 ppm) around the active hydrothermal vents of the Tagiri site, Kagoshima bay, Japan. The  $f\delta^{202}\text{Hg}/^{198}\text{Hg}$  values of the Tagiri marine sediments range from +0.8‰ to +1.7‰, which are significantly rich in  $^{202}\text{Hg}$  relative to the M3 and M1 mudstones.

The  $f\delta^{202}\text{Hg}/^{198}\text{Hg}$  values of the M2 mudstone deposited at the mineralization stage around Kuroko deposits range from -1.1‰ to +3.3‰. Arsenic, Sb and Hg concentrations of the M2 mudstones are <8,570 ppm, <90 ppm and <57 ppm, respectively. The high  $f\delta^{202}\text{Hg}/^{198}\text{Hg}$  values and high As, Sb and Hg concentrations of the Tagiri sediments and some M2 mudstones may be caused by contributions of magmatic fluids rich in isotopically heavy Hg during their sedimentation.

#### CHIMNEYS IN THE HOKUROKO GROUP OF MASSIVE SULFIDE DEPOSITS, JAPAN

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In 1981 Steve Scott first recognized ancient black smoker chimneys, which had previously been called tora-no-me (tigers eye in Japanese), in the Miocene massive sulfide deposits in the Hokuroko district of Japan. More recently, cylindrical chimney fragments, up to several centimeters long with diameters of usually 1 to 5 cm, but up to 20 cm, have been found by cutting Akita University Ore Archive samples collected from the Mazumine, Mazuki, Ezury, Furutobe, Hanawa, Ainay, Kosaka Uchinotay and Kosaka Motoyama massive sulfide deposits. Chimneys largely exhibit a mineral and trace element zonation comparable to examples from modern black or gray smoker settings, except evidence for the former initial pyrrhotite, isocubanite and anhydrite is missing. Chimneys can be sub-divided into three types on the grounds of the outer wall composition: 1) sphalerite-galena-pyrite 2) sphalerite-barite-galena and, finally 3) barite-hematite varieties. Inner walls of the chimneys are usually incrustated by drusy chalcopyrite or bornite, tennantite, galena showing elongate dendritic or bladed growth features. Axial conduit zones of the chimneys are often infilled with sphalerite, tennantite, galena and barite. Chimneys are Fe-rich sulfide-poor with elevated barite, galena and fahlores with electrum in comparison with typical MOR black smokers. However, they are very similar to black and gray smokers from modern West Pacific sites as well as examples from Paleozoic Uralian and Mesozoic Pontide oceanic arcs. The lack of tellurides and sulphoarsenides is notable. This assemblage is typical for barite-rich chimneys from Paleozoic Rudniy Altay continental arc. Laser-ablation ICP-MS study has shown a systematic trace element

distribution across the chimney wall. Outer wall colloform and euhedral pyrite contain elevated concentrations of Mn, Tl, Ni, Mo, Se and Te. Coarse-grained layers of chalcopyrite in the centre of the conduit are relatively low in most of the trace elements with the exception of Bi and Sn. Sphalerite is enriched in Au, Ag, As and Sb. In general, the grades of trace-elements in the Phanerozoic black smokers reflects the composition of host suites: ultramafic: high Se, Sn, Co, Ni, Au and U, mafic: high Co, Se and low Bi and Pb, bimodal mafic: high Te and Bi, Co with moderate Se. The chimneys associated with bimodal felsic suites, like in Hokuroko and Rudniy Altay, are characterized by elevated contents of As, Sb, Mo, Pb, Bi, Tl, Ag, W, Hg and much lower grades of Co, Te and Se.

#### FORMATION AND MODIFICATION OF THE SLAVE CRATONIC LITHOSPHERE REVEALED THROUGH A PERIDOTITE XENOLITH TRANSECT

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While a detailed understanding has been gained of the deep lithosphere beneath the central part of the Slave Craton, the age and chemical characteristics of much of the remaining craton – and that beneath the rest of Arctic Canada – remains rudimentary. The possible role played by a deep-seated plume in the generation of the Slave and other lithospheric mantles and their diamonds is still debated. Given the clear geological evidence for the variable impact of a major plume beneath the Slave craton, it provides an excellent testing ground for understanding the role of plumes in craton formation and/or destruction.

A collection of >100 mantle xenoliths was recovered from the Artemisia kimberlite. A sub-set of peridotites from this suite has been characterized for mineral compositions, bulk rock chemistry and Re-Os dating. Peridotites from this locality were extensively serpentinised leaving little original mineralogy, or were poor in/devoid of cpx, hampering the application of traditional thermobarometry techniques and requiring other approaches to estimating relative sample depth.

Re-Os dating results for Artemisia peridotites show a predominance of Meso-Proterozoic depletion ages, with Archean ages being scarce/absent. Mixture modeling picks out a dominant component (70% of the dataset) at  $1.1 \pm 0.1$  Ga, with a secondary component (~30%) at  $1.9 \pm 0.1$  Ga suggesting either significant new lithosphere generated at these times, or major re-working of existing Archean lithosphere. This contrasts with central Slave craton peridotites such as at Ekati and Diavik where Archean ages predominate (55% of data define a component at 2.6 Ga from mixture modeling) with subsidiary younger components (e.g.  $0.9 \pm 0.1$  Ga, 17% of data). When combined with existing data from Jericho, spatially between Diavik and Artemisia, we note a clear and progressive trend of an increasing proportion of Meso-Proterozoic lithosphere ages with increasing distance North from the Central Slave Province. This effect may reflect the increasing influence of the Wopmay Orogeny (1.9-2.1 Ga) and thermal/metasomatic effects relating to the McKenzie Plume head (1.27 Ga). Further to the East, at Somerset Island, beyond the postulated influence of the McKenzie plume head, there is little evidence of any 1.2 Ga disturbance in the lithosphere. The case for either disruption or replacement of the lower lithosphere beneath the northernmost part of the exposed Slave craton seems strong and poses questions about the role that this or similar plume events may have had in generating lithosphere and diamonds beneath the central Slave craton.

**PROVENANCE OF CLASTIC DETRITUS IN THE  
CRETACEOUS TO TERTIARY BONNET PLUME BASIN,  
NTS 106E, YUKON TERRITORY CANADA: EVIDENCE  
OF BASIN EXPANSION**

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WITHDRAWN

**THE IMPACT OF REGIONAL STRIKE-SLIP,  
TRANSTENSIONAL AND TRANSPRESSIONAL FAULT  
ZONES ON VOLCANIC CONES; INSIGHT FROM  
ANALOGUE MODELS**

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The activity of a regional strike-slip fault can affect or channel magma migration, can deform a volcano and can destabilise the edifice flanks. The aim of this study was to determine the location, strike, dip and slip of structures that develop in a stable or spreading volcanic cone located in the vicinity of a fault with a strike-slip component. This problem is addressed with brittle and brittle-ductile analogue models. The one hundred and twenty three models were deformed by pure strike-slip, transtensional or transpressional fault displacements. The deformation was organized around an uplift in transpressional and strike-slip experiments, and around a subsiding area in transtensional experiments. Most displacements are accommodated by a curved fault called Sigmoid-I structure, which is a steep transpressional to transtensional fault. This fault prolongs the regional fault into the cone and delimits a summit graben that is parallel to the main horizontal stress. The systematic measurements of faults strike and slip in the experiments indicate that extension along the faults in the cone increases with the extensional component of the regional fault and the thickness of the substratum ductile layer. The regional strike-slip movements damage the volcanic edifice and facilitate the collapse of its flank in a direction sub-parallel to the regional strike-slip fault strike. The results of these analogue models are compared with the structure of Guadeloupe volcano, which has been studied by the authors in a previous study.

**PALEOGEOGRAPHIC SETTING FOR LAURENTIA'S  
LATE NEOPROTEROZOIC IAPETAN RIFTING**

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In the Late Neoproterozoic, Laurentia recorded rifting and possibly plume-related magmatism along its incipient "Iapetan" margin and the Ottawa-Bonnechere rift system. These features, and the

subsequent Lower Paleozoic passive margin sedimentation are usually taken to represent the separation of Laurentia from Amazonia and Baltica, marking the formation of the Iapetus Ocean. Recent Neoproterozoic to Cambrian paleomagnetic results show, however, that the commonly depicted triple junction rifting relationships between the circum-Iapetus cratons of Laurentia, Baltica and elements of West Gondwana are difficult to justify. Late Neoproterozoic rifting along Laurentia's Iapetan margin demonstrably involved terranes whereas the postulated conjugate cratonic rifted margins have proven hard to find. A modified Late Neoproterozoic Iapetan paleogeography is possible, in which rifting along the Laurentian margin may primarily reflect the separation of terranes into an already existing Iapetus Ocean. In this paleogeographic context, the Ottawa-Bonnechere rift system may not be a direct product of Late Neoproterozoic supercontinent breakup, but instead may be more analogous to the plume-influenced East African rift system.

**TIMING AND ACTIVITY OF DOWNIE SLIDE,  
SOUTHERN BRITISH COLUMBIA**

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The Downie Slide is located at the edge of Lake Revelstoke, a hydroelectric reservoir near Revelstoke, British Columbia. Engineering works draining the slide have slowed its modern movement significantly, but reactivation of the slide could be a hazard for developments along the shoreline of the lake and might cause flooding of the toe of Mica Dam, which is north of the slide (the Revelstoke Dam to the south has been raised to prevent overtopping by tsunamis that might be generated by the slide). Information on the timing of formation and subsequent activity of the slide was sought in order to better mitigate against such an event.

The slide originally failed along a basal surface defined by regional foliation in gneisses and schists. Combined geological mapping and interpretation of LiDAR data show that the failure was either a single massive event or it occurred in phases creating separate structural domains. Parts of the slide are actively moving today, albeit slowly.

Surficial geology mapping shows that glacial till, colluviated till and colluvium are the dominant surficial materials found on the surface of the slide. Slide depressions, tension cracks and ridge and trough features were mapped and targeted for dating.

Radiocarbon and volcanic tephra dating were undertaken to determine the age and activity level of the slide over time. Numerous test pits revealed volcanic ash layers overlying till and colluvium; organic deposits were much less common. Multiple tephra layers in many of the pits were admixed, which shows that some movement has occurred on the slide surface after deposition of the ash layers. The tephra and radiocarbon data reveals that the slide has a minimum age of 7,690 calendar years BP (before present), or older than Mazama O tephra. While it is possible the slide initiated in pre-Fraser time (prior to 25,000 years ago), it is more likely that initiation began shortly after Fraser deglaciation in Holocene time.

Although the major initial slide movement occurred prior to 7690 years BP, there is evidence for smaller, more localized movements since that time. A few of the slide depressions formed between 7,690 and 5,050 years BP. One depression in the upper slide area is younger than Bridge River ash, dated at 2,350 years BP. This suggests that small localized movements could occur within the slide in the future, but that a major reactivation of the entire slide is unlikely.

## HOGARTHITE, A NEW Na-Ca TITANOSILICATE HYDRATE MINERAL FROM MONT SAINT-HILAIRE, QUEBEC

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Hogarthite, ideally  $(\text{Na},\text{K})_2\text{CaTi}_2\text{Si}_{10}\text{O}_{26}\cdot 8\text{H}_2\text{O}$ , is a new mineral discovered in altered marble xenoliths associated with quartz, calcite, fluorite, a labuntsovite-group mineral, haïneaultite and a sodic amphibole. The mineral, formerly referred to as UK75, develops in elongate, rounded patches averaging  $0.05 \times 0.1$  mm in size, composed of divergent, radiating aggregates of individual crystals. Hogarthite crystals are prismatic, elongate along [001] with square cross-section. Individuals are typically  $0.005 \times 0.1$  mm in size. The mineral is generally pale brown to brownish-orange in color (rarely white) with a vitreous lustre. It is brittle with a perfect {010} cleavage. Hogarthite is late-stage mineral, overgrowing purple fluorite and green amphibole and is itself overgrown by colorless calcite. Chemical analyses (combined WDS & EDS) suggest the average empirical formula (based on 34 anions):  $(\text{Na}_{0.78}\text{K}_{0.62}\text{Ca}_{0.09})\Sigma 1.49\text{Ca}(\text{Ti}_{1.85}\text{Zr}_{0.09}\text{Nb}_{0.06})\Sigma 2.00\text{Si}_{10.09}\text{O}_{26}\cdot 8\text{H}_2\text{O}$  with the  $\text{H}_2\text{O}$  content being calculated on the basis of results derived from crystal-structure analysis. Hogarthite is monoclinic ( $C2/m$ ), with  $a = 10.1839(5)$ ,  $b = 15.8244(6)$ ,  $c = 9.1327(7)$  Å,  $\beta = 104.463(2)^\circ$ ,  $V = 1425.1(1)$  Å<sup>3</sup> and  $Z = 2$ . The crystal structure of hogarthite, refined to  $R1 = 4.88\%$  and  $wR2 = 12.43\%$  for 1335 reflections, consists of slabs composed of six-membered rings of  $\text{SiO}_4$  tetrahedra, oriented along [100], in addition to  $\text{TiO}_6$  octahedra arranged in chains oriented along [010]. The  $\text{TiO}_6$  octahedra serve to cross-link the silicate slabs along [001], producing a three-dimensional titanosilicate framework of composition  $[\text{TiSi}_5\text{O}_{13}]^{2-}$ . Large channels ( $\sim 8.3 \times 8.7$  Å) oriented along [101], are occupied by Na and Ca ions, along with  $\text{H}_2\text{O}$  molecules;  $\text{H}_2\text{O}$  molecules lie in the channel centres, Na and Ca on the periphery. Refinement of site-occupancies for channel occupants indicate full occupancy by Na,  $\sim 1/2$  of ideal occupancy by Ca (fixed at 0.25) and partial occupancies ranging from 0.50 to 0.75 of ideal values by  $\text{H}_2\text{O}$  molecules. The crystal structure of hogarthite is strongly reminiscent of that of lemoynite and related minerals (natroleimoynite, altsite), all of which should be considered as members of one mineral group. The name honors Dr. Donald D. Hogarth, Professor Emeritus in the Department of Earth Sciences at the University of Ottawa, in recognition of his contributions to the mineralogy and petrology of alkaline igneous rocks.

## NEW INSIGHTS INTO THE AGE AND STRATIGRAPHIC/STRUCTURAL RELATIONSHIPS BETWEEN THE PALEOPROTEROZOIC KETYET RIVER AND ARCHEAN WOODBURN LAKE GROUPS, NUNAVUT

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The Rae Subprovince of the Western Churchill Province, forming the central core of the Canadian Shield, has long been recognized to have a protracted geological history. The Archean to Mesoproterozoic rocks of this province were affected by multiple orogenic events and the resultant structural complexity has led to confusion regarding the affiliation of some rock packages. This study is focused on improving understanding of the Paleoproterozoic Ketyet River group and its stratigraphic-structural relationship to the Archean Woodburn Lake group in the area NNW of Baker Lake. An additional goal is to improve understanding of the re-

gional deformational history and the role of structural reactivation in Baker and Thelon basins' development and uranium mineralization.

In the first of four areas that were investigated this past summer ("Nipterk Lake" area), 1:6,000 scale mapping revealed that the Ketyet River group comprises a succession of monomictic conglomerate, orthoquartzite and pelitic schist that unconformably overlies rhyolitic schist of the Woodburn Lake group. Four ductile deformational events ( $D^1 - D^4$ ) affected all of these rocks, and the first two strongly controlled the map pattern. First generation recumbent isoclinal folds were co-axially re-folded and transposed sub-parallel to the axial planes of second generation open-tight folds, creating a type 3 interference pattern. Two subsequent deformational events had a minor influence on the map pattern and are manifested by strong crenulation cleavages defined by micaeous minerals in the rhyolitic and pelitic schists.

Similar observations were made at "Ukalik Lake" and "Bar Lake", 4km northeast and 90km southwest of Nipterk Lake, respectively; however, some discrepancies exist between these areas and Nipterk Lake. For example, at Ukalik Lake, some orthoquartzite appears to be inter-layered with the rhyolitic schist, suggesting either that the entire sequence is Archean or that there are quartzite units of both Archean and Paleoproterozoic age. In addition, whereas the structural style at Ukalik Lake is similar to that at Nipterk Lake, it is quite different from that at Bar Lake which is a type 2 interference pattern controlled by early large-scale recumbent folds. Farther west, near the Kiggavik uranium deposit, similar stratigraphic relationships were observed; however, the  $D^2$  structures are moderately north-dipping rather than steeply south-dipping as observed at Nipterk Lake. Overall, Archean and Paleoproterozoic rocks within the region were both affected by intense  $D^1$  and  $D^2$  folding events, respectively characterized by isoclinal recumbent folding of the basement and cover, and transposition to ENE-trending upright folds associated with thrusts.

## A SOURCE OF $^{207}\text{Pb}/^{235}\text{U}$ DISCORDANCE IN MONAZITE MEASURED BY QUADRUPOLE LA-ICP-MS

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A recently installed quadrupole LA-ICP-MS system uses ablation in He, Ar +  $\text{N}_2$  carrier gas, signal smoothing, and a second rotary pump to enhance sensitivity for small crater diameters during monazite dating. Under these conditions, propagated 2SE precision  $< 1\%$  can be achieved for crater diameters as small as 24 microns. Thorough ablation cell purging, a wide torch injector, and robust plasma conditions are used to lower oxide production ( $^{248}\text{ThO}/^{232}\text{Th}$ ) to  $< 0.1\%$  while still maintain good sensitivity for Pb and U.

Laser-induced elemental fractionation corrections applied using Lolite software (Paton et al., 2010; Hellstrom et al., 2008) are shown to be robust for a wide variety of monazite standards (Thompson Mine, GSC8153, Trebilcock, 44069) and unknowns. Fractionation corrected analyses yield flat inter-element ratios independent of the monazite matrix.

Although high precision can be achieved even for small crater diameters,  $^{207}\text{Pb}/^{206}\text{Pb}$  and  $^{207}\text{Pb}/^{235}\text{U}$  show systematic biases manifest as reversely discordant horizontal arrays on Concordia. Deviations from true  $^{207}\text{Pb}/^{206}\text{Pb}$  correlate with Nd intensity implicating a  $^{144}\text{NdPO}_2$  ( $m = 206.87$ ) interference. The same molecule forms during SHRIMP sputtering of monazite (Fletcher et al., 2010). Whereas the high MRP of the SHRIMP can be used to separate  $\text{NdPO}_2$  from adjacent Pb peaks, this interference is isobaric with  $^{207}\text{Pb}$  on a quadrupole mass spectrometer. Under tuning conditions that maximize the signal for Pb and U during small crater ablation, LREE and P intensities in monazite are typically  $> 10$

Mcps and >1 Mcps respectively. Thus, even negligible formation of  $^{144}\text{NdPO}_2$  will lead to  $^{207}\text{Pb}$  overcounts. Whereas similar interferences must also exist for  $^{206}\text{Pb}$  and  $^{208}\text{Pb}$  (e.g.  $^{143}\text{NdPO}_2$  and  $^{145}\text{NdPO}_2$  respectively), the higher overall  $^{206}\text{Pb}$  and  $^{208}\text{Pb}$  intensities minimize their impact. Removing the  $\text{NdPO}_2$  interference using collision cell methods is shown not to be feasible.

Correcting this interference requires monitoring  $^{207}\text{Pb}/^{144}\text{Nd}$  because % $^{207}\text{Pb}$  overcounts will increase with decreasing age or U content. The implication, therefore, is to use matrix-matched and age-matched standards and to monitor  $^{144}\text{Nd}$  in addition to the Pb and U masses. Plotting  $\text{Ln}[(207/206)_{\text{meas}}/(207/206)_{\text{true}}]$  as a function of  $\text{Ln}[^{207}\text{Pb}_{\text{cps}}/^{144}\text{Nd}_{\text{cps}}]$  reveals a strong correlation that could be used to empirically correct for  $^{207}\text{Pb}$  overcounts.

Alternatively, the most precise and accurate ages for monazite can be achieved by assessing concordance between  $^{206}\text{Pb}/^{238}\text{U}$  and  $^{208}\text{Pb}/^{232}\text{Th}$ , neither of which show systematic matrix-related biases between standards and unknowns on the LA-ICP-MS system described here.

### A SUBSURFACE INVESTIGATION OF THE PARIS MORAINE IN THE GUELPH AREA, ONTARIO

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As communities in Ontario work towards protecting drinking water sources under the Clean Water Act, the Ontario Research Fund Research Excellence (ORF-RE) program funded a project investigating sustainable bedrock water supplies using the City of Guelph, Ontario as a model community. The local drinking water is produced from various bedrock aquifers and an artificial overburden recharge system. These groundwater sources have been extensively characterized by provincial and municipal governments. In contrast, little research has been conducted into the broader local overburden geology and its significance to the underlying aquifers in terms of groundwater recharge and contaminant transport. Within the ORF-RE study boundaries, the Paris Moraine, a parabolic shaped end moraine that was formed by the Lake Ontario lobe of the Laurentide Ice Sheet, is likely the most prominent landform. Much interest has been shown by research partners and local authorities into gaining a better understanding of the geology and hydrogeology of the moraine. Recent work by the Ontario Geological Survey and Geological Survey of Canada has focused predominately on parts of the Paris Moraine located outside of the ORF-RE study boundaries and suggest that it may be a complex landform made up of variable sediments. Thus, a sedimentological investigation of the Paris Moraine in the Guelph area was initiated within the context of the ORF-RE project.

Outcrops are limited within this section of the moraine requiring that continuously cored holes advanced to bedrock be collected within key landform elements of the Paris Moraine, including; hummocks, kames, spillways, and drumlinized till plains. These are in turn complemented with subsurface fence diagrams generated from the Ontario Ministry of Environment water well database and other borehole logs from environmental and geotechnical reports. Throughout the study area, preliminary examination of cored holes indicates a subsurface stratigraphy dominated by multiple <1-6m thick packages of clast-rich and clast-poor matrix-supported diamict lithofacies, within an average of tens of metres of overburden. Other facies include thin to very thick beds of gravel, sand, and mud. In few cases, overconsolidated clast-poor packages were found in the lower part of the succession. Bounding surfaces of various orders separate these lithofacies with some showing evidence of erosion. This data, along with data from the water well database and environmental and geotechnical reports suggests variable sedimentary facies associations within the subsurface and spatial heterogeneity, which

will likely impact recharge and contaminant transport to the underlying bedrock aquifer.

### ZIRCON: A NEW DIAMOND INDICATOR MINERAL

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Zircon is a highly refractory mineral, resistant to physical and chemical weathering. If entrained zircon can be geochemically linked to the process of kimberlite/lamproite eruption, it can potentially be used as a new diamond indicator mineral. This advance will be particularly advantageous for diamond exploration in tropical regions where traditional kimberlite indicator minerals (garnet, Cr-diopside, olivine) have low preservation potential.

Helium dating is a technique that can be utilized to detect “hot zircon” originating from the deep crust. Helium retention in zircon is temperature-dependent with a nominal closure temperature of ~200°C. Entrained zircon xenocrysts originating from depths greater than 6km will have (U-Th)/He ages equivalent to the eruption age of the kimberlite. In contrast, upper crustal zircon will have older ages, approaching the age of formation of the craton (“cold zircon”).

In order to test this hypothesis, helium dating was applied to zircon obtained from known Australian kimberlite/lamproite occurrences and their regional host rocks. At the Ellendale Diamond Mine in Western Australia, zircon xenocrysts from a diamondiferous lamproite dyke returned helium ages ( $19.5 \pm 0.1$  Ma) concordant with phlogopite Ar-Ar ages for dyke emplacement. In contrast, zircon from the regional sandstone unit hosting the lamproite yielded (U-Th)/He ages ranging from 260 to 1500 Ma.

The implication is that erosion of a kimberlite/lamproite pipe will shed “hot zircon” into the regional drainage system surrounding the kimberlite. Stream sediment samples in the vicinity of kimberlites should show bimodal zircon age distributions, where the ratio of hot/cold zircons could be used as an exploration-targeting tool. This approach was tested at the Merlin kimberlite field (Northern Territory) where zircon helium ages ( $368 \pm 4$  Ma) were also found to be concordant with kimberlite emplacement. An exploration targeting trial involving zircon helium dating of 29 stream sediment samples (1 kg) surrounding the Merlin pipes yielded: (1) a young population (250-450 Ma) corresponding to “hot zircons” from the adjacent diamondiferous kimberlite pipes and (2) an older population (500-1400 Ma) corresponding to “cold zircons” from the Cambrian Bukalara Sandstone host formation.

The ratio of hot/cold zircon for each site was compared with traditional KIM-type bulk sampling exploration methods (e.g. chromite, microdiamonds). There is a positive correlation between the presence of chromite/microdiamond and the presence of hot zircon in the stream sediments and, similar to company exploration results, our study found that KIMS (including hot zircon sourced from the kimberlites) are more prevalent southwest of the Merlin Camp.

### U-Th-Nb-REE-Y VEIN-DYKE MINERALIZATION AT KULKY LAKE, NORTHERN SASKATCHEWAN: EXAMINATION OF ITS PETROGENESIS WITH RESPECT TO THE HOST LATE TECTONIC U-Th-REE-Y-Nb PEGMATITE DYKE

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More than 40 REE-bearing mineral occurrences are identified in northern Saskatchewan. These occurrences consist predominantly of monazite and/or allanite and lesser xenotime, with variable amounts of U, Zr, Nb, and Y hosted in late-tectonic to anorogenic

granitoid and pegmatite intrusions. The Kulyk Lake REE-Y-Nb showing lies within the Wollaston Domain, a northeast-trending Paleoproterozoic metasedimentary sequence with interfolded anatectic granitoids that overlie Late Archean granitic gneiss. The U-Th-REE-Y-Nb mineralization in late tectonic, unzoned leucogranitic pegmatite-aplite dykes (>2 m wide) is localized along the N-, ENE-, and ESE-trending Wollaston Group-Archean contacts and local fault intersections.

Pink granitic dykes at Kulyk Lake intrude Wollaston Group paragneisses and are concordant with the northeastern regional gneissosity. Ilmenite-monazite-apatite mineralization is both vein-like and dyke-like (i.e. commonly termed vein-dyke) enclosed in pegmatite-aplite dykes, emplaced along fractures and (or) intrude along the central part of the pink granitic dyke. The vein-dyke body extends 15 m concordant with the pink granitic dyke and is irregular in width, ranging between 0.2 to 0.5 m. Zoned vein-dyke mineralization consists of reddish-brown, granular monazite forming as subhorizontal embayments with variable thickness. It is then followed inward by a thin, oxide component of ilmenite, and centrally located pinkish-to-beige apatite euhedra is contained within the core of the embayments or lobes. Bulk rock REE analyses for eight vein-dyke samples revealed an average  $\Sigma\text{REE}$  of 14.02 wt%, showing a negative Eu anomaly ( $\text{Eu}/\text{Eu}^* = 0.46$ ) and exceptionally high  $\text{La}_\text{N}/\text{Yb}_\text{N}$  ratio's, averaging 508. Petrographic studies of the vein-dyke zone confirmed an interlocking framework of up to 50% euhedral to subhedral monazite with 30% F-Cl-apatite, 15% interstitial ilmenite, with <5% inclusions of metamict euhedral zircons, and traces of rutile, xenotime, and thorium silicate-phosphate minerals. The analysis of six unzoned monazites from the vein-dyke samples by SEM-EDS shows they are Ce-rich, with 3.6 wt%  $\text{Y}_2\text{O}_3$ , 4.3 wt%  $\text{ThO}_2$ , and 0.7 wt%  $\text{UO}_2$ .

The bulk-rock REE analyses and high  $\text{ThO}_2$  content of the monazite crystals from the ilmenite-monazite-apatite mineralization may have deposited from orthomagmatic pegmatite fluids. A possible model for the genesis of the zoned vein-dyke mineralization may be that it was injected and crystallized from a REE-Y-Nb-bearing Fe-P-O magma that was immiscible with the final crystallization stages of the granitic pegmatite. In either of these primary pegmatite-related systems, the concentration of U, Th, Nb, REEs, and Y in the residual exsolved fluid or immiscible melt leads to the enrichment of these high-field-strength elements.

#### **GEOLOGY OF THE ALEY CREEK AREA: A RECORD OF DEVONIAN OROGENY IN THE FORELAND BELT OF THE CANADIAN CORDILLERA?**

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1:5,000 scale field mapping of the Aley Creek area (NTS 094B-042) reveals a record of Devonian contractional orogenesis previously unrecognized in the Foreland Belt of northeastern British Columbia. Two deformation events are identified within the map area: a  $D_1$  event, characterized by south-verging, recumbent  $F_1$  isoclinal folds and well-developed axial-planar  $S_1$  cleavage, and a  $D_2$  event characterized by prominent east-verging, open, asymmetric  $F_2$  folds and related  $S_2$  axial-planar cleavage. Although previously assigned to the Late Cretaceous Rocky Mountain orogeny, several key structural relationships suggest that the  $D_1$  event was synchronous with ca. 365 Ma emplacement of the Aley carbonatite complex. These include (1) the emplacement of magmatically early calcite carbonatite concordant with the  $D_1$  fabric in contrast to discordant emplacement of magmatically late dolomite carbonatite; (2) the presence of  $D_1$  fabrics in clasts of country rock sam-

pled by dolomite carbonatite and spatially related Ospika pipe diatreme; and (3) dolomite carbonatite dykes and veins intruding along axial planes of  $F_1$  folds and  $D_1$  thrusts in the country rock. Examination of stratigraphic way-up indicators show the country rock – a lower to mid-Paleozoic succession of continental margin strata – to be completely overturned within the map area. This observation, combined with the isoclinal form of  $F_1$  folds and the bedding-parallel orientation of  $S_1$  cleavage, suggests that the map area lies on the lower overturned limb of a regionally developed recumbent isoclinal fold or thrust nappe structure.

The documentation of a major Late Devonian thrust nappe in the western Foreland Belt indicates that the continental margin represented by the Aley Creek country rock experienced a contractional orogenic event in the mid-Paleozoic. This interpretation is consistent with stratigraphic studies that report a Devonian influx of westerly-derived coarse clastic sediment in the region. In contrast, mid-Paleozoic continental margin strata in the eastern Foreland Belt record passive margin conditions and easterly-derived sedimentation. Existing tectonic models depict the Foreland Belt evolving as a single Paleozoic passive margin on the western edge of Laurentia. We propose that two separate continental margin systems exist: a west-facing passive margin in the eastern Foreland Belt and an east-facing orogenically active margin in the western Foreland Belt. Carbonatite magmatism has recently been shown to be globally associated with known continental suture zones; a line of carbonatite complexes in the central Foreland Belt, including the Aley carbonatite, is thus interpreted to approximate the cryptic suture between the two margins.

#### **LEAD ISOTOPE RATIOS IN THE SUDBURY IGNEOUS COMPLEX, CANADA: INTERPLAYS BETWEEN ORES, OVERLYING MAGMATIC SILICATES, AND UNDERLYING COUNTRY ROCK LITHOLOGIES**

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The Sudbury Igneous Complex (SIC) is the preserved remnant of a 1.85 Ga meteorite impact-induced crustal melt sheet and hosts world-class Ni-Cu-PGE mineralization. The melt sheet eventually crystallized into a magmatic stratigraphy that can be traced along the entire impact basin. Surprisingly, there is a strong isotopic contrast between the North and South ranges of the SIC. This was traditionally attributed to assimilation of distinct source rocks on the two sides of the complex. Most of the ore in the Sudbury camp occurs in or is believed to have been mobilized from footwall embayments at the base of the SIC that appear to have been significantly modified by thermomechanical erosion. In this study, a new, comprehensive Pb isotope dataset is presented that was obtained to test if the isotopic stratigraphy over individual embayments can be used as a vector for mineralization.

Lead isotope ratios were obtained from meticulously separated and chemically leached feldspars from 153 rock samples. The feldspars were also analyzed for full trace element concentrations. The Pb isotope compositions of the mineral separates were much less radiogenic than those recently reported. This attests to the efficacy of the methodology. The new dataset reinforces the clear isotopic distinction between North and South Ranges. It further demonstrates that there is no straight-forward connection between the isotope composition of massive Ni-Cu ore in the North Range and the overlying SIC. Rather, it was found that stratigraphically lowest Mafic Norites are isotopically most similar to the ore. The Paleoproterozoic rocks in the South Range footwall are younger than the Neoarchean footwall rocks in the North Range, yet the former are characterized by much more ra-



diogenic Pb isotope signatures, which is also reflected in South Range ores.

The combined dataset permits two working hypotheses. First, if the original melt sheet was once isotopically homogenous, the disparity in North Range ore and SIC would imply that many North Range ore bodies never did equilibrate Pb with the melt sheet. This could be interpreted to imply that the sulphide melt did not form within the SIC but locally, within footwall embayments. Alternatively, the melt sheet may never have been isotopically homogenous and the ore bodies reflect the original isotopic heterogeneity at the base of the melt sheet, which was later narrowed into a smaller isotopic range by convective mixing. In either case, there is no straightforward Pb-isotopic vector within the SIC that could point to ore deposits.

#### **NEW U-Pb GEOCHRONOLOGY FROM THE BLAKE RIVER GROUP, ABITIBI SUBPROVINCE, QUÉBEC: IMPLICATIONS FOR GEOLOGICAL INTERPRETATIONS AND BASE METAL EXPLORATION**

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The 2704-2695 Ma Blake River Group forms part of the Abitibi Subprovince of the Superior Province. The submarine volcanic rocks of this group are host to a number of volcanogenic massive sulphide (VMS) deposits, including several world-class deposits. Nineteen new high precision U-Pb ages contribute to a high level of understanding of the time evolution of the Blake River Group and demonstrate that VMS deposits formed throughout the protracted volcanic evolution of the entire group. Important mineralizing events in the Blake River Group occur on the order of 2 m.y. and appear to be related to major magmatic episodes. The Blake River Group is host to the two largest Archean Au-rich VMS deposits (Horne and LaRonde Penna) and the large Bouchard-Hébert/Mobrun VMS deposit. These large deposits were formed during three distinct time periods (2702 Ma Horne-Quemont, 2698-2697 Ma LaRonde-Bousquet, and 2696 Ma Bouchard-Hébert/Mobrun). Age constraints on the timing of various mineralizing events contribute to better understanding the geometry of the Blake River Group and its geologic and metallogenic evolution. Recognizing the specific time-stratigraphic intervals favourable for mineralization and the associated geological settings are important aspects of future exploration models for these polymetallic deposits in the Blake River Group.

#### **GEOLOGY, GEOCHEMISTRY AND MINERALIZATION OF THE BOOTH RIVER IGNEOUS COMPLEX: NEW INSIGHTS INTO A LARGE MAFIC INTRUSION IN CANADA'S NORTHERN TERRITORIES**

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The 2025 Ma Booth River Igneous Complex (BRIC) is a large, relatively unknown, mafic intrusion in the Slave Structural Province in Western Nunavut. Exposures along the northwestern and southeastern flanks of the Burnside River Synclinorium are interpreted on the basis of geological and geophysical data to represent outcroppings of a single ~80 km × ~40 km intrusion. The

BRIC intrudes the Archean Yellowknife Supergroup and is unconformably overlain by the Goulburn Group. 1870 Ma Mara River gabbroic sills have intruded along the contact between BRIC and Goulburn Group. The northern exposure of the BRIC, which has been the focus of this study, is composed primarily of pyroxene-plagioclase±olivine ortho- and mesocumulate gabbro-norites. Most are relatively fresh with local minor to moderate alteration, with the exception of rocks within the metamorphic contact aureole of the Mara River sills, which are more strongly altered. Rare igneous layering indicates that the intrusion dips shallowly to the south-east.

The BRIC is mineralogically and geochemically relatively homogenous and only weakly differentiated, but the northern exposure can be subdivided into lower (marginal) and upper zones. The lower zone is dominantly gabbroic with a basal layer of norites overlain by ~1100m of homogeneous gabbro-norite with lenses of anorthosite. Within the western half of the study area, the lower zone also contains olivine-bearing gabbro-norite and anorthositic xenoliths, which are locally abundant near the basal contact. The basal contact of the BRIC is very irregular with a wavelength of ~2 km and an amplitude of ~600 m, which appears to represent diapiric upwellings of meta-sedimentary rocks from a destabilized footwall sequence. Large rafts of country rock are present within the lower zone several hundred metres above the basal contact and are spatially associated with these plumes. Assimilation of such xenoliths could represent an effective crustal contamination mechanism. The upper zone is ~1200 m thick and dominantly picritic with a ~300 m wide olivine-bearing gabbro-norite interval and thin, feldspathic peridotite and anorthosite lenses. The modal, compositional, and textural changes between units are typically gradational. Pegmatoidal Fe-Ti-V-rich ferro-gabbro pods, ~1-7m in diameter, occur throughout the BRIC and appear to truncate layering. These pods commonly contain minor Fe-Ni-Cu sulfide mineralization. The weak degree of differentiation of an intrusion the size of BRIC is relatively uncommon, but this phenomenon in other generally thinner intrusions has been attributed to initial near-eutectic parental magma compositions.

#### **BEDROCK GEOLOGY OF THE STOKES MOUNTAINS AREA, SOUTHERN QUEBEC APPALACHIANS-STRATIGRAPHIC IMPLICATIONS FOR THE DUNNAGE ZONE**

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In the Canadian Appalachians, the Humboldt and Dunnage zones are remnants of the Laurentian continental margin and adjacent oceanic domain that amalgamated during the Ordovician Taconian orogeny. In southern Quebec, the Dunnage zone consists of the Southern Quebec ophiolite Belt, the Saint-Daniel Mélange, the Mago Group, and the Ascot Complex. In the Stokes Mountains, the Mago Group overlies the ca. 460 Ma Ascot Complex, interpreted as a Taconian volcanic arc. Detailed geologic mapping of the Stokes Mountains area has been conducted during the summer 2010 in order to study the stratigraphy and structure of that region. The main goals of this mapping project are to precisely define the nature of the Mago-Ascot contact and the location of the La Guadeloupe fault to the NE of the Stokes Mountains, and to identify field evidence for pre-Acadian deformation in the Ascot Complex, if any. The geochemical analysis of volcanic and plutonic rocks collected during the field campaign will be used to suggest correlations with volcanic rock units of the Ascot Complex cropping out southward, in the Sherbrooke area.

Preliminary results show that in this area, the Magog Group is mainly made up of the St-Victor Formation, and mostly consists of turbiditic and volcanic sandstones and of two distinctive horizons of conglomerates. The lowermost conglomerate contains felsic volcanic clasts (including a significant proportion of hematite-rich iron formation and exhalite), whereas the uppermost one is characterized by abundant boulders of felsic intrusive rocks. The Magog-Ascot contact, previously described as a major fault, has been observed in the field and is clearly depositional. The Ascot Complex is made up of interlayered, mafic and felsic metavolcanic rocks and of a crosscutting synvolcanic granitic intrusion. Both the Magog Group and the Ascot Complex are unconformably overlain by the Upper Silurian Lac Aylmer Formation that consists of interbedded limestone, dolomite, sandstone and shale. The base of the Lac Aylmer is marked by a boulder-rich conglomerate and massive dolomite, whereas its upper part is characterized by discontinuous horizon of slumped calcareous siltstone and limestone conglomerate. To the SE, the Ascot Complex is bounded by the La Guadeloupe fault, a major NW-verging Acadian reverse fault that marks the contact with the Silurian-Devonian rocks of the St-Francis Group to the SE. Clear field evidence for pre-Acadian deformation in the Ascot Complex has not been observed yet, but more mapping is planned for summer 2011.

#### **THE ARCHEAN WESTWOOD GOLD DEPOSIT, ABITIBI: CONTRASTING STYLES OF AURIFEROUS MINERALIZATION AND HYDROTHERMAL ALTERATION**

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The Westwood gold deposit (reserves and resources of 9.35 Mt at 11.5 g/t Au, 3.4 Moz) is located in the ~26 Moz Au Doyon-Bousquet-LaRonde mining camp in the eastern part of the 2704-2695 Ma Blake River Group of the Abitibi belt. It is situated about 2 km east of the Doyon intrusion-associated Au±Cu quartz-pyrite vein deposit (5.4 Moz Au), 4 km west of the Bousquet 1 Au-rich sulphide stockwork-disseminated deposit (2.1 Moz Au), and approximately 8 km west of the Bousquet 2-Dumagami (3.9 Moz Au) and the LaRonde Penna Au-rich VMS deposits (9.2 Moz Au).

The Westwood deposit is hosted in the highly strained, steeply dipping and south-facing volcanic rocks of the ca. 2700-2696 Ma Bousquet Formation. The mineralization is located in three stacked corridors from north (base) to south (top): zone 2 extension, north and Westwood-Warrenmac. The partly transposed auriferous quartz-pyrite veins of the zone 2 extension are at a shallow angle with the stratigraphy and the east-trending foliation, in the lower part of the Bousquet Formation. These veins share strong analogies with the Doyon mine zones 1 and 2 vein systems. The north corridor mineralization is located in the central part of the Bousquet Formation and forms discontinuous auriferous sulphide-quartz veins and disseminations that show hybrid characteristics between “zone 2-type” veins lower in the stratigraphy and VMS-style mineralization higher in the stratigraphy. The ore zones of the Westwood-Warrenmac corridor, which are located in the same stratigraphic interval as the massive sulphide lenses at Bousquet 2-Dumagami and LaRonde Penna in the upper part of the Bousquet Formation, consist of stratiform auriferous semimassive

to massive sulphide lenses containing significant amounts of Cu, Zn, and Ag.

A genetic link between the intrusion-associated Au±Cu quartz-pyrite veins at Doyon and the Bousquet 2-Dumagami and LaRonde Penna Au-rich VMS deposits can be inferred at camp scale based on similar ages and overall geological settings. However a close examination of the relationships between the contrasting ore styles at Westwood is needed to confirm this hypothesis. Despite superimposed deformation and metamorphism that hinder recognition of primary relationships, preliminary results show that the different styles of mineralization are part of a pre-main stage deformation protracted volcano-plutonic hydrothermal system, with the large-scale VMS-associated alteration locally overprinted or telescoped by the Au±Cu vein-related alteration. This would perhaps suggest a setting similar to what is seen in younger belts where a genetic link between porphyry and epithermal Au-Cu systems has been demonstrated.

#### **PICRITIC UNDERPLATING AND THE NEO-ARCHEAN REWORKING OF THE UNGAVA CRATON**

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The Neo-Archean was an important era of continental crust formation and a time of wide-spread mafic magmatism related to global-scale mantle melting. The Neo-Archean Ungava craton of northern Quebec is dominated by relatively-potassic ca. 2.74-2.72 Ga granitoids emplaced into an older, regionally-extensive ≥2.8 Ga crust. A large number of small (<10 km<sup>2</sup>) mafic/ultramafic bodies, collectively referred to as the Q-suite, outcrop across much of the Ungava craton. Zircon U-Pb data indicate that these small intrusions were emplaced coevally with the 2.74-2.72 Ga granitoids, suggesting that underplating by mantle-derived magma may have played a key role in the cratonization of the Ungava peninsula. Field observations, such as internally zoned dyke-like bodies that intrude the surrounding ca. 2.74-2.71 Ga granitoids, ubiquitous brecciation of ultramafic bodies by the surrounding granitoids, large volumes of undeformed, coarse grained granitoid rocks containing enclaves of the Q-suite equivalents, and the existence of the “hybrid” zones of intermediate compositions suggest a link between craton-wide mafic magma emplacement, crustal melting and cratonization.

A comparison of mafic/ultramafic intrusions situated ~250 km apart, within the isotopically-defined Hudson Bay (TDM=3.9-2.9 Ga) and Riviere Arnaud (TDM=3.0-2.8 Ga) terranes provides insights into the link between mafic underplating and reworking of the Ungava craton. The intrusions are generally fresh, comparable in size, internally zoned with high MgO peridotitic cores, and display complex margins that are brecciated by coarse grained, <1 m wide pegmatitic dykes and veins. The Q-suite intrusions from the Hudson Bay terrane contain significant orthopyroxene and evolve from peridotite to hornblende websterite to hornblende gabbro. In contrast, the intrusions from the interior of the craton, within the Riviere Arnaud terrane, lack orthopyroxene and evolve from dunite to olivine clinopyroxenite to hornblende gabbro. The contrasting mineralogies likely reflect the differences in the depth of emplacement and composition of the assimilated country rock between the two terranes. Nonetheless, the whole rock (Mg#<sub>max</sub>=82.2) and olivine (Fo<sub>max</sub>=83) compositions from the peridotitic cores in both terranes require picritic parental magmas (Mg#≤59.5) that are significantly more Fe-rich than modern hot-spot or subduction related picrites. Furthermore, the Q-suite intrusions in both terranes have indistinguishable incompatible trace element abundances and key incompatible element ratios, such as Zr/Nb and Zr/Y, suggesting underplating by a common parental magma. The voluminous crustal melting that

resulted in the ca. 2.7 Ga stabilization of the Ungava craton thus appears to be in part related to the sub-crustal emplacement of Fe-rich picritic magmas.

#### **ORIGIN OF DIAMONDS IN ARCHEAN DIAMONDIFEROUS CONGLOMERATE FROM WAWA, N. ONTARIO**

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Analysis of mineral inclusions in a suite of 65 diamonds from the Wawa sedimentary conglomerate provides new insight into the state of the Archean mantle of the Southern Superior craton. The conglomerate is one of the oldest diamond deposits in the world (2.7 Ga), located 12 km northeast of the town of Wawa, within the Michipicoten greenstone belt (MGB) of the Superior Craton. The primary source for the conglomerate diamonds may have been the ca. 2.7 Ga diamondiferous lamprophyric breccias found 20 km north of the town of Wawa, or eroded kimberlites.

Electron microprobe analysis of mineral inclusions suggests that all studied diamonds formed in the harzburgitic mantle. The diamonds contain forsterite (Fo<sub>93</sub>), Mg-chromite with 60-70 wt% Cr<sub>2</sub>O<sub>3</sub> and harzburgitic garnet with 6-10 wt% Cr<sub>2</sub>O<sub>3</sub>. The majority of chromite compositions fall within the diamond inclusion field. Garnet-olivine thermometry yields temperatures from 997 to 1248°C at 50 kb. Univariant P-T lines of the garnet-olivine thermometry for the studied inclusions intersect the 40 mW/m<sup>2</sup> geotherm at pressures of 50 to 75 kb. Geobarometry based on the maximum Cr<sub>2</sub>O<sub>3</sub> content of harzburgitic garnet yields pressure of 50 kb for a 40 mW/m<sup>2</sup> geotherm. Thermal regimes hotter than 42 mW/m<sup>2</sup> are unlikely as the pressure-temperature estimates for the diamonds would not plot in the diamond stability field.

The diamondiferous Wawa conglomerate (2.700-2.697 Ga) is coeval with diamondiferous lamprophyric breccias (2.68-2.74 Ga), which erupted shortly before the Kenoran orogeny (2.7 Ga) of the Superior MGB. The origin of the diamonds in a cold subducted slab is therefore a possibility. We reject it based on the absence of eclogitic diamonds in the studied suite.

The diamondiferous Wawa conglomerates formed simultaneously with the third cycle of basaltic-rhyolitic magmatism (2.7 Ga) of MGB. Emplacement of basalt requires high mantle temperatures, contrasting with the necessary presence of a cool cratonic root. Two models may explain this contradiction. The first model would require the preservation of the cold diamondiferous cratonic mantle at depth, despite high temperatures of the shallow mantle that produces basalt. This was reported in India where diamondiferous kimberlites were emplaced at the time of the most intense Deccan flood basalt activity. The second model would ascribe a shallow allochthonous origin to the MGB so it is detached from the original mantle root. A similar detachment was shown to exist in the Limpopo Mobile Belt, where the relatively hot crust is underlain by the cool diamondiferous harzburgitic mantle.

#### **CARBONATITES AND ALKALINE ROCKS IN THE SOUTHERN CANADIAN CORDILLERA**

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This study provides new insights through U-Pb and Sm-Nd age dating of previously undated and/or unknown carbonatites and accompanying alkaline rocks in British Columbia in order to better understand the mineralogical and chemical differences between the individual magmatic bodies and the geodynamic setting during their emplacement. It will further help to distinguish between dif-

ferent episodes of carbonatite and alkaline magmatism during the Devonian and Carboniferous in the Canadian Cordillera.

Recently the rare earth elements (REE) together with high field strength elements (HFSE) have become the focus of worldwide exploration activities due to their importance in e.g. green technologies and China restricting REE exports.

One major source for rare metals are carbonatites (e.g. Mountain Pass/USA) or carbonatite related deposits (Bayan Obo/China). In British Columbia (B.C.) carbonatites, nepheline and sodalite syenite gneisses and related alkaline rocks are found in a broad zone which is parallel to, and on either side of the Rocky Mountain Trench. Three subzones are distinguished as hosts for the above rock types (1) the Foreland Belt & Cassiar Mountains, (2) the Omineca Belt – alkaline rocks are hosted by metamorphosed Precambrian to Early Cambrian strata and (3) the Omineca Belt – alkaline rocks are hosted by core gneiss complexes. From the 14 known carbonatite occurrences in B.C. seven have been dated directly or indirectly with reported intrusion ages between 357 Ma (Verity) and 202 Ma (Howard Creek). Most ages cluster around 320 to 350 Ma, which corresponds to a time when the passive continental margin of ancestral North America became an active margin with an extensional back-arc basin developing in the Carboniferous. All carbonatites were subsequently affected by (multiple) greenschist to amphibolite facies metamorphism.

#### **TEXTURAL COARSENING BY THERMAL CYCLING IN A BASALTIC MAGMA AND A MAGMA ANALOG**

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Igneous textures are commonly used to infer a magma's cooling history. For example, large crystals in porphyritic rocks are frequently assumed to represent an early-crystallizing phase that grew to be large during a period of slow cooling. However, alkali feldspar megacrysts, common in granodiorites, cannot grow early; phase equilibria and the lack of alkali feldspar crystals in crystal-rich dacites confirm that alkali feldspar is a late-crystallizing phase in granodioritic magmas. These facts indicate that another mechanism must be the cause of the large crystal growth in megacrystic granodiorites.

We performed experiments in two different chemical systems in order to test the effects of thermal cycling on crystal size. Results from heating-stage experiments, using the ammonium thiocyanate-cobalt chloride system at temperatures ~50°C, indicate that crystal growth rate increases ~10-fold by cycling the temperature with an amplitude of ~4°C and a period of 10 minutes. Crystal growth occurred primarily via melt-refreeze recrystallization and by coalescence of adjacent crystals; Ostwald ripening at constant T was a measurable but minor process. In addition, we observed crystal alignment parallel to the thermal gradient during thermal cycling experiments.

Experiments were performed for a range of durations between 20 to 120 hours at ~1160°C in a basaltic system at 1 atm in a gas-mixing furnace at Ni-NiO. Results indicate that thermal cycling of ±10°C at a period of 20 minutes changes the texture of the quenched material dramatically. Cycling causes a dramatic change in the size distributions of the two crystalline phases, olivine (Fo<sub>80</sub>) and plagioclase (An<sub>70</sub>). Average crystal area increases by a factor of 2 to 4 after cycling. Results from these sets of experiments indicate that crystal growth and resultant igneous textures can be altered by temperature cycling during crystallization and that igneous textures that conflict with phase equilibria need to be reexamined.

# MINERALOGY AND GEOCHEMISTRY OF LEACHED AND SUPERGENE ZONES IN DARREHZAR AND PARKAM PORPHYRY COPPER DEPOSITS, IRAN: CRITERIA FOR DISCRIMINATING BARREN AND ENRICHED Cu DEPOSITS

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Darrehzar and Parkam porphyry copper deposits, located in Kerman porphyry belt, southern Iran, are considered examples of high- and low-grade Cu ores, respectively.

X-ray diffraction analysis and microscopic observation shows Darrehzar deposit is characterized by having higher abundances of hematite in the leached zone and chalcocite and covellite in the supergene zone, compared to those in Parkam. In contrast, the leached zone isn't well developed in Parkam and principal oxide minerals are goetite and jarosite. A comparison of the average assays of selected metals from the leached zones of the two deposits shows that the leached zone in Darrehzar contains higher concentrations of Pb, Mo and Fe than that in the Parkam. The average grade of copper from the enrichment zone of Darrehzar is 0.6% and in enrichment zone from Parkam is 0.4%. Many factors, including the topography, active tectonic, higher ore grade of hypogene and larger hypogene zone have contributed to greater Cu enrichment in Darrehzar deposit.

## A SEDIMENTOLOGICAL HISTORY OF THE EARLY PLIOCENE AGED BEAVER POND SITE (ELLESMERE ISLAND, NUNAVUT)

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The Early Pliocene aged Beaver Pond site, found in Canada's High Arctic (Ellesmere Island, NU), has produced a rich vertebrate fauna. The site is composed of a thick sequence of peat and sands. Tertiary peat accumulations are common occurrences in the Arctic, but this site is unique due to its associated vertebrate fossil finds and its accumulation of beaver cut sticks. Although the site has been the subject of intense paleontological investigations for almost two decades, no detailed stratigraphy or paleoenvironmental analysis has been performed. Recent field studies resulted in several measured sections within and surrounding the site in order to establish the stratigraphy and lateral continuity of the units. Sedimentological evidence suggests a variable paleoecological system through time. At some point, environmental conditions became favourable for the development and preservation of a freshwater ecosystem, which attracted a unique floral and faunal assemblage. This assemblage is represented by exquisitely preserved fossil remains. Facies changes suggest an initial high-energy fluvial system that carried boulders. This environment changed to a fen-type wetland that supported peat accumulations up to 2 metres thick. Whereas peat extends widely along the outcrop, this increased thickness is localized at the fossil site and is uncommon at other Tertiary arctic peat sites. Abundant beaver-cut sticks are associated with this facies, a characteristic after which the site is named. The peat is overlain by fine-grained sands rich in organic matter and charcoal. Alignment of small sticks may suggest gentle wave action that concentrated coarse organics in shallow water or a stream entering a lake. The upper two units significantly differ from those associated with the fen and lake system. A grain size increase to medium to coarse sand with abundant pebbles and cobbles was observed. These units also lacked organic matter. Poor sorting and rounding of the components point towards glacial transport and consequently a possible hiatus between deposition of the units.

The boundary between units is not sharp which indicates reworking of the underlying lake sediments. Ongoing work and comparisons with other fossil deposits and documented climate variability will help determine how changing environmental parameters influenced the floral and faunal assemblage at the Beaver Pond site.

## LIMITATIONS OF THE SPHALERITE GEOBAROMETER: EVIDENCE FROM EXPERIMENTALLY DETERMINED CATION DIFFUSIVITIES IN SPHALERITE

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For more than 40 years the Fe content of sphalerite in assemblages containing pyrite + pyrrhotite has been used to estimate the pressure of equilibration, and it is referred to as the "sphalerite geobarometer" (SG) (e.g. Scott, 1973, 1976). Based on theoretical considerations, some workers have questioned the validity of the SG (e.g. Kalogeropoulos, 1983, Banno, 1988). There are also serious problems with phase relations at low-temperatures in the Zn-Fe-S system. Studies of the solubility of chalcopyrite in sphalerite and textural-compositional relations of sphalerite in a sample from the metamorphosed Ducktown VMS deposit, Tennessee suggest that original compositions have been disturbed by lower-temperature events subsequent to its original precipitation (Toulmin et al., 1991), and this may be due to the kinetics of diffusion in sphalerite. We have conducted sulfide synthetic experiments that highlight the conditions under which the SG can and cannot be applied.

The interdiffusion coefficients of Zn-Fe in sphalerite were experimentally determined using  $f_{S_2}$  buffering materials such as iron and/or synthetic pyrrhotite at temperatures between 950° and 500°C and electron microprobe analyses and (Mizuta, 1988). Radiotracer diffusion coefficients of <sup>65</sup>Zn, <sup>59</sup>Fe, <sup>63</sup>Ni and <sup>60</sup>Co in sphalerite crystals were determined by thinning methods (Mizuta and Scott, 1988) and by SIMS analysis (Mizuta et al, 1990). From the experimental Zn and Fe tracer diffusion data, the mean displacement (x) of cations in sphalerite can be calculated using the following equation,  $x=(Dt)^{0.5}$  [D: diffusion rate (cm<sup>2</sup>/sec) in fixed temperature, and t: time (sec)]. If the sphalerite crystals were kept at 400°C for 10,000 years, the mean displacement would be 920µm (microns), at 300°C: 85 µm, and at 200°C: 3.2 µm, respectively.

The textures and chemical compositions of sphalerite containing chalcopyrite and pyrrhotite inclusions from some skarns, together with our experimental data on diffusivity, have permitted rates of exsolution (geospeedometry) and cooling histories of the skarns to be estimated (Mizuta and Scott, 1997). The measured compositional profiles of sphalerite indicate that caution must be used in the application of the sphalerite geospeedometer. Valid results can be obtained where Zn-Fe-S system minerals have been held at moderate temperature (400-200°C, 1 m.y.) during the retrogressive stage of metamorphism (decreasing pressures and temperatures). Additionally, the mode of occurrence of the Zn-Fe-S minerals is critically important. For example, if the assemblage occurs together with elastic minerals such as quartz, micas and chalcopyrite, FeS contents of the sphalerite would increase with decreasing pressure. The SG should only be applied where the sphalerite-pyrite-pyrrhotite assemblage occurs in inert and cleavage-free silicates (e.g. garnet) and sulfide minerals (e.g. pyrite, arsenopyrite).

## ATMOSPHERIC CORRECTION OF OMEGA DATA TO DETECT SURFACE COMPOSITION AND EVALUATE AEROSOL EFFECTS

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Reflectance spectra, obtained from the imaging spectrometer OMEGA onboard Mars Express, are corrected for atmospheric effects to retrieve surface albedo spectra and used to investigate surface ice composition in the polar and equatorial regions of Mars. Strong, unambiguous, absorption bands, not masked by dust, are located at 1.4, 1.6 and 2.0  $\mu\text{m}$  for  $\text{CO}_2$  ice and at 1.5 and 2.0  $\mu\text{m}$  for  $\text{H}_2\text{O}$  ice. In this study, seasonal  $\text{CO}_2$  ice and permanent  $\text{H}_2\text{O}$  ice at the poles as well as residual  $\text{CO}_2$  ice in the south and seasonal  $\text{H}_2\text{O}$  ice in Hellas Planitia are observed by OMEGA. However, if the reflectance considers light scattering by aerosols as well as the extinction of incoming and outgoing radiation due to aerosol and atmospheric absorption, the effect on the surface albedo spectra can be evaluated by comparing “dusty” versus “clear” periods. Here, the optical depth on Mars at clearest conditions is 0.3–0.5 during the northern summer and at dustiest conditions is 2–5 during the northern winter. By analysing the effect on reflectance with varying optical depth and surface albedo including light scattering using data generated from a 1-D delta-Eddington two-stream radiative transfer model, both bright and dark surfaces and bright and dark dust are investigated. In this study, Olympus Mons and Hellas Planitia, during both “dusty” and “clear” periods, were analysed and revealed that a thin layer of bright dust exists over a bright Olympus Mons and a thick layer of bright dust exists over a dark Hellas Planitia. For the latter region, an approximate aerosol optical was determined to be  $\sim 0.35\text{--}3+$  at the end of the southern summer, which falls within the “dusty” range.

## THE NATURE AND EVOLUTION OF THE NECHALACHO REE DEPOSIT, NWT, CANADA

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The Nechalacho rare metal deposit at Thor Lake, NWT, Canada comprises one of the world’s largest high-grade Rare Earth Element (REE) and High Field Strength Element (Y, Zr, Nb, Ta) deposits, and is of particular economic interest due to its enrichment in heavy REE (HREE). The principal REE-bearing minerals, zircon, allanite, fergusonite, bastnäsite, synchisite and monazite are present in a variably disseminated or condensed upper zone enriched in light REE and a lower layered cumulate zone enriched in HREE. The host rock is an aegirine-nepheline-sodalite syenite of miaskitic to agpaitic composition, the Nechalacho Syenite. This unit is part of a large, layered peralkaline complex characterized by highly variable grain size (from pegmatitic to fine-grained), low-viscosity flow textures, compositionally distinct cumulus layers, cyclic micro-layering, and a variety of secondary alteration features. In the upper zone, significant metasomatic remobilization of REE is indicated by veins of bastnäsite and vein-style aggregates of zircon. Our study focuses on the contact relationships within the complex, the primary mineral assemblages and late-magmatic alteration processes in the host rocks and mineralized zones. Recent borehole data suggests that the Nechalacho Syenite intruded a gradational igneous sequence represented by the Thor Lake Syenite and the overlying Grace Lake Granite. The crystallization sequence and geochemical evolution of the complex were established on the basis of petrographic relationships and mineral and whole-rock chemical analyses. The primary mineral assemblage is perthitic, iron-rich and oxidized, as indicated by abundant near end member aegirine, containing up to 0.6 wt.% zirconium.

Primary carbonate minerals and fluorite are present in the deep succession. Late magmatic, auto-metasomatic alteration was more reducing, leading to the formation of magnetite at the expense of aegirine. Locally, aegirine was altered to riebeckite or replaced by zircon. Late-stage hydrothermal replacement of magnetite by hematite indicates a return to oxidizing conditions. In the micro-layered cyclic sequence of foyaites and microsphenites of the cumulate zone, aegirine was completely replaced by magnetite and hematite, and primary zircon-silicates were pseudomorphed by zircon, allanite, quartz and fluorite. At depth, the magmatic assemblage grades into layered biotite-aegirine-amphibole-sodalite-syenite hosting zircon, pyrochlore, Na-zirconosilicates and sodic amphiboles, which occur as primary phases, but also form late-magmatic overgrowths on biotite. The transition from silica over- to under-saturated lithologies, the formation of cumulus layers, the spatial variation of REE mineralogy, and the presence of volatiles in the magmatic and alteration stages were all key factors in the formation of the Nechalacho deposit.

## WATER DEPTH OF MASSIVE SULFIDE FORMATION: EVIDENCE FROM MODERN SEAFLOOR HYDROTHERMAL SYSTEMS

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Constraining water depth represents one of the most challenging aspects of volcanological studies reconstructing the environment of massive sulfide formation in the ancient rock record. Although distinctive volcanic facies characteristics develop above the storm wave base in near-shore environments, unequivocal indicators for water depth are generally absent in the host rock successions of massive sulfide deposits that form under deeper marine conditions. At present, the results of three decades of modern seafloor research provide the most reliable information on the limitations of water depth on massive sulfide formation as over 170 high-temperature deposits have been discovered at the ocean floor.

Water depth of modern seafloor vent sites correlates with plate tectonic setting and regional magmatic and volcanic setting. Mid-ocean ridge hydrothermal systems occur at water depth ranging from 5000 m to 2000 m with the shallowest deposits being located at intermediate-rate and fast-spreading ridges. Water depth in mature intraoceanic back-arc basins is comparable to mid-ocean ridges spreading at intermediate and fast rates, but sulfide formation has been observed at water depths as shallow as 1600 m where back-arc spreading centers approach the volcanic front. Sulfide formation associated with the rifting of intraoceanic crust and continental margins is restricted to a water depth interval of 2000 to 700 m. Polymetallic sulfide deposits on arc volcanoes are typically located at water depths ranging from 1600 to 500 m, although some vent sites occur at water depths as shallow as 25 m. The results of modern seafloor exploration suggest that the formation of massive sulfide deposits is not necessarily restricted to deep marine settings. A continuous spectrum of deposit types ranging from relatively deep marine massive sulfides to shallow marine and subaerial epithermal deposits occurs in suprasubduction settings.

However, the base metal content of modern seafloor hydrothermal fluids and related sulfide deposits is controlled by hydrostatic pressure, which essentially equates to water depth. In general, copper-rich massive sulfides appear to form under deeper marine conditions. Exceptions are rare copper-rich sulfide deposits at arc volcanoes that formed by unusually oxidizing fluids having

high-sulfidation characteristics. In contrast to copper, high zinc grades occur over a wide range of water depths and are commonly encountered in shallow water. Anomalous gold enrichment is also common but not unique to shallow water hydrothermal systems. This implies that water depth is only one control on gold enrichment in massive sulfide deposits.

#### **GEOLOGY OF THE HORNE MASSIVE SULFIDE DEPOSIT, ROUYN-NORANDA, QUEBEC**

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The Horne deposit in the Noranda mining district, northwestern Québec, represents one of the largest volcanic-hosted massive sulfide deposits in the world. Between 1927 and 1976, the mine produced 260 t of Au and 1.13 Mt of Cu making it one of the largest gold producers of its class. Over the past years, an extensive research program has been carried out to better define the volcanological and stratigraphic setting of the deposit.

Detailed surface mapping has shown that the host rock succession of the Horne deposit is dominated by a proximal facies association comprising coherent rhyolite and associated volcanoclastic rocks that formed by autobrecciation and quench fragmentation. Effusive and shallow intrusive volcanism occurred broadly contemporaneously with the deposition of mass-flow derived volcanic debris containing pyroclasts generated by felsic explosive eruptions. Deposition of volcanoclastic lithofacies occurred, at least in part, in topographic depressions that are bounded by synvolcanic faults. Synvolcanic faults are commonly marked by abrupt changes in volcanic facies and the presence of felsic and mafic dikes or apophyses of synvolcanic intrusions. The synvolcanic faults also appear to control the location of sulfide mineralization and associated hydrothermal alteration. Field relationships indicate that massive sulfide formation broadly coincided with a shift from felsic to mafic volcanism as the felsic-dominated host succession is crosscut by a mafic dike swarm that extends towards a succession of less intensely altered mafic rocks in the hanging wall to the deposit.

Massive sulfide formation occurred over a prolonged period of time resulting in the formation of a stratigraphically stacked, hydrothermal ore system. Widespread sulfide infiltration and replacement of permeable volcanoclastic strata and associated hydrothermal alteration suggest that processes of seafloor replacement were important in contributing to the unusual size of the Horne deposit. However, incorporation of massive sulfide clasts into mass-flow derived volcanoclastic deposits suggests that massive sulfides were at least locally exposed at the ancient seafloor.

TIMS U/Pb dating of a rhyolite sill showed that the Horne succession formed at  $2702.2 \pm 0.9$  Ma. This is comparable to the emplacement age of a coherent rhyolite occurring in the footwall of the Quemont massive sulfide deposit, located immediately to the north of the Horne Creek fault. Based on these age constraints and lithological similarities between the host rock successions, it appears likely that the gold-rich Horne and Quemont deposits formed broadly contemporaneously during an early period of felsic-dominated submarine volcanism of the Blake River Group.

#### **HIGH FIELD STRENGTH ELEMENT ENRICHMENT OF JURASSIC-CRETACEOUS ISLAND ARC MAGMATISM: THE SANANDAJ-SIRJAN ARC-BASIN SYSTEM, IRAN**

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The intra-oceanic Sanandaj-Sirjan subduction system is linked to the northeastern ward subduction of the Neo-Tethys oceanic domain beneath the Sanandaj-Sirjan Structural Zone in the Iranian convergent margin environment. These magmatic activities have exposed with Jurassic-Cretaceous age in magmatic-sedimentary-turbiditic basin along a 1300 km Sanandaj-Sirjan arc-basin system, and they range in composition from transitional to calcalkaline affinities.

The volcanic suites exhibit low  $^{87}\text{Sr}/^{86}\text{Sr}$  (0.7043-0.7044) and low  $^{143}\text{Nd}/^{144}\text{Nd}$  (0.51281-0.51292) ratios and have more fertile mantle (E-MORB-like) trace element patterns characterized by slightly enrichment in High Field Strength Element (HFSE) like Nb, Ta, Ti, Zr, Th, U and total REE relative to P-mantle and average N-MORB. REE modeling indicates that these rocks formed by partial melting of a garnet-spinel lherzolite mantle source.

However, the new trace element data suggest that the mantle wedge in the Sanandaj-Sirjan island arc is enriched by possible addition of a sediment melt, or supercritical aqueous fluid subduction components into a mantle source. The proportions of slab-derived HFSE-REE components transferred to basalt sources in the mantle wedge. Because the subduction of oceanic slab controls the arc geochemistry, so the HFSE enrichment along the Sanandaj-Sirjan arc can imply that a residual mineral, most likely rutile, controlled extremely high HFSE partitioning into subduction-related fluids that equilibrated with mantle source region above the subducted slab.

The arc-basin system collided with the Arabian passive margin in the late Cretaceous along the Main Zagros Thrust Belt. The Zagros orogenic belt is a young Tertiary collision zone generally considered a recent analogue of the Alpine-Himalayan orogenic system.

#### **COMPOSITIONAL DATA ANALYSIS TO CONSTRAIN THE GEOCHEMICAL FOOTPRINT OF IRON OXIDE COPPER-GOLD DEPOSITS, GREAT BEAR MAGMATIC ZONE, NORTHWEST TERRITORIES, CANADA**

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Iron oxide copper-gold (IOCG) systems are characterized by a wide range of hydrothermal alteration types that indiscriminately and intensively replace their host rocks over several kilometres. The resulting alteration imprint can be reproduced irrespective of the nature of the original host and intense alteration is usually the norm over areas of  $>100$  km<sup>2</sup>. Consequently, mass-balance systems analysis (e.g. Gresens's equations) cannot be used systematically for lithogeochemical characterization of geochemical zonation and partitioning within the alteration zones of IOCG systems.

For effective geochemical evaluation of these rocks, the use of log-ratio transforms has been applied as they overcome the closure constraint inherent with geochemical data and permits the use of multivariate statistical tools for geochemical process identification. To provide robust discrimination parameters for IOCG hydrothermal alteration with multivariate statistical methods, the geochemical data must have accompanying reliable and carefully documented field observations. Cataloguing this additional information provides useful qualifications for understanding the para-

genesis of the host hydrothermal system and associated mineralization.

The numerous IOCG hydrothermal systems of the Great Bear magmatic zone in the north-western Canadian Shield are good candidates to undertake such multivariate statistical studies using the log-ratio approach. These systems encompass a wide range of hydrothermal alteration emplaced in different protoliths and are sufficiently intense to have completely replaced the original rock. Their evolution history is well constrained within an alteration to mineralization zoning model. A database of fully documented geochemical analysis is available.

Principal component analysis (PCA) was done on the litho-geochemistry of 458 hydrothermally altered and mineralized rocks from the Port Radium-Echo Bay IOCG district and various IOCG systems within the Southern Great Bear magmatic zone (including the NICO and Sue Diane deposits). PCA analysis records strong partitioning between LREE and HREE in most alteration zones. Decoupling of typical element association (e.g. Ca and Sr) is commonly observed. Calcium and K-Na are either decoupled or negatively correlated, whereas K and Na are sometime positively correlated. PCA analysis also indicates that the influence of protolith composition on resulting alteration signature is only weak to moderate as very distinctive signatures are not observed, indicating that the alteration signature dominates over the protolith signature. A linear discriminant analysis confirms the difference between the various alteration types of the IOCG model. Current modelling is unable to retrace significant chemical modification of high-temperature alteration from the low temperature alteration overprints in the IOCG systems that have been studied.

#### **OBSERVATIONS OF NEAR-SURFACE FOG AT THE PHOENIX MARS LANDING SITE WITH IMPLICATIONS FOR SUBSURFACE ICE**

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The northern polar regions of Mars show evidence of extensive ground ice deposits as inferred by the Gamma Ray Spectrometer onboard the Mars Odyssey spacecraft. Additionally, numerous geomorphological features formed by interaction between the ground ice and the atmosphere are present, including polygons and scalloped depressions. In order to fully understand how this ground ice reservoir is evolving in the current era, it is important to quantify processes that tend to deposit ice directly upon the regolith.

The Phoenix Mars Lander has measured this precipitation on the northern plains by using the Surface Stereo Imager (SSI) and the LIDAR in tandem. On four occasions during the mission, the SSI was used to observe the laser beam while the LIDAR laser was transmitting. These SSI observations permitted measurement of the scatter from atmospheric aerosols below 200m where the LIDAR emitter and receiver do not overlap fully. The observed laser scattering was used to estimate the ice-water content (IWC) of near surface fog.

Values of IWC up to  $1.7 \pm 1.0 \text{ mg m}^{-3}$  were observed. Compared to air aloft, fog formation was inhibited near the surface, which had accumulated at least  $30 \pm 24 \text{ mg m}^{-2}$  ( $0.030 \text{ pr-}\mu\text{m}$ ) on sol 113. Microphysical modeling shows that when precipitation is included, up to  $0.48 \text{ pr-}\mu\text{m}$  of water may be present on the surface at the time of measurement. Integrated over the entire night, this represents up to  $2.5 \text{ pr-}\mu\text{m}$  of water taken up diurnally by the surface, or 6% of the total water column. This provides a source from

which the ground ice may be replenished once temperatures increase at the end of the night.

#### **RADIATION-INDUCED DEFECTS IN CLAY MINERALS: A NEW EXPLORATION TOOL TO TRACE PAST TRANSFERS OF URANIUM-RICH FLUIDS IN THE ATHABASCA BASIN (SASKATCHEWAN, CANADA)**

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Uranium prospecting uses classical exploration methods (research of petrol, minerals, gas...) and methods specifically devoted to the radioactivity and to the effect of  $\alpha$  particles on minerals. These ionizing radiations cause damages in the mineral structure detectable using Electron Paramagnetic Resonance Spectroscopy, which evidence the residence (ancient or recent) of radioelements near these minerals. Some studies on quartz grains from the Athabasca basin (Saskatchewan, Canada) and on kaolin minerals and dioctahedral smectites from recent geological environments (<50 My), were previously realized.

The Athabasca basin represents one of the privileged targets for the uranium prospecting. Indeed, this basin contains deposits with the highest grade and the highest tonnage in uranium actually known in the world, related to an unconformity between Late Paleoproterozoic sedimentary sandstones and Archean to Paleoproterozoic metamorphic basement rocks. These deposits are systematically surrounded by clay minerals in alteration halos, formed during the tectonic and hydrothermal events which instigated dissolution, transport and mineralization of uranium. This study presents the first unequivocal identification of Radiation-Induced Defects (RID) in kaolinite, illite and sudoite (di-trioctahedral Al-Mg chlorite) constituting the alteration halo in the Athabasca basin. These clay minerals, which are assumed to behave similarly under irradiation, provide information on ancient pathways of uranium-rich fluids at different scales. At the global basin scale, RID are similar in nature, but their concentrations vary over several orders of magnitude. The maximum fluctuations in defect concentrations are observed along the unconformity between the lower sandstones and the basement rocks and close to crosscutting brittle structures. These discontinuities appear to be the main vectors of uranium-bearing fluids transfer in the basin. In the basement, some Hudsonian faults connected to this unconformity also show high defect concentrations, attesting that uranium-bearing fluids may have circulated in the fracture network. At the regional scale, the She114 drill-hole example (Shea Creek deposit), which intersects several mineralized ore bodies in sandstones, at the unconformity and in the basement, confirms the importance of the unconformity and the associated fractures network for the circulation of fluids. The defect concentration increases at proximity of the unconformity as the light rare earth elements (LREE)-rich APS, contemporaneous of alteration clay minerals. Moreover, the non-correlation between the defect concentration and the total dose rate confirms the existence of past migrations of radioelements, which occurred after the clays formation.

#### **THE TABLELANDS OPHIOLITE OF NEWFOUNDLAND: A CANADIAN MARS ANALOGUE SITE**

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Canada hosts a handful of unique sites that are being studied as Mars analogues. The interest in these sites ranges from Mars-re-



lated science to studies of technologies that may be used for the exploration of the red planet. The Tablelands Ophiolite, on the west coast of Newfoundland, is one site in Canada that is being studied to determine habitability and detection of life on Mars.

The Tablelands Ophiolite is a site of present-day continental serpentinization. The serpentinization reaction is a suspected source of putative hydrocarbons on Mars. Serpentinization produces  $H_2$  and the reducing conditions necessary for abiogenic hydrocarbon synthesis, while also producing conditions amenable for chemolithotrophic life.

The Tablelands Ophiolite is an analogue site that is ideal for testing methods of life detection in an extreme environment of high pH and low microbial biomass characteristic of sites of serpentinization. Multiple ultrabasic reducing springs characteristic of present-day serpentinization have been identified and characterized based on their geochemistry and microbiology. Field-based instruments were deployed for the detection of microbial activity (ATP), gram negative bacteria, and minerals. The measurements were validated using conventional laboratory measurements. In this talk I will give an overview of the in situ measurements of life detection and put these measurements in context of geochemistry, microbiology, carbon source and reaction pathways.

#### **CANADA BASIN REVEALED: SEISMIC DATA ACQUISITION IN THE ARCTIC OCEAN**

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Seismic acquisition programs in the central and western Arctic Ocean were conducted during the past 5 years in order to study the geology, sedimentary history and geomorphology of the region. These programs resulted in acquisition of more than 13,000 line-km of multi-channel seismic reflection data and 120 sonobuoy seismic refraction records over abyssal plain and continental rise regions of Canada Basin, Northwind Ridge and Alpha-Mendeleev Ridge. The success of these programs was achieved through novel technical modifications to equipment to permit towing in heavy ice conditions and through collaboration between multiple Canadian and US agencies and institutions, enabling utilization of two ice breakers during seismic and multibeam data acquisition in heavy ice.

Gravity and magnetic data show the broad scale structure of Canada Basin but do not permit ready explanation for observed anomalies and mechanisms of basin formation. Results from the recent field expeditions have not been fully realized, but clearly they show broad correspondence of anomalies and basement structures. The seafloor of Canada Basin is remarkably flat-lying in its central region, with little bathymetric change over most of its extent. The sedimentary succession is generally flat-lying with reflections extending over 100s of km. These reflections onlap and truncate against bathymetric highs such as Alpha and Northwind ridges. The sedimentary succession is thickest in the Beaufort Sea region, reaching more than 10 km, and generally thins to the north and west. Reflection characteristics suggest that sediment volume input to the Arctic Ocean has been high and dominated by turbidity current deposition, similar to Amundsen and Nansen Basins of the eastern Arctic. Earliest in the sedimentary succession of Canada Basin, infilling of basement topography and thinning from south to north is apparent. Anomalous patterns in the southern half correspond with the central basin gravity low and reflect a ridge-valley-ridge system. Above this earliest interval sedimentary succession thinning largely occurs from east to west, with sediments likely sourced from the Canadian Archipelago. The

youngest interval shows thinning from SE to NW, sourcing from the MacKenzie River and spreading rather symmetrically throughout Canada Basin. There is no evidence of contemporaneous or post-depositional reworking by bottom currents. Additionally, there is little evidence of tectonic deformation after primary basin-forming events except in the NE quadrant, nearer Alpha Ridge.

#### **CANADA'S PROGRAMME FOR AN EXTENDED CONTINENTAL SHELF SUBMISSION IN THE ARCTIC**

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After ratification of the United Nations Convention on the Law of the Sea (UNCLOS) in 2003, Canada has ten years to prepare a submission to a United Nations Committee to define the outer limits of its extended continental shelf in the Atlantic and Arctic Oceans. As a result, Natural Resources Canada, the Department of Fisheries and Oceans and the Department of Foreign Affairs and International Trade undertook active field programs over the past several years to acquire the data required to define the outer limits. This work is especially challenging in the Arctic Ocean, due to the remoteness of the area as well as unpredictable weather and ice conditions. Moreover, little or no data existed in the Arctic upon which to base a submission. The types of data required are bathymetric and geologic in nature, and the analysis requires defining the foot-of-slope and determining the sediment thicknesses. Field activities included ice camps and ice breaker acquisition programs involving international partners. These expeditions quadrupled previous data holdings in this remote region, acquiring more than 13,000 line-km of multi-channel seismic reflection data and over 130 seismic refraction records.

Gravity and magnetic data show the broad scale structure of Canada Basin but do not permit ready explanation for observed anomalies and mechanisms of basin formation. Of the two major submarine ridges in the Central and Western Arctic Ocean, the Lomonosov Ridge has been shown to have continental seismic velocities and the Alpha-Mendeleev Ridge is a complex volcanic province in its surficial expression, and appears to have high seismic velocities at its core. Most of these two complexes are shallower than 2500 meter. The Canada Basin contains a substantial accumulation of sediment, in excess of 10-km along the Beaufort margin; thinning to the north and west. Based on these preliminary findings it seems that Canada will be able to define an extended continental shelf of substantial size in the Arctic Ocean.

#### **THE CRUSTAL EVOLUTION OF SOUTHERN LABRADOR**

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U-Pb dating resolves the geological history of southeast Labrador into four major orogenic events: the Makkovik orogeny (1860-1790 Ma), the Labradorian orogeny (1710-1600 Ma), the Pinwarrian (1520-1460 Ma) and the Grenville orogeny (1085-985 Ma). Although ages represent the time of igneous and metamorphic events, they do not necessarily reflect the time of separation of the involved crustal material from the mantle. Nd isotopic data provide a tool for doing this, hence permitting regions having differing (and perhaps older) crustal information ages to be recognized, even if this is not apparent from U-Pb geochronological data.

Previous Nd isotopic data produced crustal formation ages for the Makkovik Province (1.93-2.21 Ga), and within the eastern Grenville Province, 1.88-2.12 Ga for the Groswater Bay, Hawke River, and Lake Melville terranes, and a range of 1.70-1.79 Ga for the Pinware terrane. This data suggests that Makkovik crust ex-

tends into the northern part of the eastern Grenville Province, whereas juvenile Labradorian crust is present in southeast Labrador. However, sampling was not detailed enough to establish the nature of any boundary between these crustal realms.

The data from the present study provides Depleted Mantle model (TDM) ages that yield mean values of  $(1.94 \pm 0.04)$  Ga for the Hawke River terrane,  $(1.87 \pm 0.10)$  Ga for the Lake Melville terrane and  $(1.91 \pm 0.08)$  Ga for the Mealy Mountains terrane (excluding samples showing geochemical evidence for later mantle derived components). These overlapping mean compositions suggest that these terranes are representative of one crustal realm, probably the product of mixing between Pre-Labradorian and Labradorian crustal components.

In contrast, within the Pinware terrane, two crustal-formation age signatures are present. The northern portion has Nd signatures similar to those from the Hawke River, Lake Melville and Mealy Mountains terranes, whereas the southern portion has ages indicating a juvenile Labradorian source. From sampling along the Trans-Labrador highway, the differing signatures suggest a boundary between the two crustal regions to be situated a few km north of Red Bay.

The data are interpreted to mean that the original edge of the Makkovik continental margin reached into southernmost Labrador. The position of the boundary in interior parts of southern Labrador remains to be determined.

#### **MAGNETIC AND GPR SURVEY TO ASSIST ARCHEOLOGISTS IN HUACA COLORADA, PERU**

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I applied magnetic and ground-penetrating radar (GPR) surveys at archaeological ruins of the Moche civilization in Huaca Colorado of the Jequetepeque Valley, Peru. Huaca Colorado, a large mound with massive adobe walls adjacent to a more vegetated eastern area, is rich with broken ceramics and skeletal remains of both marine and land animals. The site was occupied from AD 600-800. My survey showed the effectiveness of using the magnetic and GPR method to locate archaeological structures in the subsurface including large artefacts, such as kilns. My results assisted archaeologists in excavating and mapping the entire area. Specific objectives were broken down to individual sectors within Huaca Colorado. Some particular features found using the GPR method are suggestive of kilns that were used by the Moche civilization for copper production. A magnetic anomaly identified prior to excavation was found to be a burial site with two skeletons inside a temple. The large-scale magnetic survey also improved the identification of some adobe walls revealed by the GPR and thus provided insights about the general layout and extent of the entire settlement in Huaca Colorado. My magnetic and GPR results offer suggestions to the archaeologists for future excavations and expansions.

#### **DEFORMATION AND REMOBILIZATION OF Ni-Cu-PGE ORES AT GARSON MINE, SUDBURY, ONTARIO**

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Although magmatic Ni-Cu-PGE deposits formed by primary igneous processes, all have been modified to some degree by post-magmatic deformation, metamorphism, and/or hydrothermal alteration. The Garson deposit in the South Range of the 1.85 Ga Sudbury structure is one of several deformed magmatic Ni-Cu-PGE deposits in the Sudbury Camp. The ore bodies in the Garson deposit are coincident with steeply south-dipping, amphibolite grade, D<sub>1</sub> shear zones, which imbricated the stratigraphy and the

ore during south-directed flexural slip at the SIC-basement contact during regional buckling of the Sudbury Structure. The shear zones were reactivated as north-directed high angle reverse shear zones during D<sub>2</sub> during greenschist facies metamorphism. The ore bodies are tabular and elongate sub-parallel to coplanar L<sub>1</sub> and L<sub>2</sub> stretching lineations, which suggests strong structural controls on mineralization. Sulfide mineralization comprises predominantly inclusion-rich pyrrhotite-pentlandite-chalcopyrite semi-massive sulfide ores, but also includes minor pyrrhotite-pentlandite-chalcopyrite disseminated sulfide ores in norite and syn-D<sub>2</sub> chalcopyrite-rich quartz-calcite veins. Semi-massive sulfide ore exhibits dachsbewegung texture, which involved detachment, fragmentation, rotation, boudinage, and milling of competent silicate wall rocks in a flowing mass of ductile sulfide. Silicate rock inclusions in massive sulfide ores deformed during D<sub>1</sub> define a foliation and stretching lineation that mimic fabrics and metamorphic assemblages in the wall rocks. However, the sulfides do not show deformation textures or oriented fabrics. The sulfide ores consist of large near-equant pentlandite 'eyes' set in a matrix of coarse-grained, equigranular, polygonal pyrrhotite aggregates, similar to magmatic ores. Pentlandite 'eyes' overgrow metamorphic ferroschermakite defining S<sub>1</sub>, and together with the observed textures and fabrics, suggest that the sulfide ore recrystallized after having completely reverted to a metamorphic monosulfide solid solution (mss) and was mechanically remobilized for distances of up to hundreds of meters as a homogeneous mss. Thickened pyrrhotite-rich massive ores in mesoscopic F<sub>2</sub> fold hinges and dilatant structures and pyrrhotite-rich massive ores that transgress S<sub>2</sub> indicate ductile flow of massive sulfide ore during D<sub>2</sub>. In high D<sub>2</sub> strain zones, massive sulfide ore display banding defined by discontinuous pentlandite-rich zones, which are aligned parallel to a locally preserved, strongly developed foliation defined by elongate grains of pyrrhotite. Magnetite grains deformed brittly under greenschist facies metamorphism, but chalcopyrite and, to a lesser extent, pyrrhotite were ductilely mobilized in microfractures within magnetite.

#### **BLACHFORD LAKE INTRUSIVE SUITE: NEW GEOCHEMISTRY AND ND ISOTOPIC DATA**

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The Nechalacho REE deposit, located 100 km SE of Yellowknife, NT, occurs in an evolved central phase of the larger Blachford Lake Intrusive Suite (BIS). Situated along the southern margin of the Slave province, the BIS is an Apebican alkaline complex consisting of multiple gabbroic, granitic, and syenitic phases, that together cover an area >200 km<sup>2</sup>.

The BIS can be sub-divided into an older mafic portion that is crosscut by younger more felsic phases that host the Nechalacho deposit. Previous work done around the Nechalacho deposit was unable to develop a coherent genetic model to describe the economic concentration of REE, largely due to the confined scope and detailed nature of the investigations. In an effort to understand the large scale processes leading to the formation of the Nechalacho deposit, this study aims to decipher the evolution of the BIS as a whole. As part of this study, regional mapping and sampling programs of the entire suite have been performed. From this field work we present new geochemical, Nd isotopic data, and geochronological data.

The geochemical and isotopic signatures of phases in the BIS suggest that they are genetically linked, the source melt was mantle derived, and variations between phases are related to both crystal fractionation and crustal contamination. New and existing geochronological data indicates that most phases were injected

within a period of ca. 10 Ma. The isotopic and geochemical similarities between the BIS and the Simpson Island Dyke, suggest that they might also be linked by a common source.

The formation of the BIS around 2180 Ma marked the end of a 300 Ma period of igneous inactivity in the Slave Province. It has been noted previously that this alkaline complex, and others in the southern slave, may represent events related to the break-up of the Scandia super-continent. Therefore, characterization of the BIS mantle source (and the Simpson Island Dyke), is of great importance in describing the evolution of mantle beneath the Slave Province.

#### **GEOTECTONIC SETTING OF IRON-OXIDE COPPER GOLD DEPOSITS IN THE GREAT BEAR MAGMATIC ZONE, NORTHWEST TERRITORIES**

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Felsic to intermediate stratovolcano complexes of the Great Bear magmatic zone (GBMZ), Northwest Territories, Canada, formed during an extensional tectonic event that post-dated east-directed subduction under the western margin of the Slave Craton. Extension tectonics generated southeast (SE) trending crustal fractures with magmatic infill coeval with volcanic rocks. These SE trending structures are systematically right-laterally dislocated by north-east (NE) trending transverse fault and shear zones. Total NE shear displacement appears to exceed 200 km in a series of step-over faults but is not well constrained, and locally, extension may exceed several kilometres, as evidenced by the total width of plutons, stocks, dikes, and hydrothermal veins that infill these structures and the myriad associated fractures. Locally, pull-apart structures also occur along individual NE transverse faults, and in at least one instance host economic mineralization (past-producing Eldorado and Echo Bay Mines) at Port Radium. Extension and transverse dislocations in the GBMZ are oblique to the N-S trending western margin of the Slave craton and earlier subduction front in a pattern that repeats systematically throughout its entire length. This geotectonic setting is presently interpreted as an incipient pull-apart rift basin. The cause can be attributed to a left-lateral offset along a major transverse fault system that disrupted the western margin of the Slave craton, producing a segmented pattern of tectonic extension similar to that of present day Baja California

Overall, hydrothermal alteration and mineralization are most prominent along and at the intersections of these SE and NE trending syn-volcanic fault and fracture corridors, and to a lesser extent along the myriad faults and fractures in all orientations associated with these and earlier crustal stresses.

#### **Ni-Cu-PGE-Cr-Fe-Ti-V AND VMS MINERALIZATION OF THE RING OF FIRE INTRUSIVE SUITE, ONTARIO**

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The komatiitic  $2734.5 \pm 1.0$  Ma Ring of Fire intrusive suite (ROF) was emplaced into an older suite of arc-related rhyolites ( $2770.7 \pm 0.8$  Ma) and related subvolcanic tonalitic to granodioritic intrusions ( $2773.4 \pm 0.9$  Ma). At its deepest structural levels the ROF suite comprises several dikes containing mesocumulate to orthocumulate-textured olivine + chromite  $\pm$  orthopyroxene  $\pm$  clinopyroxene  $\pm$  plagioclase cumulates with fine-grained mesostasis; these rocks are classified as melagabbro-norites based on their norms although in the field they are generally classified as peridotites. Above the dikes are sill-like ultramafic bodies comprising adcumulate-textured dunite, chromitite, orthopyroxenite and ferrogabbro. At its highest levels the complex includes a tectonically dismembered layered intrusion containing layers of norite, leuconorite, anorthosite, ferrogabbro, and magnetitite. The complex

is structurally overlain by coeval ( $2737 \pm 7$  Ma) rhyolites which host the McFaulds Lake Cu-Zn VMS deposits. The ROF complex is remarkable for hosting, in a limited geographical area, examples of the entire spectrum of mineral deposit types known to be associated with Archean and Proterozoic ultramafic magmatism. Our interpretation of this collection of mineral deposits is that a mantle plume appeared beneath the margin of the North Caribou micro-continent. Passing through extensional faults, the komatiitic parental magma interacted with sulfide-bearing metasediments including iron formation, causing saturation with sulfide liquid and the collection of massive to net-textured magmatic sulfides in short-lived orthocumulate-textured mush zones at the bases of dikes (Eagle's Nest, Eagle 2, AT12 deposits). In higher, longer-lasting, sill-like feeders chromite and olivine were segregated mechanically into layers and lenses from the highly contaminated komatiite magma (Blackbird, Black Creek, Big Daddy, Black Thor, Black Label deposits). Although the ROF chromitites lack high Pt contents like chromitites of the Upper Critical Zone of the Bushveld complex, they do show characteristic Ir, Ru enrichment typical of Lower Critical Zone chromitites. The magma residual to the deposition of the sulfide, dunite, chromitite, and pyroxenite passed up into a layered intrusion, whereupon continued crystallization led to the deposition of norite, anorthosite, ferrogabbro, and V-rich titanomagnetite layers (Thunderbird deposit). Heat-driven circulation of hydrothermal fluids through the overlying sedimentary and volcanic rocks caused the deposition of massive Cu-Zn sulfide mineralization where these fluids vented at the sea floor. Subsequent metamorphic fluid flow through shear zones caused the formation of mesothermal Au mineralization in the Triple J Au occurrence directly adjacent to the Blackbird and Eagle 2 deposits.

#### **LESSONS FROM RECOMMENDATIONS OF THE COMMISSION ON THE LIMITS OF THE CONTINENTAL SHELF**

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Under the United Nations Convention on the Law of the Sea (UNCLOS), a coastal State is obliged to make a submission to the Commission on the Limits on the Continental Shelf in order to establish the outer limits of their continental shelf. The provisions under which this is achieved are set out under Article 76 of UNCLOS. Article 76 contains both technical and legal concepts with the possibility of significant variation in interpretation of these concepts. These concepts include the legal and scientific natural prolongation of the landmass to the outer edge of the continental margin; the determination of the outer edge of the continental margin; the constraints to be applied and the treatment of submarine ridges and elevations among others.

To date, in excess of 50 submissions have been received by the Commission on the Limits of the Continental Shelf. Recommendations have been issued for eight submissions establishing a significant body of practice from the Commission. In particular, the recommendations give some insight into, inter alia, how the Commission treat the determination of the base of the continental slope; what constitutes a submarine elevation versus a submarine ridge and how the formula and constraints outlined in Article 76 are applied. The recommendations provide specific insight into: how to treat gradually gently sloping margins, how to incorporate slope processes into the determination of the foot of the slope, as well as what constitutes a submarine elevation and how they are linked to the continental margin.

These recommendations provide coastal States with valuable guidance on how to apply the provisions of Article 76 of UNCLOS and allow for the development of successful technical and legal strategies in their submissions to the Commission. This paper will provide an overview of the recommendations, the examples they set and how this can be applied to other, similar situations.

## DEVONIAN-CARBONIFEROUS MAFIC COMPLEXES OF THE RHEIC OCEAN: RECYCLING OF CAPTURED NEOPROTEROZOIC OCEANIC LITHOSPHERE?

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The Rheic Ocean formed at ca. 500 Ma when some peri-Gondwanan terranes (e.g. Avalonia, Carolina) drifted from the northern margin of Gondwana, and was consumed during the Late Carboniferous collision between Laurussia and Gondwana, a key event in the formation of Pangea. Several mafic complexes ranging from ca. 400–330 Ma preserve many of the lithotectonic and/or chemical characteristics of ophiolites. They are characterized by anomalously high  $\epsilon_{\text{Nd}}$  values that are typically either between or above the widely accepted model depleted mantle curves. These data indicate derivation from a highly depleted (HD) mantle and imply that (i) the mantle source of these complexes displays time-integrated depletion in Nd relative to Sm, and (ii) depletion is the result of an earlier melting event in the mantle from which basalt was extracted.

The extent of mantle depletion indicates that this melting event occurred in the Neoproterozoic, possibly up to 500 million years before the Rheic Ocean formed. If so, the mantle lithosphere that gave rise to the Rheic Ocean mafic complexes must have been captured from an adjacent, older oceanic tract. The transfer of this captured lithosphere to the upper plate enabled it to become preferentially preserved. Possible Mesozoic–Cenozoic analogues include the capture of the Caribbean plate or the Scotia plate from the Pacific to the Atlantic oceanic realm. Our model implies that virtually all of the oceanic lithosphere generated during the opening phase of the Rheic Ocean was consumed by subduction during Laurentia–Gondwana convergence.

## TECTONOMETAMORPHIC EVOLUTION AND ORE MINERALIZATION IN THE LINK BETWEEN HOPE BAY AND ELU LINK GREENSTONE BELTS, NE SLAVE CRATON

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In the NE Archean Slave Craton, the Hope Bay greenstone Belt (HBB) hosts important gold deposits as compared to the adjacent underexplored Elu Belt (EB). The Elu Link that joins the two belts consists of pillowed metatholeiites with subordinate interleaving metadacites ± metarhyolites and discrete metapsammities and iron formation. The rock sequence derived from sedimentary sources and mixed upper and lower mantle melts exhibits D<sub>1</sub>+D<sub>2</sub> strain events and forms discontinuous lenses of various sizes and orientations intruded by syn- to late-D<sub>2</sub> sheet-like bt ± am metagranites and am ± bt metagabbros. A syn-D<sub>1</sub> migmatite orthogneiss in the EB eastern flank denotes a progressive eastward metamorphic gradient and shows that the Elu Link represents the HBB deep level

equivalent. Late Archean to Paleoproterozoic NE-trending dolerites and pegmatites intruded the entire rock assemblage.

The supracrustal rocks and the migmatite contain M<sub>1</sub>+M<sub>2</sub> metamorphic mineral assemblages defining S<sub>1</sub>/S<sub>2</sub> foliation. By contrast, the metagranites and metagabbros depict M<sub>2</sub> assemblage overprinting relic magmatic minerals (M<sub>0</sub>) and delineating S<sub>2</sub> fabrics. Zoned alm-rich garnets present with chl+ms in the felsic metavolcanic rocks, in particular, show that M<sub>1</sub>+M<sub>2</sub> represent post-hydrothermal prograde and retrograde assemblages, respectively. Intersecting garnet isopleths in pseudosections suggest that both M<sub>1</sub>+M<sub>2</sub> developed along a clockwise path with ~ 5.9 kbar and ~ 551°C peak P-T estimates. By contrast, hbl-pl thermobarometry of the metagranites reveals a counterclockwise path with emplacement P-T estimates (4.6 ± 0.7 kbar and 680 ± 55°C) comparable to peak conditions in the host rocks and denoting shallow magmatic bodies. This together with lack of hornfels textures and diagnostic contact aureole minerals indicates dominant regional metamorphism. A strain-free late greenschist retrograde assemblage (M<sub>3</sub>) in the dolerites and the pegmatites and related host rocks illustrates a Paleoproterozoic thermal event due to the Thelon Orogeny.

Assay results indicate meaningful As-Cu-Zn-Au contents in all the rocks. The related base-metal sulfides pertain to M<sub>1</sub>-M<sub>3</sub> assemblages. M<sub>1</sub> sulfides include anhedral, microfolded, and broken grains parallel to S<sub>1</sub> and forming inclusions in gangue minerals. Anhedral M<sub>2</sub> sulfides occur in D<sub>2</sub> shear zones, boudin necks, S<sub>2</sub> fabrics, and quartz veins and form inclusions in M<sub>2</sub> minerals. By contrast, M<sub>3</sub> sulfides often containing inclusions of early-formed ones are mostly euhedral, but anhedral grains well defined along fractures in dolerites are also present. All these textures characterize syn- to post-tectonic remobilization of pre-metamorphic sulfide deposits. However, syn-D<sub>2</sub> intrusions with disseminated M<sub>2</sub>+M<sub>3</sub> sulfides suggest coeval introduction of juvenile fertile fluids illustrating multiple phases of mineralization.

## THE LITTLE ICE AGE AND BEYOND: SIMULATING LONG-TERM CHANGES IN CLIMATE, SEA ICE AND THE OCEANS

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Long term changes in climate, sea ice, ocean properties and wind have been reconstructed using a global reduced complexity climate model to answer questions about the causes and the nature of past and recent climate changes. Reconstructed wind-stress fields that take into account the North Atlantic Oscillation (NAO) and one Atmosphere-Ocean General Circulation Model wind-stress field, together with three radiative forcings (volcanic activity, insolation changes and greenhouse gas changes) are used in the UVic Earth System Climate Model to simulate long-term climate. Specifically, this reduced complexity model simulates the surface air temperature (SAT), the sea-ice cover in both hemispheres, global ocean properties (heat content and hydrography) and the Atlantic meridional overturning circulation since 1500, a period that includes the Little Ice Age (LIA).

The simulated Northern Hemisphere SAT agrees well with several temperature reconstructions. Interestingly enough, the simulated sea-ice cover in each hemisphere responds quite differently to the forcings. Only in the Northern Hemisphere is the simulated sea-ice area and volume noticeably larger during the LIA than during the present-day area and volume. It is also shown, among other things, that changes in the upper ocean heat content are mainly driven by radiative forcing changes, except in the polar regions where the varying wind-stress drives multi-decadal advective events into the high latitudes.

## THE TRANSITION FROM NEOPROTEROZOIC KAZA TO CARIBOO GROUPS IN THE SOUTHEASTERN CANADIAN COORDILLERA: OUTCROP EXPRESSION OF THE TRANSITION FROM BASIN-FLOOR PROXIMAL LOBES TO SLOPE CHANNELS

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Deep-water slope and basin-floor deposits represent important hydrocarbon reservoirs, and over the past decades have been intensively studied in both modern and ancient systems. However, significantly less attention has been paid to the slope-basin floor transition (SBFT), and as a result many important issues remain unresolved.

In most places where the SBFT has been reported from the ancient sedimentary record (e.g. Magallanes basin, Chile; Karoo basin, South Africa; and Namurian basin, Ireland), the exposures are scattered, and stratigraphic context equivocal. At the Castle Creek study area (east-central B.C.), however, the SBFT is spectacularly exposed and sandwiched between well-developed sheet-like basin floor and channelized slope deposits. Here, detailed work in a 400 m-thick and >1.5 km wide outcrop belt demonstrates that the SBFT is stratigraphically complex and made up of a uniquely heterogeneous assemblage of architectural elements, including channel-mouth lobe complex, channel complexes, levees, fine-grained sheets, mass-transport deposits, and large-scale scours. Moreover, it illustrates the gradual change upward from deep-water siliciclastic to carbonate and mixed strata.

The base of the SBFT comprise a channel-mouth lobe complex, consisting of multiple laterally-extensive, sandstone- and mudstone-rich “sheet-like” units with common internal erosional elements, such as scours and shallow channels. Large-scale scours are less than 1 m thick and more than 100 m wide, and contain patchily distributed erosional remnants as coarse-grained sandstone, mudstone-clast breccia and stratified sandstone. They are the result of bypass currents that transited the deep-water transition zone. Broad, shallow channels are less than 3 m deep and up to 350 m, wedge-shaped, commonly filled with thick-bedded, amalgamated, coarse sandstone, with widespread flat and shallow erosion surfaces. They represent (intralobe) distributary-like channels.

The upper part of the SBFT, in contrast, comprises channel complexes encased within sheets of thin, fine-grained turbidites with common large mass-transport deposits, suggesting gravitationally unstable conditions most likely associated with a location on the base of a prograding slope. These slope channel complexes exhibit different styles (leveed, weakly confined and erosional), but regardless of kind they are typically composed of several vertically-stacked channels filled with thick, highly amalgamated pebble conglomerate and coarser grained sandstone.

Therefore, observations in the SBFT at Castle Creek should provide important new insights into the stratigraphic nature and evolution of basin floor and slope transition, which then can be applied to understanding the internal stratal geometries within some deep-water reservoirs (e.g. Amazon, Gulf of Mexico and West Africa fans).

## MIDDLE AND LATE ORDOVICIAN STROMATOLITES IN THE TACONIC FORELAND BASIN (OTTAWA EMBAYMENT): STRATIGRAPHIC MARKERS OF REGIONAL FLOODING AND ENVIRONMENTAL CHANGE

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Within the foreland basin succession in the Ottawa Embayment, stromatolites are prominent only within two stratigraphic intervals that occur in the Middle Ordovician Carillon and Upper Ordovician Pamela formations. They document abundant microbial growth coincident with prominent regional flooding events and major backstepping of the coastal margin of the Ottawa Embayment. In both formations, stromatolites form 1-1.2 m thick beds, and possess a densely packed organization of stratiform, domal, nodular and laterally linked hemispheroidal geometries. The microfabric architecture includes light and dark laminar couplets that consist of the following components: 1) light laminae of microspar or clotted micrite with microspar that grades up into 2) dark clotted micrite. Some Carillon stromatolites show well defined lamination with darker more clay-rich laminae that alternate with lighter, coarser laminae and no microbial structures. These have filament molds and microbial clots that occur sporadically at 1-4mm intervals, and are associated with iron-stained exposure surfaces. There is no evidence of macrofossils that co-existed with the stromatolite biofacies in either formation. Stable isotope (C, O) data from Pamela stromatolites are as follows:  $\delta^{18}\text{O}_{\text{PDB}} = -9.9$  to  $-5.8\text{‰}$ , and  $\delta^{13}\text{C}_{\text{PDB}} = -6.7$  to  $-4.0\text{‰}$ . The light microspar laminae represent an alteration fabric, and this is supported by the negative displacement of  $\delta^{18}\text{O}$  relative to Late Ordovician marine  $\delta^{18}\text{O}_{\text{calcite}}$ . In contrast,  $\delta^{18}\text{O}$  values from dark clotted micrite within the Carillon stromatolites fall within the expected range of marine dolomite,  $-4.3$  to  $-3.9\text{‰}$ , but have  $\delta^{13}\text{C}_{\text{PDB}}$  values ( $-6.6$  to  $-6.3\text{‰}$ ), like those of the lower Pamela stromatolites, that are more negative than a marine source of bicarbonate. The carbon isotope data suggest that there was a 50:50 mixture of marine and diagenetic sources of bicarbonate, the latter dominated by bacterially mediated sulphate reduction which produces an expected initial composition for bicarbonate of  $\sim 15\text{‰}$ . The Pamela and Carillon stromatolites form the only prominent microbial intervals within the foreland basin succession. Although their formation clearly follows regional subsidence across the Ottawa Embayment, the anomalous abundance immediately following these events may be connected to otherwise inhospitable environmental conditions linked to recycling of coastal margin sediments along the leading edge of the transgression.

## MINERALOGY AND TEXTURES OF Cu-Ni-PGE-RICH MINERALISATION IN THE MORRISON (LEVACK FOOTWALL) DEPOSIT, SUDBURY, ONTARIO

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The Morrison deposit is a footwall-type Cu-Ni-PGE deposit that cuts through a zone of Sudbury breccia in the Archean Levack Gneiss Complex beneath the North Range of the Sudbury Igneous Complex. It consists of sharp-walled veins that are enriched in Cu-Pt-Pd-Au relative to contact-type mineralisation. The Morrison deposit can be subdivided into a pyrrhotite-rich upper domain, a chalcopyrite-rich lower domain, and a transitional domain based on vein geochemistry, mineralogy, texture, and morphology. All domains contain i) steeply to vertically dipping first-order (trunk) sulphide veins, ii) irregular and discontinuous second-order sulphide veins, and iii) disseminated sulphides in the country rocks. First- and second-order veins can be further subdivided into a) inclusion-free veins typically within Sudbury breccia matrix or

along clast-matrix boundaries, and b) very irregular and inclusion-rich veins associated with leucosomes in mafic gneiss clasts and granophyric textured dikes. Disseminated mineralisation generally occurs in felsic domains (felsic gneisses, leucosomes, granophyric dikes) adjacent to first- and second-order veins. First-order veins in the upper domain are thinner (less than 1.5m) and richer in pyrrhotite with lesser pentlandite, chalcopyrite, magnetite, and pyrite. Second-order veins in this domain are, on average, slightly more chalcopyrite rich than first-order veins and both vein types become more chalcopyrite rich with depth. These veins contain metal tenors of 0.2-5 wt% Cu, 4-7 wt% Ni, 0.1-5g/t Pd and 0.1-5g/t Pt. First-order veins in the lower domain are thicker (up to 5m) and contain chalcopyrite, cubanite, pentlandite, and pyrrhotite with lesser magnetite and sphalerite. Second-order veins have variable mineralogy and may be composed primarily of chalcopyrite, pentlandite  $\pm$  chalcopyrite, millerite  $\pm$  chalcopyrite and/or bornite, or bornite. The metal tenors of the first order veins are 20-35 wt% Cu, 0.1-10 wt% Ni, 0.5-50g/t Pd and 0.2-20g/t Pt. The transitional domain contains veins that contain pyrrhotite and chalcopyrite in fairly equal proportions with lesser pentlandite, cubanite, sphalerite and magnetite. The metal tenors of this domain are 5-20 wt% Cu, 0.1-10 wt% Ni, 0.5-5 g/t Pd and 0.2-5 g/t Pt. The distributions of Ni, Cu, and PGEs at the Morrison Deposit are broadly consistent with fractional crystallisation and segregation of MSS followed by ISS from a sulphide liquid. The upper domain consists dominantly of an MSS cumulate, the transitional domain consists of an MSS and ISS cumulate, and the lower domain consists of an ISS cumulate along with other products that formed from the residual liquid left from the crystallisation of ISS.

#### MINERALOGICAL DIVERSITY OF THE INTRUSIVE METACARBONATIC ROCKS FROM ITATUBA, NORTHEASTERN BRAZIL

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At the Itatuba region geological mapping has detailed an intriguing ellipsoidal structure and the abundance of igneous rocks. In this region the following geological units occur: (i) a core of hornblende-biotite-bearing augen gneiss (Salvador Unit; SHRIMP U-Pb zircon age of 2.3 Ga, and model age (TDM Nd) of 2,285 Ma), and a tonalitic-banded migmatitic complex, which is widely distributed in the region (Floresta Complex; U-Pb zircon ages ranging from 2.4 to 2.15 Ga), and include restricted intercalations of garnet-biotite paragneisses; (ii) intrusive rocks related to different magmatic pulses comprising metagabbro-dioritic (retroeclogites) and metatrandjemitic (SHRIMP U-Pb zircon ages of 2,086 Ma and 1,953 Ma; model age of 1,999 Ma) rocks; and (iii) late intrusive rocks of minor occurrence comprising meta-alkali granites (Fe-hastingsite and biotite), metasyenogranites (including riebeckite-garnet-muscovite-bearing ones; SHRIMP and TIMS U-Pb zircon ages from 621 to 549 Ma) and metacarbonatic rocks, which have metalamprophyres (Ti-augite-barkevikite-kaersutite) and skarns associated.

The metacarbonatic rocks formed small (less than 3 km<sup>2</sup>), and round- to lenticular-shaped bodies. They range from massive to brecciated facies, and some bodies present features similar to pyroclastic rocks. The brecciated facies shows abundant rock (xenoliths) and mineral (xenocrystals) fragments that are round to angular shaped and have size varying from micrometric to metric scale. The xenocrystals are composed of microcline, plagioclase, augite-diopside and hornblende, while the xenoliths consist of

metagranites, metatonalites and metamafic-ultramafic rocks. The occurrence of nodules and xenoliths of pyroxene, hornfels, fluid-flow structure, and the interstitial texture of the carbonatic matrix between angular xenoliths, denote the intrusive character of these rocks. REE geochemistry and C-O isotope data preclude a pure mantle source for these rocks, but the association with felsic and mafic alkaline rocks suggests some minor juvenile component in the formation of the them (linear carbonatites of mobile belts?). Similar examples occur worldwide, such as in the Grenvillian Oaxacan terrane (Mexico), in the Hymalayan syntaxis, in the Eastern Ghats (India), and in the Panafrican belt of the eastern desert of the Egypt and Sudan.

Optical microscopy, EMP, and SEM-WDS analyses reveal that these metacarbonatic rocks are mainly composed of calcite (45-80 vol.%; magnesian, and locally pink-colored), diopside + augite (5-30 vol.%), hornblende + Mg-hastingsite + Fe-hastingsite (<10 vol.%), and olivine (0-10 vol.%). Apatite, Cr-bearing spinel (light blue colored), titanite, allanite, ilmenite, Ba-V-bearing rutile, and scapolite are common accessory minerals. Occasional Ti-clinohumite (reddish brown colored; olivine pseudomorphs), phlogopite, and riebeckite also occur.

#### RADIOLOGICAL PROPERTIES OF GROUNDWATER FROM TWO URANIFEROUS REGIONS OF IBERIA: NISA (PORTUGAL) AND CIUDAD RODRIGO (SPAIN)

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Uranium, radium and radon concentrations in groundwater were investigated in two uraniferous regions of Western Iberia, Nisa (Portugal) and Ciudad Rodrigo (Spain). The two regions differ by the fact that several ore deposits were exploited in the past in the area of Ciudad Rodrigo, while in the Nisa sector the presence of important uranium ores were recognized but exploitation did not occur. The typology of the mineralization is similar in both regions, being mainly composed by secondary uranium minerals associated with breccia fillings (e.g. autunite, torbernite, saleite), located at shallow depth (<50 m). The most important deposits are related to pelitic levels of the Precambrian-Cambrian complex of schists and graywackes that are present in both regions, always in the close vicinity of late Hercynian granites. Smaller deposits can also be found within granites, associated with fault filling materials.

In this study we have investigated the radiological properties of groundwater from both referred regions, including the locations of the ore deposits and a large surrounding area of several km<sup>2</sup>. Analyses were carried out by liquid scintillation spectrometry, using a Perkin Elmer Quantulus 1220 equipment available at the Laboratory of Natural Radioactivity of the University of Coimbra. A total of 32 representative samples were studied, most with percolation in schists and greywackes in the case of Ciudad Rodrigo (n=13), and in granites in the case of Nisa (n=19).

<sup>226</sup>Ra and <sup>222</sup>Rn show higher average activities in the region of Nisa relatively to Ciudad Rodrigo, with 0.042 versus 0.015 Bq·l<sup>-1</sup> and 908 versus 381 Bq·l<sup>-1</sup>, respectively. Total uranium concentrations in the groundwater is slightly higher in the Salamanca region, with 9.0 ppb versus 7.3 ppb, but the average result in the first case is influenced by a single sample with a very high U concentration (32.9 ppb). <sup>234</sup>U/<sup>238</sup>U ratios are similar in both regions and close to the unit (0.93 and 0.91), showing the maintenance of isotopic equilibrium. According to the transfer coefficients defined by the International Commission on Radiological Protection and the average radionuclide concentration observed in both regions, we estimate an annual average dose for the population resulting from the water consumption of 0.015 mSv for Nisa and 0.009 mSv for Ciudad Rodrigo.

We conclude from the results that natural weathering and leaching of surficial uranium ores can be a more effective process of radionuclide transfer to the environment than mining works under similar geological conditions.

#### **THECAMOEBIANS AS AN INDICATOR OF PALEOLIMNOLOGIC CHANGE IN MEROMICTIC PINK LAKE, GATINEAU PARK, QUEBEC**

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Thecamoebians (testate amoebae) are known to be useful paleolimnological indicators of various parameters including pH, nutrient loading, oxygen concentration, salinity and metal contamination. We used thecamoebians to characterize climatic and paleolimnological trends and cycles archived in sediments from meromictic Pink Lake, Gatineau Park, Quebec. A 745 cm Livingstone core was recovered from a shallow part of the lake currently above the thermocline. A sand and shell lag deposit below 680 cm (~13,500 cal y BP) and overlying clay were deposited when the isostatically depressed basin was part of the Champlain Sea. Transition to a freshwater basin began ~11,800 cal y. BP as organic rich gyttja began to gradually replace clays, as isostatic rebound isolated the lake basin from the retreating Champlain Sea. A diverse fauna of thecamoebians (average Shannon Diversity Index (SDI)=2.02) suddenly appeared in the core at 590 cm (~10,000 cal y BP). Most of the species, including several Diffugia species (e.g. strains of *D. oblonga* and *D. urceolata*) are not tolerant of brackish conditions, indicating that the lake basin was entirely fresh and oligotrophic by this stage. The sudden appearance of a fully developed fauna of thecamoebians in Pink Lake is probably due to chance avian transport. Above the 500 cm core interval (~7500 cal y BP) the fauna became progressively stressed (average SDI=1.19) and dominated by generalist taxa such as *Arcella vulgaris* and various centropoid species, especially *C. aculeata* 'discoides'. Water depth in the lake basin may have become deeper and the site of the core may have moved closer to the paleothermocline, which would have impacted productivity amongst the primarily benthic thecamoebians. Gytja deposition was interrupted at 255 cm (5500 cal y BP) by the appearance of a marl unit, the domination of the eutrophic indicator species *Cucurbitella tricuspidis*, and greater diversity, suggesting the temporary onset of higher productivity in a shallower and warmer water basin, coeval with the Holocene Hypsithermal. Following a return to a stressed thecamoebian fauna there was a gradual increase in thecamoebian fauna beginning at 150 cm (~3200 cal y BP) suggesting that water depth in this part of Pink Lake was now permanently well above the thermocline. The development of a very diverse thecamoebian fauna characteristic of eutrophic conditions through the upper few cm of the core corresponds to increased run-off as the area around the lake was cleared for settlement beginning in A.D. 1826 by the Pink family.

#### **GEOLOGICAL SETTING AND MINERAL CHEMISTRY OF THE MBALAM IRON ORE PROJECT, NORTHERN EDGE OF THE CONGO CRATON, SOUTHEAST CAMEROON**

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The Mbalam iron ore deposit, southeastern Cameroon is located to the northern edge of the Congo craton, a region previously unexplored for iron ore mineralisation. Exploration works by various companies in this region to date have focused on Archean-Proterozoic itabirite host rocks of the Congo craton and indicates the potential for a world class iron ore region with high grade (>60% Fe) iron ore deposit. The protolith of the high-grade hematite rock is an itabirite (BIF) rock. The Mbalam deposit is delimited by a series of NE-SW to N-S trending faults that truncated a roughly E-W-striking isoclinal fold structure.

Previous studies in this area have focused on the tectonic evolution of the area (Toteu et al., 1994; Ngako et al., 2004; Milesi et al., 2006; Toteu et al., 2006; Ngako et al., 2008; Suh et al., 2008), with little to the economic potential of the iron ore deposit. This paper presents the geological setting of the Mbalam iron ore deposit as baseline information into the potential world class iron ore province as well as the chemistry and mineralogical characterization of the supergene modified iron ore deposit.

The itabirite of Mbalam vary in character along strike with generally very steep dips. The itabirite equally shows great variation in the thickness of alternating quartz-rich and Fe-rich layering and in overall Fe content. The variations are due in part to primary depositional features and partly to the intense deformation and metamorphism. The layering varies from sub-mm fine laminations to cm scale. High grade enriched soft laminated (biscuity) supergene ore (Fig. 4) at Mbalam are limited or related to a very well defined plateau with deep soil and areas of laterite development. Enrichment of iron ore in this area follows the principal NE-SW structural corridor which can extend for more than 8km. The hard hematite is a late epigenetic type of mineralisation which forms flat-lying to gently north dipping veins up to 10m thick or more that follow low angle brittle south-verging thrust faults. Folds are tight to isoclinal that have been refolded by a later generation folds.

Sundance Resources Ltd confirmed extensive supergene mineralisation from surface to drill depths averaging around 50 m and inferred mineral resource of direct shipment ore (DSO) quality hematite at the Mbarga and Mbarga South Deposits to a tune total 220 million tonnes at an average grade of 60.1% Fe with 0.09% P.

#### **ARSENIC DISTRIBUTION AND SPECIATION IN APPALACHIAN SERPENTINITES IN NORTHERN VERMONT, USA**

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High concentrations of As in ground waters are noted in many parts of New England (Ayotte et al., 2003). Previous work by Ryan et al. (2009) documented that serpentinites in northern Vermont contain high As, up to 449 ppm. We selected representative samples of serpentinite and examined the distribution and speciation of As in the samples. The serpentinites are composed of serpentine with minor Cr-spinal, magnetite, and carbonates. The XRD spectra



of the samples show that antigorite is the serpentine phase. Carbonate minerals are magnesite and dolomite with very minor calcite. Cr-spinel grains are variably altered to ferritchromite and magnetite in their rims. Samples are separated into a magnetic fraction and a non-magnetic, serpentine-rich fraction. Leaching of a serpentine-rich fraction with  $\text{NaH}_2\text{PO}_4$  (0.1M) yielded As, which is less than 10% of the total As recovered by hot  $\text{HF}/\text{HNO}_3$ . The data suggest that As is mostly incorporated in the crystal structure of antigorite. This is further confirmed by the quantitative analysis of minerals using an electron microprobe. Antigorite contains variable, but high concentrations of As, up to 1300 ppm. X-ray absorption spectra at As K-edge show that As is +3. Local atomic structures around As are calculated based on the EXAFS spectra. The results show that the coordination number of As is 4.0 and that the atomic distances are  $1.778 \pm 0.009$  Å between As and O,  $3.196 \pm 0.070$  Å between As and Si, and  $3.4875 \pm 0.032$  Å between As and Mg. The data suggest that As replaces Si in the tetrahedral site of antigorite.

Earlier study of serpentinites in north western Himalayas suggested that As is +5 replacing Si in antigorite (Hattori et al., 2005). The data from the two locations suggest that antigorite is capable to incorporate As (+3) and As (+5) into its tetrahedral site.

#### **ARSENIC DISTRIBUTION AND SPECIATION IN APPALACHIAN SERPENTINITES IN NORTHERN VERMONT, USA**

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#### **MINERALOGY AND ABUNDANCE OF PLATINUM-GROUP ELEMENTS IN ALKALINE Cu-Au PORPHYRY DEPOSITS IN BRITISH COLUMBIA: A RECONNAISSANCE STUDY**

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WITHDRAWN

#### **INFLUENCE OF INTERACTIVE MICROBIAL HETEROTROPHIC AND CHEMOTROPHIC IRON REDUCTION ON FE LEACHING FROM MINE HYDROMETALLURGICAL RESIDUES**

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Hydrometallurgical processing of sulfide-rich mineral ores is a highly efficient method for extraction of base metals, such as nickel. The waste product of hydrometallurgy is a hematite- and elemental sulfur-rich residue that must be contained and managed to meet environmental standards. Disposal of these residues can lead to acidity generation and release of soluble  $\text{Fe}^{2+}$  causing concern for wastewater treatment management and environmental contamination. Complex organic additives used in the processing of the ores as well as carbonates and gypsum added post-processing remain in the residues which in addition to iron and sulfur sub-

strates provide energy for diverse microbial metabolisms that influence the residue geochemistry. Specifically, there is the possibility of heterotrophic iron reduction as well as chemotrophic sulfur oxidation using ferric iron as the terminal electron acceptor with both processes generating  $\text{Fe}^{2+}$ . The objective of this study was to determine the microbial metabolic pathways and the organisms involved in  $\text{Fe}^{2+}$  leaching from hydrometallurgical residues. Laboratory enrichments of 3 depth-slices of 3 residue core samples has demonstrated the widespread presence in the residues of aerobic and anaerobic iron reducing prokaryotes (IRP) as well as anaerobic sulfur oxidizing prokaryotes respiring ferric iron (SoxP). Sulfate-reducing prokaryotes (SRP) were not determined to be a major component of the microbial community, indicating that capture of  $\text{Fe}^{2+}$  by precipitation as iron sulfide is unlikely. Sequencing of the  $^{16}\text{S}$  rRNA genes of environmental and enrichment DNA has revealed the metabolically-relevant species. Batch experiments using sterilized residues were set up under 4 microbial experimental treatments: 1) aerobic IRP; 2) anaerobic IRP; 3) layered aerobic IRP, anaerobic IRP and anaerobic SoxP and 4) a sterile abiotic control. Porewater [ $\text{Fe}^{2+}$ ], pH,  $\text{O}_2$ , and  $\text{Fe}^{2+}/\text{Fe}^{3+}$  of the overlying water (sterile residue pond water) and microbial community dynamics were tracked for greater than 2 weeks. The combined geochemical and microbial results suggest that highly dynamic and potentially linked microbial iron and sulfur processes are the likely cause of elevated  $\text{Fe}^{2+}$  concentrations. These results will be presented highlighting the importance of identifying the linkages between geochemistry and interactions within the microbial community in order to better understand environmental processes.

#### **DRIFT PROSPECTING APPLIED TO IRON OXIDE COPPER GOLD EXPLORATION IN THE GREAT BEAR MAGMATIC ZONE, NORTHWEST TERRITORIES, CANADA**

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As part of Canada's Geomapping for Energy and Minerals (GEM) Program, an applied Quaternary research activity under the IOCG-Great Bear Project was undertaken in the Great Bear magmatic zone (GBMZ) to provide a practical guide to geochemical and indicator mineral exploration for iron oxide copper-gold (IOCG) deposits in glaciated terrain. Initial work completed in 2007 consisted of an orientation study around the NICO Co-Au-Bi deposit, interpreted as a magnetite-group IOCG deposit.

During subsequent field work in 2009 and 2010, detailed sampling was completed in the vicinity of the Sue-Dianne Cu-Ag-Au hematite-group IOCG deposit and near additional showings thought to be part of large polymetallic IOCG systems within an IOCG-porphyry-epithermal continuum across the GBMZ. Bedrock (n=111) and till (n=102) samples were collected up-ice, proximal to, and down-ice from mineralization, hydrothermally altered host rocks and least altered bedrocks. The physical properties and the minor and trace element composition of non-ferromagnetic indicator minerals and the till matrix geochemistry will be used to evaluate the degree of preservation of diagnostic IOCG deposit mineralization or alteration signatures in glacial sediments.

Preliminary results indicate the presence of chalcopyrite, apatite, pyrrhotite, andradite, Mn-epidote, bornite, allanite, ferroactinolite, fluorite and gold in various concentrations within the indicator mineral fraction (0.25-2 mm; SG>3.2). Surface bedrock

samples collected at the Sue-Dianne deposit contain chalcopyrite, malachite, bornite, allanite, gold and hematite/magnetite. Till collected over or immediately down-ice of Sue-Dianne contains apatite and tourmaline grains, while gold, chalcopyrite, gahnite and Mn-epidote are present in lower concentrations. SEM examination revealed trace amounts of iron oxides as inclusions and/or fracture filling in gahnite, apatite, tourmaline and andradite grains (0.25-0.5 mm) from till samples collected down-ice of Sue-Dianne and other showings. Some chalcopyrite grains (0.25-1 mm) are found in association with specular hematite suggesting leads for the identification of IOCG signatures in indicator minerals. Future work include further examination of selected grains, electron microprobe analysis and LA-ICP-MS analysis.

#### **EVALUATING HYDROTHERMAL ALTERATION TYPES ASSOCIATED WITH THE SARKUH PORPHYRY COPPER DEPOSIT, IRAN**

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Sarkuh porphyry copper deposit is located at 6 km southwest of the Sar-Cheshmeh Cu mine, Kerman province, Iran. In this area, the Eocene volcano-sedimentary complex is intruded by Oligo-Miocene granodiorite, granite, diorite and quartzdiorite stocks. Field and petrographic observations show that quartzdiorite is responsible for the mineralization, alteration and construction of porphyry system in the Sarkuh. Four alteration types associated with the quartzdiorite intrusion are potassic, propylitic, phyllic and argillic. Potassic alteration occurs in the central parts of stock and propylitic alteration in its periphery and the surrounding volcanic rocks.

The highest grades of Cu ore are limited to the potassic alteration zone. Fluid inclusion studies on mineralized quartz veins indicate that potassic alteration has originated from a high temperature (~400°C) magmatic fluid with high salinity (30-50 wt% NaCl equiv). Propylitic alteration which occurred simultaneously with potassic alteration but in the peripheral of stock, originated from meteoric waters having low salinity (<10 wt% NaCl equiv) and temperature (~200°C). The meteoric water which subsequently penetrated into the internal parts of stock along a network of late fractures mixed with magmatic water and produced a hydrothermal fluid with salinity ranging from 10 to 15 wt.% NaCl equiv. This fluid produced limited phyllic and argillic alteration in the Sarkuh porphyry copper deposit.

#### **ANATOMY OF THE HIGHLY METAMORPHOSED IZOK LAKE VHMS DEPOSIT, NUNAVUT TERRITORY**

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The Izok Lake deposit in the Archean Point Lake greenstone belt, Slave Province, represents one of the largest undeveloped volcanic-hosted massive sulfide deposits in North America. The deposit comprises a measured and indicated resource of 14.8 Mt grading 12.8% Zn, 2.5% Cu, 1.3% Pb, and 71 g/t Ag. A new research project aiming at better understanding the anatomy of the deposit has been initiated to support ongoing exploration at Izok Lake. Amphibolites facies metamorphism and localized intense deformation have so far limited reconstruction of the volcanic stratigraphy and the geometry of the massive sulfides.

Deformation at Izok Lake was heterogeneous with strain partitioned into the hydrothermal alteration halo enveloping the massive sulfide mineralization. Preservation of primary volcanic textures in less altered zones allows details on the deposit genesis to be revealed. Volcanic facies analysis has shown that the strati-

graphic footwall of the deposit is dominated by aphyric rhyolite that was likely emplaced as domes, lava flows, or shallow intrusions. The occurrence of in situ monomict rhyolite breccia, clast-rotated equivalents, and stratified monomict rhyolite breccia along the margins of individual rhyolite units suggests that quench fragmentation and autobrecciation were important clast-forming processes. Sulfide infiltration of the matrix surrounding clasts in the rhyolite breccia and the preservation of rhyolite clasts within massive sulfides suggest that the mineralization may, at least in part, have formed by subseafloor replacement processes within a felsic volcanic succession. The immediate hanging wall of the deposit is dominated by less intensely altered coherent andesite, minor aphyric rhyolite and an extensive gabbroic sill and dike complex. Deposit formation must have broadly coincided with a shift from felsic to more mafic volcanism.

A semi-coherent zoning in metamorphic mineral assemblages is preserved in the footwall to the deposit. The distal portion of the footwall alteration halo is characterized by quartz-rich, muscovite-poor schist, representing metamorphosed silicified rhyolite. Closer to the massive sulfide mineralization, muscovite increases in abundance and small intergrowths of sillimanite and muscovite become prevalent. This mineral assemblage probably represents the metamorphic equivalent of the former sericite alteration halo. With increasing proximity to ore, biotite and porphyroblastic garnet occur within a zone interpreted to have originally been dominated by chlorite. The findings of the present study suggest that a direct correlation between metamorphic mineral assemblages and primary hydrothermal alteration zones is possible.

#### GLOBAL GEOPARKS: A NEW REALITY IN CANADA

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Canada is fortunate to have a wide array of national and provincial parks as well as other kinds of protected areas. Typically they protect large areas of provincial and federal land. A new idea for protected areas that arose in China and Europe has developed rapidly over the last decade: the concept of a Global Geopark. A Global Geopark is a territory with geological heritage of international significance and a sustainable development and public education strategy. There may be several sites within a Global Geopark; each must have international significance in terms of scientific quality, rarity, and aesthetic appeal, and they should also be related to aspects of archaeology, ecology, history and culture. Geoparks embrace geological history and its influence on the history, culture and economic development in the territory. A geopark is developed with the specific aims of sustainable economic development based on geotourism and public education within the territory.

Canada has North America's first Global Geopark based on a territory in southern New Brunswick encompassing the City of Saint John and surrounding towns and villages. It is called the Stonehammer Geopark and it embraces a billion years of Earth history from Proterozoic to Quaternary/Neogene, with outcrops representing all periods except the Jurassic. It also embraces the important role played in the early history of Earth science by residents of the Saint John area and the key link of its late nineteenth century historic stone buildings to local quarries. It was approved in October 2010 and is now developing rapidly as a major site for geotourism and public education, serving tourists (including 200,000 cruise ship visitors annually) and local residents. It is one of 77 Global Geoparks in the world.

The sites in the area that are first to be developed as Stonehammer attractions include Reversing Rapids where the tidal effects and a major terrane boundary are interpreted, as well as the early history of the fishing industry. Some sites are accessible by

water and a company operates kayak tours under the Stonehammer banner that include a visit to the first-ever described Precambrian life (George Matthew's stromatolites). Other key sites include the New Brunswick Museum, Fundy Trail Parkway, Irving Nature Park, Lepreau Falls, Rockwood Park, a proposed fossil forest interpretive centre in the village of Norton. Each of these sites will develop geotourism and educational opportunities under the banner of the Stonehammer Geopark.

#### GEOVISTAS: A PROJECT FOCUSED ON THE DEVELOPMENT OF ENHANCED GEOLOGICAL INTERPRETATION AND EDUCATION IN CANADA'S PARKS

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As part of the International Year of Planet Earth program of activities in Canada, a project proposal for interpretive brochures of iconic views in national parks received funding from the Canadian Geological Foundation in 2009. The project, a partnership with Parks Canada and other organizations, is based in Jasper National Park in Alberta and Grasslands National Park in Saskatchewan. The interpretive brochures will be available to park visitors from tourist information centres and will also be downloadable from suitable web sites. Individual Geovistas brochures will consist of a colour photograph of a vista, a GPS location for the view and instructions on how to get there, a succinct summary of the geology and geological processes exhibited, and their environmental and cultural implications, illustrated with additional graphics as required.

The content for a series of eight brochures featuring views in Jasper National Park has been produced. These views are readily accessible to all visitors and include the following sites: Disaster Point, Jasper Lake, Cold Sulphur Spring, Old Fort Point, Maligne Canyon, Maligne Lake and Athabasca Glacier. The sites represent a broad cross section of geological features offering insights into local tectonics, ephemeral lakes and dunes, mineral springs, glacial geomorphology and processes, cave systems, erosion and rockslides. The text has been developed by Ben Gadd, a well known local author and geologist, under the guidance of the overall Geovistas Project. Up to three brochures are being developed for Grasslands National Park and the sites interpreted will include two in the vicinity of a Cretaceous – Tertiary boundary locality in the East Block badlands and one site in the West Block.

The content of these brochures will contribute to additional educational resources linking the geology, landscape, ecology, history, culture, and regional economy in both parks. The Jasper Geovistas will be part of the Environmental Stewardship curriculum at the Palisades Stewardship Education Centre in Jasper, thus ensuring a broadening of geological knowledge among interpreters.

The principal target audience includes teachers and students, tourists (local, national and international), local residents and park staff members.

This project is envisaged as a pilot project for which a Geovistas brochure template is developed that can be used by others wishing to explain geological features in an environmental, ecological and cultural context in national, provincial and other kinds of protected places across Canada.

# REDOX-SENSITIVE METAL SYSTEMATICS IN BLACK SHALE OF THE BASINAL ASSEMBLAGE OF THE NEOPROTEROZOIC LITTLE DAL GROUP, MACKENZIE MOUNTAINS SUPERGROUP, NWT

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The Neoproterozoic is arguably one of the most interesting and elusive intervals in Earth history. It witnessed a series of planetary scale glaciations, the first occurrences of preserved complex life forms, rapid changes in oceanic redox conditions, and complex rearrangement of continental plates. Critical for a better understanding of this complicated series of events is a better understanding of open-ocean conditions in the lead-up to the first glaciation, which witnessed a return to a ferruginous ocean and concomitant deposition of banded iron formation.

This work presents the first detailed geochemical study of black shale of the Basinal assemblage of the Little Dal Group (Mackenzie Mountains supergroup; <1083 Ma, >779 Ma). The group was deposited in a subtly and erratically extensional epicratonic basin and underlies deposits of the first Neoproterozoic glaciation (Rapitan Group). The Basinal assemblage consists of about 500 m of dark shale and carbonate mudstone. Truly black shale is rare in the Neoproterozoic of the Mackenzie Mountains, and the black shale of the Basinal assemblage is of limited aerial and stratigraphic extent.

Thirty-five samples from Basinal assemblage black shale were examined for their major and ultra-trace element chemistry as well as a detailed analysis of reactive Fe, total S and C, and carbonate C. The redox-sensitive trace elements are very well behaved in these black shales and show strong positive correlations in enrichment factors. Authigenic redox-sensitive metal enrichment is related to reactive Fe content and consistent with sulfidic (euxinic) bottom water conditions. The extent of Mo enrichment (< 10 ppm) is limited and in very good agreement with data for Mesoproterozoic black shales, and much lower than in Paleozoic black shales (typically > 100 ppm Mo).

The new data confirm that the sulfidic Neoproterozoic ocean had a much lower Mo concentration than the Paleozoic ocean either because Mo from continental run-off was continuously removed into an ocean-wide blanket of black shale, or because the supply of Mo into the Proterozoic ocean was limited for an as-yet unexplained reason.

## GEOCHEMISTRY AND PETROGENESIS OF THE ABU KHURUQ RING COMPLEX, EASTERN DESERT, EGYPT: A CASE STUDY FROM THE LATE CRETACEOUS ALKALINE MAGMATISM OF NE AFRICA

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The Late-Cretaceous rocks of the Abu Khuruq ring complex (AKRC) of the south Eastern Desert, Egypt, comprise phonolite, trachyte, syenogabbro, essexite, quartz syenite, alkali syenite and nepheline syenite as well as quartz- and nepheline-bearing pegmatites. The rocks of the complex are dominantly of metaluminous affinity and show enrichment in both large ion lithophile (LIL) and high field strength (HFS) elements with lack of negative Nb anomaly in their normalized rare-earth element (REE) patterns. Silica-undersaturated and saturated rocks of the AKRC have high LREE content relative to HREE and show weak to steep fractionated REE patterns  $[(La/Yb)_n = 5.56-18.58]$  and display the geochemical characteristics of A-type suites generated in rift-related tectonic environments. The syenogabbros display REE patterns  $[(La/Yb)_n = 11.8-14.20]$  that do not differ significantly from those

of the essexite rocks and essexitic xenoliths found in the nepheline syenites  $[(La/Yb)_n = 15.55-18.58]$  and  $[(La/Yb)_n = 11.98-13.70]$ , respectively]. The syenogabbros however have relatively weak fractionated HREE patterns  $[(Gd/Yb)_n = 2.98-3.69]$  and low  $(Yb)_n$  and  $(Lu)_n$  values (< 10) with the absence of a Eu anomaly. The syenogabbros ( $MgO\% < 3\%$ ,  $Cr_2O_3\% < 0.002\%$  and  $Ni < 20$  ppm) do not represent a primitive mantle-derived magma and could be formed by fractional crystallization of a primary basaltic magma. The syenogabbro melt was further crystallized to yield the more evolved essexites through the dominant removal of plagioclase and Ca-pyroxene.

The silica-undersaturated intermediate rocks of AKRC (i.e. phonolite, alkali syenite and nepheline syenite) show uniform trace element and REE patterns  $[(La/Yb)_n = 10.75-14.17]$ , with no real change in LILE and HFSE and selective negative Ba, Sr, Ti and Eu anomalies. The trachytes have low MgO and CaO contents relative to the phonolites and their normalized-trace element and REE patterns are quite similar. The geochemistry and petrological characteristics of the phonolites and nepheline syenites suggest comagmatic relationships and they may have formed from an essexitic melt by subsequent simple fractional crystallization processes. The quartz syenites exhibit moderately fractionated REE patterns  $[(La/Yb)_n = 9.32-14.37]$  with a negative to nearly positive Eu anomaly  $[(Eu/Eu^*)_n = 0.51-1.13]$ . These rocks could represent the primary nepheline syenitic magma in the complex and their geochemical signature was likely modified by crustal contamination.

## MINERALOGICAL TRANSITION FROM BIOTITE TO KAOLINITE DURING WEATHERING: EVIDENCE FROM THREE WEATHERING PROFILES OF DIFFERING AGES FROM THE SOUTH MOUNTAIN BATHOLITH, NOVA SCOTIA

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The end product of biotite weathering is typically kaolinite. However, in the process of weathering to kaolinite, a number of transition or intermediate phases are commonly found. In Nova Scotia, three distinctly different ages of weathering have been identified on the Devonian-aged South Mountain Batholith: Pre-Carboniferous, Pre-Jurassic, and Pre-Quaternary. In addition to stratigraphic, geochemical, and textural differences, biotite crystals in these three profiles exhibit significant differences in the intermediate phases and their textural development and indeed, in some cases, in the trace element content of the kaolinite end-product. The breakdown of biotite during the Pre-Carboniferous weathering event resulted in the retention of Ti in oxides in the immediate area, defining the cleavage and borders of the original biotite in some cases. The initial breakdown products of biotite in the Pre-Carboniferous profile shows an increase in Fe-Mg-Mn and Al, and a concomitant decrease in Si with increased weathering. Weathering of the biotites during the Pre-Pleistocene resulted in the loss of K and slight loss of  $Fe^{2+}$  (tot), similar to that of the Pre-Jurassic, however the proportion of  $Fe^{2+}$  (tot) lost relative to K is considerably less in the Pre-Pleistocene, and the increase in total  $SiO_2$  relative to  $K_2O$  is minimal in the Pre-Pleistocene, unlike the relative  $SiO_2$  enrichment in the Pre-Triassic samples. It is proposed that intense weathering conditions prevailed during Pre-Carboniferous times, prior to Nova Scotia moving from a warm-temperate climate to more arid conditions, as evidenced by the development of redbeds with granite-derived uranium deposits. Intense, but with seasonal arid conditions prevailed during Pre-Jurassic times, whereas Pre-Pleistocene weathering reflects a moderate weathering event in which the climate was likely temperate but warmer than today, either during Aptian-Albian times, or in the early

Eocene. The biotite had the same original chemistry in all three profiles, however the series of breakdown products is distinctive to each weathering episode. Alteration sequences within each of the three profiles indicate that although all have kaolinite as a common end product, the intermediate products reflect environments prevailing during the weathering process itself, and are recorded by changes in the relative proportions of cations. Microprobe spot analysis, combined with XRD and X-ray mapping provide a more complete picture of the breakdown process in biotite, than does XRD alone.

#### **DEVELOPING RESEARCH SKILLS IN THE UNDERGRADUATE YEARS FOR ALL STUDENTS: A TALE FROM TWO CONTINENTS**

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How do we do research in earth sciences? Certainly not the clean way we report it, or at least, not in the order in which we report it. Most of us have learned research skills by persevering in response to our natural curiosity, and if we were lucky, by having a mentor at some point in our learning careers. If undergraduates are fortunate, they may have summer research scholarships or employment in a research setting, or they may have to find out the hard way when they undertake an honours thesis. However, not all students are exposed to these particular pathways. The skills students develop as they learn the techniques and processes of research are valuable research skills, but they are also valuable job-related skills, and every student should be exposed to numerous opportunities to learn these techniques and skills. In working with third year students on an authentic research project a couple of years ago, one in which the students undertook original research, I learned a number of things: (1) we may assume that students know how to read technical text-if they can't, we may assume it is because they are not reading-in reality, it is likely they do not know how to read the text effectively; (2) we may assume they can write and communicate their findings-when they don't manage to do this unaided, we fail to realize that we have not given them ample opportunity to practice; (3) we assume they are just as curious as we are, and that they know how to frame the next question and focus their pursuit-when they don't, we assume it is because they are not competent, but the reality is that we have not encouraged or nurtured their questions on their way. As I worked through helping students learn to do research in this third year class, at the other end of the world, unknown to me at the time, work at Adelaide University in Australia on a scheme to scaffold student research skills in the undergraduate years, led to the creation of a developmental model for undergraduate research skills. In the fall, I met with a number of faculty at both Adelaide University and Monash University in Australia where they are integrating this developmental model of undergraduate research into their undergraduate classes. This study integrates findings here in Canada with those of the Adelaide-Monash team.

#### **MID PALEOZOIC ACCRETION OF THE ROBERT'S ARM AND VICTORIA ARC COMPLEXES: CONTRASTS IN SALINIC OROGENESIS ACROSS THE RED INDIAN LINE OF CENTRAL NEWFOUNDLAND**

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In north-central Newfoundland, the Ordovician Roberts Arm Group comprises the hanging wall sequence of the northwest-dipping Red Indian Line overthrust. It is composed of regional green-schist to amphibolite facies Abukuma-type metamorphic rocks of Late Ordovician – Early Silurian age. These are exposed within

northwesterly-elongated domes and basins defined by foliation-parallel thrust faults. In the southeastern part of the group, displacement on amphibolite facies faults of early Telychian age affected late Sandbian and older metavolcanic and metasedimentary strata together with reworked Hirnantian – Rhuddanian migmatites. A subsequent latest Telychian or older event produced southeast-dipping reverse shear zones that uplifted a thrust stack of inverted Darriwilian and Sandbian strata from beneath the tectonic cover of an earlier-formed nappe. Occupying a synformal klippe in the footwall sequence of the antithetic southeast-dipping shear zones, the older northeastward-transported nappe disposes the mineralized Floian volcanic rocks that are characteristic of the Roberts Arm Group. This rapidly uplifted schist and gneiss belt is interpreted to record a relatively high grade, synplutonic, Early Salinic orogenic episode on the peri-Laurentian composite margin and is postulated to have accompanied Rhuddanian and Telychian pulses of Early Silurian terrestrial volcanism that developed farther west in Laurentia.

The Middle Ordovician arc-related formations of the peri-Gondwanan Wild Bight Group and the Victoria Lake Supergroup or, more commonly, the stratigraphically overlying Sandbian shales and Katian turbidites, comprise the footwall sequence of the Red Indian Line overthrust. A westward-closing anticlinal nappe in the western part of the Wild Bight Group is associated with the underplating of chlorite grade slate beneath the Early Salinic schist and gneiss belt. Two groups of oblique-slip contractional faults of Silurian age are recognized east of the Red Indian Line. Those predating a late Telychian episode of terrestrial volcanism are horseshoe-shaped thrusts that place the older arc-related rocks above the Katian turbidites and, where cross folded, produce antiformal windows through the peri-Gondwanan strata into the Katian flysch of the Badger Group. A later group of northwest-dipping reverse faults is responsible for situating the Roberts Arm Group and the Red Indian Line mélange belt structurally above the Badger Group prior to the emplacement of early Ludlovian plutonic rocks; crenulation cleavage is locally imposed on the Late Ordovician footwall sequence. These late Wenlockian and older cleavage-producing events are interpreted to have formed during a Late Salinic orogenic episode. The early phase of Late Salinic deformation and the low-grade regional metamorphism are postulated to have occurred in the Llandoverly between the early and late pulses of peri-Laurentian terrestrial volcanism, possibly when the latest Aeronian – late Telychian part of the upper Badger Group accumulated above the peri-Gondwanan realm.

#### **SUBMARINE HYDROTHERMAL SYSTEMS: A MAJOR CLUE FOR THE CHEMICAL, BIOLOGICAL AND TECTONIC EVOLUTION OF THE EARTH**

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Steve Scott has played a major role in developing a widely-accepted theory concerning the origin of submarine hydrothermal deposits. It postulates that submarine hydrothermal fluids developed through seawater-rock interactions in submarine volcanic terranes, and that submarine hydrothermal deposits, such as VMS and BIFs, formed primarily by the mixing of hydrothermal fluids and local seawater. An important implication of this theory is that the chemical and isotopic compositions of ancient submarine hydrothermal deposits and hydrothermally-altered submarine volcanic rocks may provide information about the chemistry of the contemporaneous ocean water (i.e. concentrations of O<sub>2</sub>, CO<sub>2</sub>, H<sub>2</sub>S, SO<sub>4</sub>, Mo, U, W, etc), which in turn provide information on the chemistry of the atmosphere and continental crust, the nature

of the marine and terrestrial biospheres, and the geochemical cycles of elements through the atmosphere-hydrosphere-lithosphere.

Results of our 30+ years of investigations on submarine hydrothermal systems of various age suggest that since at least ca. 3.5 Ga, the deep-ocean waters have been rich in O<sub>2</sub>, U, Mo, SO<sub>4</sub>, Li and Ba, but poor in Fe and H<sub>2</sub>S, except in local anoxic basins. This further suggests that: by ca. 3.5 Ga (1) oxygenic phototrophs (e.g. cyanobacteria) had evolved; (2) the atmospheric O<sub>2</sub> content had increased to within  $\pm 50\%$  of the present level; (3) the modern-styled geochemical cycles of redox-sensitive elements (C, S, Fe, Mo, U, etc) through the atmosphere – continental crust – oceans – oceanic crust – mantle systems had been established. Subduction of the oxidized and U-enriched oceanic crust has created the heterogeneity of the mantle since ca. 3.5 Ga, including the feature known as “the lead paradox” where the Pb in the mantle is more radiogenic than in the bulk earth.

#### **GEOLOGICAL COMPILATION OF THE MAINLAND REGION, NORTHWEST TERRITORIES: CONTRIBUTING TO THE “MAP OF EVERYTHING”**

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The project aim is to use existing digital geological data to assemble and compile a 1:250,000 scale representation of the bedrock geology of the NWT for inclusion in a Geographic Information System. Current work is focusing on mainland NWT. Subsequent work will concentrate on the Arctic Islands to complete the database.

The bedrock geology of the mainland region (Mackenzie Mountains & Interior Platform) has been mapped and compiled at a variety of scales and degrees of detail. Compilation and synthesis have resolved the many inconsistencies among the actual representations of the geology in each map. However, several factors such as differing and evolving nomenclature systems, details available only in reports and areas where new information alters geological interpretations, result in an ever-changing and evolving database. Moreover, previous compilation work was at different data densities (equivalent to scales of 1:1,000,000, 1:500,000 and 1:250,000) and limited to the NWT. Therefore, the addition of data at larger scales where available, and further integration of adjacent geology in Yukon Territory, Nunavut and northernmost British Columbia are required to make the map and database seamless and internally consistent.

Digital map database files are the basis for map images and plots at various scales. These can also contain a higher density of information than is usually included on published regional maps. Such information includes paleontological and radiometric ages, rock unit descriptions, locations of measured sections, well core data, mineral occurrence data, etc. essential for comprehensive synthesis of all geological information. The ultimate goal is to provide a bedrock map as a base upon which as many geological data as possible may be incorporated – the “Map of Everything”.

Current work is utilizing previous compilations covering 1:1,000,000 scale International Map of the World grid map sheets: Great Bear River, Peel River, Redstone River. Parts of Ross River, Firth River and Horton River sheets will soon be incorporated into these earlier compilations to expand the current and consistent regional bedrock database. Where necessary, data density will be revised to be equivalent to 1:250,000 scale but will include greater detail equivalent to 1:50,000 scale or greater where available. A new comprehensive legend spreadsheet will be compiled from the compiled map, correlation charts and supplementary data in government and industry reports.

This phase of the NWT mainland geological compilation will be completed with the addition of the Geological Survey of Canada’s geological compilations of the Bear and Western Churchill structural provinces.

#### **CARBON ISOTOPE STRATIGRAPHY AND GEOCHEMICAL STUDIES/INVESTIGATION FOR CHANGES ACROSS BENTONITES IN THE UPPER CRETACEOUS (CENOMANIAN-TURONIAN) SUCCESSIONS OF WCSB CANADA**

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A high-resolution study of isotopic and stratigraphic trends that characterized the aftermath of volcanic events in Cenomanian-Turonian sections from the Western Canada Sedimentary Basin (WCSB) is presented. The research is based on  $\delta^{18}\text{O}$ ,  $\delta^{13}\text{C}$ ,  $\delta^{13}\text{C}_{\text{org}}$ ,  $\delta^{15}\text{N}$ , N and TOC analyses of about 140 fossil (foraminifera, inoceramid) and whole rock samples combined with previously archived data.

Stable isotope (O, C) data were acquired from three sections in the WCSB; Vermilion River VR1 & VR2 and the drill-core from well 6-34-30-8W4 (Youngstown), to (1) investigate the trends in the sedimentary sequences deposited in the aftermath of Cretaceous volcanic eruptions and (2) for chemostratigraphic correlation within the Western Interior Seaways (WIS) of North America.

Planktic foraminifera of the genera *Heterohelix*, and *Hedbergella*, and inoceramid shells used in the analysis were precipitated in isotopic equilibrium with sea water and show no significant diagenetic or vital effects;  $\delta^{13}\text{C}$  values range between  $-8.86\text{‰}$  and  $3.72\text{‰}$ ,  $\delta^{18}\text{O}$  value range from  $-13.93\text{‰}$  to  $-3.77\text{‰}$ , and  $\delta^{13}\text{C}_{\text{org}}$  value range between  $-28.68\text{‰}$  to  $-23.94\text{‰}$ . The  $\delta^{13}\text{C}$  values shift positively by about  $\sim 5\text{‰}$ , the  $\delta^{18}\text{O}$  values shift negatively by about  $\sim 5\text{‰}$  and  $\delta^{13}\text{C}_{\text{org}}$  values shift negatively by  $\sim 1\text{‰}$  all within the late Cenomanian. These shifts all coincided at the onset of the Ocean Anoxic Event 2 (OAE2), similar to other CTB sections within the WIS/WCSB and worldwide.

The results are similar to those obtained from other sections in the WIS/WCSB and generally reflect two major trends/events; the mid Cenomanian cool period and the warm late Cenomanian/early Turonian period, which incorporates the OAE2.

The TOC as well as  $\delta^{13}\text{C}_{\text{org}}$  results indicate that the low organic content that characterized the mid Cenomanian Belle Fourche Formation, became relatively high by time of the deposition of the late Cenomanian Keld member/Second White Specks Formation, but again become low by the early Turonian. The C/N ratio,  $\delta^{13}\text{C}_{\text{org}}$  and  $\delta^{15}\text{N}$  results indicate that the main source of organic matter is from C3 plants of terrestrial origin.

Across the bentonites,  $\delta^{18}\text{O}$ ,  $\delta^{13}\text{C}_{\text{org}}$  and TOC generally increases while  $\delta^{13}\text{C}$  decreases. The  $\delta^{18}\text{O}$  increases by  $0.57\text{‰}$  to  $2.14\text{‰}$  across the bentonites  $\geq 5\text{cm}$  thickness, indicating cooling of  $\sim 2.28^\circ\text{C}$  –  $8.56^\circ\text{C}$ . The environmental recovery time from the effects of volcanic events was found to be 8 to 18 kyr.

The observed  $\delta^{13}\text{C}$  and  $\delta^{13}\text{C}_{\text{org}}$  trends from the three sections from WCSB indicate that a correlation exists with the North American stratotype section of the Cenomanian-Turonian OAE2 boundary at Pueblo, Colorado.

#### **POLYPHOSPHATES ARE A POSSIBLE BIOCHEMICAL CHEMICAL PATHWAY FOR LEAD IMMOBILIZATION WITHIN BIOLOGICAL APATITE**

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The mechanism of biological apatite nucleation in the vertebrate skeleton is still a subject of debate, as the mechanism by which

lead ions report to the apatite mineral in the vertebrate skeleton. Recently, the role of a calcium-polyphosphate precursor to biological apatite mineralization was proposed. This mechanism involves the enzymatic polymerization of phosphate into a polyphosphate (phosphate polymer), which has a strong chelation affinity for cations such as calcium. The calcium-polyphosphate complex is a neutral species that represents a local concentration of calcium and phosphate, without contributing to the local free calcium or free phosphate concentrations. The relative saturation of apatite is negligible in a system containing calcium polyphosphate.

This strategy of concentrating calcium and phosphate as calcium polyphosphate, while retaining a low apatite relative saturation, may occur when bone undergoes the normal process of resorption (dissolution) by osteoclast cells. Osteoblasts, the cells that build new bone, may also concentrate calcium and phosphate by building calcium polyphosphate granules that are dispersed within new bone tissue (osteoid). When mineralization is desired, alkaline phosphatase, the enzyme associated with skeletal mineralization, cleaves polyphosphates, and produces orthophosphates. This depolymerization process also releases chelated calcium, increases the relative saturation of apatite, and favours apatite nucleation from the depolymerizing calcium polyphosphate complex.

The use of polyphosphates to capture cations, then depolymerise into orthophosphates and form a phosphate mineral, is under investigation as a treatment strategy to chelate cations such as  $\text{UO}_2^{2+}$ . Polyphosphate can form a soluble neutral complex with  $\text{UO}_2^{2+}$ . As the polyphosphates break down into orthophosphates,  $\text{UO}_2^{2+}$  can be sequestered within precipitating autunite  $(\text{X}_1-2[(\text{UO}_2)(\text{PO}_4)]_2 \cdot n\text{H}_2\text{O})$ , where X is any monovalent or divalent cation that offers a low solubility. It is possible that the mineralizing vertebrate skeleton uses the same strategy to chelate and then sequester toxic cations such as lead. The formation of a lead-polyphosphate complex would immediately reduce its bioavailability. This lead-polyphosphate complex could be transported to regions of mineralizing bone, where alkaline phosphatase may depolymerise the polyphosphate, resulting in the precipitation of a lead apatite mineral amongst the mineralizing skeleton. The lead would be sequestered within the low solubility apatite mineral, which offers a high tolerance for substitutions.

#### THE SLAVE PROVINCE: LITHOSPHERIC EVOLUTION AND MINERALIZATION OVER 4 BILLION YEARS

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The Slave Province in northwestern Canada hosts precious, base, and rare metal, diamond, rare earth metals, and industrial mineral deposits. Although the province is generally considered to be an Archean craton, it also has Proterozoic and Phanerozoic rocks that are an important contributor to its mineral endowment. Mineralization is related to many key geologic-metallogenic evolutionary events that are summarized below, and exemplary deposits are given in parentheses.

A Mesoarchean (ca. 2.85-2.82 Ga) sedimentary cover sequence with mafic-ultramafic intrusions unconformably overlies a Mesoarchean to Hadean basement complex throughout the central part of the craton. Overlying this cover sequence are Neoarchean (ca. 2.72-2.70 Ga) greenstone belts. A younger group of ca. 2.69-2.67 Ga arc-like bimodal volcanic rocks overlies the greenstone belts and crops out throughout the craton. Extensive 2.66-2.62 Ga greywacke-mudstone turbidite packages, some with

interbedded banded iron formation, overly the volcanic rocks. Volcanic granitic plutons were emplaced at ca. 2.60-2.58 Ga. Late stage, lithospheric-scale transpressional faulting resulted in local deposition of <2.58 Ma conglomerate units.

Mineralization associated with the above events is as follows. Stratabound Ni-Cu-PGE mineralization associated with the cover sequence has been recently discovered in the mafic-ultramafic intrusions (Credit Lake). Volcanogenic-hosted massive sulphide deposits are hosted in the ca. 2.67 Ga mafic and intermediate volcanic rocks (Izok Lake, Hackett River, Sunrise, High Lake, Indian Mountain). At least two stages of orogenic gold mineralization are recognized: 1) at ca. 2.67 Ga and hosted in ca. 2.67 Ma mafic volcanic rocks (Hope Bay, Ulu) and 2) ca. 2.59 Ma mineralization hosted in greenstone belts (Yellowknife, Tundra) and in greywacke-mudstone turbidites and interbedded iron formation (Ormsby, Lupin, Discovery, Damoti, Goose Lake). This later mineralization is concomitant with late-stage transpressional faulting and S- and I-type granitic intrusions. Pegmatite dykes associated with S-type intrusions are hosts to rare metal (Li-Ta) deposits (Moose).

The Paleoproterozoic (ca. 2.18-2.17 Ga) alkaline Blachford Intrusive Suite was emplaced into Archean rocks of the Slave Province during intracontinental extension. The syenite endmembers host a rare earth element deposit (Nechalacho) that is also rare metal rich (Zr, Nb, Ta, Ga), while the gabbroic endmembers host Ni-Cu mineralization (Caribou). Numerous mafic dyke swarms intruded the Slave Province during the Paleoproterozoic; some of these contain base metal prospects and remain attractive exploration targets (Muskox).

Diamondiferous kimberlites were emplaced intermittently during the Phanerozoic (Ekati, Diavik, Snap Lake). Diamond formation ages range from Paleoproterozoic to Paleoproterozoic, indicating a long and varied modification of the Slave lithosphere.

#### THE FAILURE OF SILICATE FOAMS CAUSED BY BUBBLE EXPANSION: INVESTIGATION BY X-RAY MICROTOMOGRAPHY

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The mechanisms of volcanic eruptions have been studied for many decades, but there are still many unknowns due to our inability to observe the process in situ. In this research we will couple microtomographic imaging of synthetic volatile-rich volcanic glass foams with Monte Carlo simulations in order to investigate the bubble size distributions as well as the changing dimensions of the walls between the bubbles during failure of these silicate foams.

Synchrotron X-ray microtomography will be used to image experimentally produced, hydrous melts as they vesiculate, expand and ultimately fail. The microtomographic imaging will be conducted as the melt is heated at 1200°C in order to image the sample at near 1µm resolution from the beginning of bubble expansion all the way through to critical failure. This will lead to bubble size distribution data over the entire lifespan of the foam as well as data for the width of the bubble walls. These data will then be used as the input for computer simulations of foam failure to model volcanic eruptions.

Based on preliminary analyses and simulations, the bubble size distribution is hypothesized to play an important role in the strength of the foam even at constant total vesicularity. The strength of the magmatic foam is governed by the width the melt between the bubbles, as the width of the bubble walls decreases so does the strength. A reduction in strength could lead to critical failure of the foam, which in turn could trigger a violent volcanic eruption.



The bubble walls will be simulated by a random fibre bundle model (FBM) where the width of the walls becomes the width of the fibres. A uniform force will be applied to the fibres and if the average force per fibre is greater than the strength of an individual fibre, it will fail. The number of fibres decreases and the force per fibre is recalculated and more fibres possibly break. This process is repeated until either the remaining fibres have enough strength to maintain the load or critical failure of the foam occurs. This type of failure analysis will lead to further research in eruption mechanics and can also be applied to other problems in geoscience.

## THE MOON: AN IMPORTANT DESTINATION FOR SOLAR SYSTEM EXPLORATION

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There is a common misconception in popular understanding that the Moon is a “been there, done that” body. However, there are still many unanswered questions about the Moon that have remained since the Apollo missions of the 1960s and 1970s. There are still fundamental questions about whether the Moon has, or had, a differentiated core, when the lunar feldspathic crust formed, and whether there was a period of cataclysmic bombardment in the Moon’s early history. These kinds of questions highlight the fact that our understanding of lunar formation, differentiation, evolution, and impact history is still not complete. Furthermore, such questions transcend lunar studies and inform us about processes in the solar system as a whole and, in particular, the early Earth–Moon neighbourhood. They are fundamental for understanding the evolution of the solar system, the formation of the Earth–Moon system, the differentiation of terrestrial planets, conditions on the early Earth, and even the origins of life on Earth. As a result, the need to return to the Moon is clear.

The recent flotilla of international orbiting spacecraft have answered some questions, but as the resolution of the imagery and other data increases, so new questions have been asked. These recent missions have stimulated renewed interest in the Moon. The formation of the NASA Lunar Science Institute (NLSI) in 2008 has provided the resources and the networking opportunities in the U.S. that have generated much new research in diverse areas of lunar science. Here in Canada, the Canadian Lunar Research Network (CLRN: <http://clrn.uwo.ca/>) was the first member of the NLSI and is now one of several international partners. CLRN is a network of scientists and engineers from across Canada and from academia and industry. The Google Lunar X PRIZE and initiatives such as Moon Zoo have also stimulated interest in the wider community.

This invited contribution will provide a brief overview of recent advancements in lunar science and highlight some of the big outstanding questions. Upcoming missions will be highlighted. Finally, with the growing interest in utilizing terrestrial analogues for the Moon – both for scientific and exploration purposes – the Canadian impact cratering record will be discussed, and showcased, as a unique opportunity for future development and collaborative research.

## USING PLANETARY SCIENCES TO RAISE GENERAL SCIENCE INTEREST

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Why is it that children become fascinated with trains, dinosaurs, magic, and space? What is it about these topics that captivates them and holds their interest and attention? An interest in the un-

known? A desire to explore? Perhaps it is the use of their imagination? Based on the premise of all of these things, the Centre for Planetary Science and Exploration (CPSX) at the University of Western Ontario is developing a program that raises interest in science through the already existing interest in Space. Currently, the activities being performed by the centre can be divided into three broad categories: (1) educational/curriculum based activities, (2) outreach/community based activities, and (3) training. The first, is where the push for an increase in interest for science is really critical.

Using inquiry-based teaching methods, Grade 9 students study various topics under the guidance of a CPSX graduate students – the first activity to be developed was on impact craters. In this activity, the high school students create their own experiments to study how the cratering effects change based on changing impactor characteristics. What would happen if an impactor hit a planetary surface at an angle? These students are answering their own questions through experiments they create. Earth sciences seem to come alive when students realize that some of the rocks brought into their classroom were hit by outerspace debris. Why are these rocks different? How do scientists know these rocks were hit? Students become interested in scientific topics without realizing it. CPSX graduate students also make other activity-based presentations in high schools, aimed at raising interest in science by encouraging students to ask questions and be curious. Having a ‘space expert’ in the classroom can help to take the pressure off teachers who may not be as comfortable in guiding discussions on space related science topics.

The success of this educational program is achieved by working in collaboration with education centred groups such as the Science Teachers Association of Ontario (STAO), the Thames Valley District School Board, Virtual Researchers on Call (VROC), and Smarter Science. The fusion of science and education through the already existing interest in Space, allows students to see the ‘fun’ aspects of science. After all, as scientists aren’t we are still interested in the unknown, exploration, and the use of imagination to solve the problems reality cannot?

## HETEROGENEITY OF THE LOWER CRUST, MOHO AND UPPER MANTLE FROM STATISTICAL ANALYSIS OF NEAR-VERTICAL AND WIDE-ANGLE SEISMIC REFLECTION DATA

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Stochastic distribution of crustal heterogeneities exhibit power-law scaling, often described by the von Karman autocorrelation function. We make use of the high quality near-vertical-incidence reflection data recorded along Line 1 of LITHOPROBE’s 1997 SNORCLE seismic experiment in northwestern Canada to directly extract the power law parameters (lateral correlation length and Hurst number, or power law exponent) by adopting a novel statistical analysis technique. This is possible due to the conservation of the von Karman power law heterogeneity in the recorded near-vertical seismic data. Our objective is to provide robust estimates of the power law parameters and consequently a better understanding of the stochastic nature of the lower crust, the Moho transition zone and the upper mantle beneath the Great Bear magmatic arc, part of the Paleoproterozoic Wopmay orogen. Because the SNORCLE experiment included co-located reflection and refraction surveys, two approaches, stochastic inversion for the power law parameters and forward modeling of both near-vertical and wide-angle reflection data, are combined, a unique undertaking. The parameters derived from the inversion procedure, together with

velocities from seismic refraction/wide-angle reflection studies, are used to construct 2-D stochastic velocity fields. To further constrain the power law parameters, synthetic wide-angle and near-vertical seismograms are calculated from the velocity fields and compared to the observed seismic data using a 2-D visco-elastic finite-difference wave propagation algorithm. We also compare seismic attributes of the synthetic recordings with those of the observed data. Our preferred velocity model from these analyses contains three stochastic regions: the lower crust, the Moho transition zone, and the uppermost mantle, all with a von Karman-type heterogeneity distribution. The Moho transition is a 3-km-thick zone at 33 km depth that is characterized by the highest lateral correlation lengths (average ~940 m) possibly due to mafic intrusions. This transition zone is responsible for the generation of the pronounced coda trailing the PmP phase observed on the wide-angle data and the multicyclic band of reflections observed at Moho level on the near-vertical data. The uppermost mantle is characterized by the lowest values (average ~260 m), which we interpret as the result of vertically migrating magmas that may interrupt existing horizontal lineations in the upper mantle. The lower crust has intermediate average lateral correlation lengths of ~730 m. Low correlation lengths within the crust can be associated with folding/faulting surfaces. This study demonstrates that statistical analysis combined with synthetic modeling can serve as an effective interpretation tool for deep seismic imaging.

#### **INDICATOR MINERAL AND TILL GEOCHEMICAL DISPERSAL PATTERNS ASSOCIATED WITH THE PINE POINT Pb-ZN MISSISSIPPI VALLEY-TYPE (MVT) DEPOSITS, NORTHWEST TERRITORIES**

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Indicator mineral and till geochemical exploration methods for diamond and gold have proven to be very successful in glaciated terrain.

Research by the Geological Survey of Canada (GSC) under its Geo-mapping for Energy and Minerals (GEM 2008-2013) is currently underway to develop similar methods for base metal and uranium exploration. As part of this indicator mineral research, the GSC, University of Alberta, Tamerlane Ventures Incorporated and Teck Resources Limited initiated a case study in 2010 to document the indicator mineral and till geochemical signature of the Pine Point Pb-Zn Mississippi Valley-Type (MVT) deposits and to describe the glacial dispersal signature at varying distances down-ice from the deposits.

The Pine Point mine district is located on the southern shore of Great Slave Lake, Northwest Territories on the northeast margin of the Western Canada Sedimentary Basin. During the Quaternary, the Laurentide Ice Sheet inundated western Canada, eroded the landscape and deposited glacial sediments of varying thickness. A minimum of three phases of ice flow trajectories were identified from striations on exposed shoulders of several open pits as well as constructional and streamlined landforms observed on aerial photographs and satellite imagery. Cross-cutting relationships of striae indicate an earliest sustained ice flow direction to the southwest (~230°) with an intermediate phase to the northwest (~300°) followed by the last phase, during deglaciation, to the west southwest (~250°). Glacial flutings formed by this last phase of flow are the dominant landscape feature.

Till sample locations were chosen following a reconnaissance of each open pit at the Pine Point mine site. Pit O-28 was chosen for detailed sampling because mineralization sub-cropped, ice

flow history was well documented by striae on exposed bedrock surface and approximately 6 m of till overlying bedrock was available for sampling both up and down ice at the pit edges. Till samples were collected from hand dug holes in sections and from the bedrock surface. Additional till samples were collected from pits to the northeast and southwest of Pit O-28. Sixty bedrock samples were collected from Tamerlane Ventures Inc. drill core, waste rock piles and mineralized float samples collected from Pit O-28. Detailed mineralogical and petrographical studies were carried out on polished thin sections. Bedrock and till samples have been processed to recover indicator minerals and the till matrix (<0.063 mm) analyzed to define geochemical pathfinder elements. A second field season is planned in summer 2011 for the collection of additional regional and detailed till samples at selected sites and to decipher the complicated ice-flow history of the region.

#### **SHORT DIFFERENTIATION TIME FOR VESUVIUS AND CAMPI FLEGREI ALKALINE MAGMAS: EVIDENCE FROM CSD STUDIES**

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Catastrophic eruptions are supplied by Si-rich magmas, that have been generated at shallower level in crust by the evolution of mantle liquids. The timescale of these evolution processes is a crucial factor, because of its control on the length of repose interval that leads to high magnitude events.

The alkaline volcanic systems of Campi Flegrei and Somma-Vesuvius, that are located respectively at few kilometers west and east of Neapolitan metropolitan area, have produced a variety of eruptions ranging from not explosive lava flows and domes, to highly destructive eruptions. Both these high risk volcanoes are in repose time, since the last eruption occurred in the 1538 and 1944 BP, respectively. A wide low velocity layer interpreted as an extended magmatic body has been detected at 8-10 km depth beneath these volcanoes by geophysical investigations. The capability of this reservoir to erupt explosively again, strongly depends on magma differentiation degree, therefore the knowledge of the time lapse necessary at not explosive mafic liquids to differentiate toward explosive magmas is very crucial to predict the size of a possible short-term eruption in the Campanian area.

Our petrologic data indicate that a multi-depth supply system was active under the Campanian Plain at 2.5 kbar since 39 ka. Fractional crystallization during magma cooling associated with upward migration of less dense evolved liquids appears to be the prevalent differentiation process. Our results indicate that huge steam exsolution occurred during the late stage of trachyte and phonolite crystallization thus accounting for the high Volcanic Explosivity Index (VEI) of eruptions supplied by these melts. Moreover our CSD data on phenocrysts reveal rapid crystallization and differentiation time for alkaline Campanian magmas (in the order of decades to few centuries). This evidence implies that the 400 km<sup>2</sup> partial melting zone detected by tomography study at 8-10 km depth beneath Vesuvius and Campi Flegrei, should consist of differentiated magma already capable to produce also large scale (plinian) explosive events in case of renewal of the activity from the present closed-conduit state.

## **GEOLOGY AND GEOCHEMISTRY OF CARBONATE-HOSTED NONSULPHIDE ZN-PB MINERALIZATION IN SOUTHERN AND CENTRAL BC**

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Carbonate-hosted, nonsulphide base metal deposits are derived from sulphide mineralization (i.e. MVT, SEDEX, Irish-type, vein-type deposits and skarns) by supergene processes. Several carbonate-hosted sulphide deposits in the Kootenay terrane (Salmo district), adjacent Cariboo terrane (Quesnel Lake district), and elsewhere in BC have near-surface Zn- and Pb-bearing iron oxide-rich gossans. Such gossans form when carbonate-hosted, base-metal sulphide mineralization is subject to intense weathering and metals are liberated by the oxidation of sulphide minerals. The metals can be trapped locally, forming direct replacement, nonsulphide ore deposits ("red ores") or they can be transported by percolating waters down and away from the sulphide protore, forming wallrock replacement nonsulphide deposits ("white ores"). Wallrock replacement deposits can be located in proximity to protore or up to several hundreds of metres away.

The direct replacement nonsulphide deposits consist predominantly of Fe-oxyhydroxides, goethite, hematite, hemimorphite, and minor smithsonite, hydrozincite and cerussite. In the Salmo district, direct replacement deposits contain 0.8-23 wt.% Zn, 0.7-5 wt.% Pb, and >20 wt.% Fe. Zinc content of sphalerite ranges from 56.6 to 67.3 wt.%, and iron content of sphalerite ranges from 0.03 to 9.4 wt.%; both show a negative correlation with a general increase in Fe from the southern to the northern deposits. The direct replacement deposits form oxidation zones over carbonate-hosted zinc-lead sulphides in which they replace (pseudomorph) the sulphide aggregates. They mainly occur as large irregular replacement masses, encrustations, or open-space fillings. Direct replacement deposits of the Quesnel Lake district consist of pervasive fine-grained sulphide and nonsulphide disseminations and aggregates forming pods and masses, sulphide- and nonsulphide-bearing quartz ( $\pm$ calcite) veins, and crackle breccias. Sulphides are galena, sphalerite, and trace amounts of pyrite. Nonsulphides are smithsonite, hemimorphite, cerussite, hydrozincite, and possibly anglesite. Grab samples assayed 17.3-51.0 wt.% Zn, 0.1-1.5 wt.% Pb, and 0.4-0.8 wt.% Fe. Zinc and iron content of sphalerite is fairly constant and ranges from 65.8 to 67.2 wt.% and 0.4 to 0.8 wt.%, respectively. In most occurrences, the spatial continuity and/or the close spatial relationships in combination with morphological similarities between sulphide and associated nonsulphide zones suggest direct replacement of sulphides by nonsulphide base metal-bearing minerals. The wall-rock replacement deposits were observed only in the Salmo district. They consist mainly of hemimorphite, smithsonite and hydrozincite, and minor Fe-oxyhydroxides and carbonates. No remnants of sulphides were observed. They contain 31.5-49.8% Zn, 0.13-0.19% Pb and <3% Fe.

## **FUZZY CLASSIFIERS FOR GLACIAL LANDFORM MAPPING USING DEM DERIVATIVES AND SPECTRAL SATELLITE IMAGERY**

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Remotely-sensed imagery has been paired with geomorphological research since the early 20<sup>th</sup> century when aerial photographs were classified manually by human interpreters for regional mapping efforts. There are three principal components in an image that are exploited by the interpreter for mapping: tone, relief and context. The challenge in developing semi-automated techniques is to ad-

dress these three components and the human cognitive component of terrain analysis.

For many years, spectral satellite (LandSat, Aster, MERIS) imagery has been a standard data source for mapping land use, land cover, and surficial materials in glaciated landscapes. Analysis and classification of spectral satellite imagery, however, addresses only one of the three components of terrain analysis – tone. Furthermore, the use of "crisp" classifiers forces arbitrary boundaries on a landscape which does not always contain discrete boundaries. New research is required to advance glacial landform mapping capabilities using multiple data sources and novel computational techniques that can more effectively replicate the human cognitive components of terrain analysis based on tone, relief and texture.

The increasing availability of Digital Elevation Models (DEM) has led to an explosion of methods for quantitative analysis of landforms. DEM are able to incorporate other aspects of the landscape which are typically used by the interpreter, making them ideal for characterizing glaciated landscapes. These advantages make it clear that classification should not be confined to a simplistic analysis of landform spectroscopy and boundaries.

This study aims to apply fuzzy classification techniques to spectral imagery and DEM derivatives, to classify glacial landforms in the barren lands East of Great Slave Lake, (e.g. NTS 75I, Beaverhill Lake) Northern Canada. Fuzzy analysis proves informative to geomorphologists as land soil materials change more gradually than a crisp classifier implies. Furthermore, mixed membership helps to identify which classes exhibit poor separability and hence lower classification accuracies. Therefore, landscape analysis using spectral imagery and DEM derivatives within a fuzzy logic modelling environment provides a framework for understanding the dynamics of glacial materials.

## **USING GEOENVIRONMENTAL MODELS TO REDUCE ENVIRONMENTAL IMPACTS AT OROGENIC LODE GOLD MINES ACROSS CANADA**

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The mining and milling of gold from orogenic lode gold deposits can result in significant risks to the environment and human health without appropriate mine planning, environmental management, and monitoring programs. Orogenic, or mesothermal, lode gold deposits are hosted mainly by quartz-carbonate veins and occur in deformed greenstone and metasedimentary terranes around the world. These deposits are the main source of gold in Canada, and are presently the focus of considerable exploration and development. This presentation will summarize the key environmental characteristics of this deposit type using examples from recent research in Nova Scotia and British Columbia, and will provide practical examples of how geoenvironmental models can be used to reduce risks throughout the mining life cycle.

Gold mining in Nova Scotia, mostly between 1861 and 1942, has left many arsenic-rich tailings areas across the province owing to the widespread occurrence of arsenopyrite in gold-bearing quartz veins and surrounding host-rocks. These tailings also contain high mercury concentrations derived from historical amalgamation activities. Today, many of these tailings deposits are located in close proximity to residential areas, and the mine wastes are frequently used for racing off-road vehicles. Human exposure to arsenic via ingestion or inhalation of the tailings is the primary concern at these sites; however, unconfined disposal of the tailings

has also led to high concentrations of arsenic and mercury in water, sediments, and biota downstream of former mining areas. In British Columbia, mine drainage with high concentrations of arsenic and/or antimony is the key environmental concern at orogenic lode gold deposits in the Bridge River Mining District. Our studies focused on the past-producing Bralorne, King, and Pioneer gold mines, which together represent the largest historical gold producer in the Canadian Cordillera (> 4.15 M oz. between 1932 and 1971). Detailed characterization of stream water, sediment, waste rock, tailings, and mine drainage from these deposits, as well as several antimony and mercury deposits in the Bridge River District, has led to improved understanding of the controls on mine drainage quality and the naturally occurring levels of metal(loid)s in these mineralized areas.

The results of these studies are being used to develop a geo-environmental model for Canadian orogenic lode gold deposits. This model will assist industry and regulators to understand the key environmental characteristics of this type of ore deposit, and will help to minimize the environmental impacts associated with past, present, and future gold extraction.

#### **USING EARTH SCIENCE DATA TO INFORM RISK ASSESSMENTS AND MANAGEMENT DECISIONS AT HISTORICAL GOLD MINES IN NOVA SCOTIA**

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Recent studies of historical gold districts in Nova Scotia have identified several areas where exposure to mine wastes may represent a potential risk to both ecosystem and human health. Arsenopyrite (FeAsS) occurs naturally in the ore and surrounding bedrock in these gold deposits, and was concentrated in the tailings during milling operations. In 2005, the Province of Nova Scotia established the Historic Gold Mines Advisory Committee to examine these risks in more detail (<http://www.gov.ns.ca/nse/contaminatedsites/goldmines.asp>). Since that time, detailed studies have been carried out to examine the concentration, chemical form and bioaccessibility of arsenic (As) in tailings, airborne particulates and forest soils near these sites to clarify the spatial extent of mine tailings, the mineral hosts for As, and the fate of wind-blown tailings dusts. The Province has also completed environmental assessments at two former mines (Montague and Goldenville) where dusty, high-As tailings are located close to residential areas and are used for recreational activities (e.g. off-road vehicle racing).

Mineralogical characterization of the tailings and windblown dusts show that As is hosted in arsenopyrite and a variety of weathering-related phases including scorodite (FeAsO<sub>4</sub>·2H<sub>2</sub>O), Ca-Fe arsenates, and As bound to Fe oxides. These phases have varying solubilities that strongly influence the environmental fate and bioaccessibility of As in the tailings. Samples of surface soil (0-5 cm) collected within the mine districts, but away from tailings, show naturally elevated levels of As that exceed the 12 mg/kg Canadian Soil Quality Guideline for As. In general, the concentrations of As are generally higher down-ice (south) of the ore zones in these gold districts, reflecting glacial erosion and transport of mineralized bedrock containing arsenopyrite and other sulphide minerals.

Remediation strategies for high-As mine wastes at publicly accessible sites like those in Nova Scotia typically employ clean soil covers to reduce human exposure and dust generation. However, burying the tailings under soil may trigger dissolution of the

As-bearing minerals and lead to accelerated release of As to local streams and groundwater. Our ongoing research at Montague and Goldenville uses laboratory experiments and field tests to investigate the biogeochemical stability of different tailings types to design the best plan to protect downstream surface and ground waters and reduce risks to human health. This research will provide experimentally tested recommendations applicable to many of the thousands of active and abandoned mine sites across Canada.

#### **SEDIMENTS, SOURCE TERRANES AND TIMING: TESTING THE PENRHYN-PILING CONNECTION**

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Similarities in lithostratigraphy between the Penrhyn Group on Melville Peninsula and the Piling Group on Baffin Island have led to historic correlation between these two sedimentary packages. Both the Penrhyn and Piling groups (Foxy Fold Belt) are Paleoproterozoic-aged mixed carbonate-siliciclastic successions, traditionally thought to be deposited in a passive margin or continental rift setting which later evolved into a foreland basin during the Trans-Hudson Orogeny. Recent geological investigation on Melville Peninsula through the Geological Survey of Canada's Geo-Mapping for Energy and Minerals (GEM) Program has enabled more detailed stratigraphic and geochronological analyses of these sequences in order to test the above hypotheses. This correlation is critical for identifying strata favorable to mineralization in the Penrhyn Group, particularly given the presence of known gold occurrences in the Piling Group (e.g. in the Bravo Lake Formation).

The lowermost strata of both the Penrhyn and Piling groups resemble passive margin sequences, but may have initiated as continental sag or rift basins; the latter is less likely in the absence of coarse-grained sedimentary rocks and syn-sedimentary faults. The Piling Group contains tholeiitic to alkaline basaltic flows and sills, which indicate extension, potentially in a continental back-arc or rift setting. These flows and sills are associated with sulphur-rich fine-grained sediments, iron-rich hydrothermally-altered rocks and immature siliciclastic rocks. In contrast, basaltic flows have not thus far been identified in the Penrhyn Group. The Penrhyn Group is highly transposed, hindering estimates of sediment thickness. By contrast, the Piling Group represents a better preserved sequence to understand basin evolution and tectonic setting.

Preliminary detrital zircon geochronology constrains the maximum age of deposition of the Penrhyn Group to <2320 Ma. Existing geochronologic data from the Piling Group indicate a maximum age of deposition of ca. 2160 Ma (the age of the youngest detrital zircon from the lowermost strata), and a minimum age constraint of ca. 1897 Ma (the age of a granodiorite intrusion in the uppermost turbidite strata). Ongoing geochronological analysis will further resolve further similarities and/or differences between the timing of basin inception in these two groups, as well as the provenance of the sediments, ultimately contributing to the understanding of the geodynamics of source terranes during the deposition of these sequences.

## EXTRAPLAC: GEOLOGICAL COMPLEXITIES OF THE FRENCH EXTENDED CONTINENTAL SHELF

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Mostly because of its overseas territories, located in the Atlantic, Pacific and Indian Ocean, France has the second largest Exclusive Economic Zone in the world and consequently important possibilities to extend its continental shelf. Therefore in April 2002, the French government started the program EXTRAPLAC aimed to construct the proposed outer limits of the French continental shelf to be submitted to the United Nations, and to present and defend them before the Commission on the Limits of the Continental Shelf. The geographic distribution of the French territories and their geological settings make that EXTRAPLAC covers a wide variety of classic and not so classic geological contexts, some of which are dealt with in the guidelines, and others that require original approaches. As such, the potential extended continental shelf claims for France include a classic passive margin, a transform margin, a subduction zone, a fracture zone, an oceanic plateau, an intra-plate volcanic island, and an island on a mid-ocean ridge. In each of these cases, the key element is natural prolongation. Once this prolongation established, the application of the rules set out in Article 76 for the determination of the outer limit can be straight forward in some, but rather complex in other cases. In this presentation, we will provide an overview of the different geological situations encountered and of the associated scientific and technical approaches.

## CHALCOPHILE AND SIDEROPHILE ELEMENT CONCENTRATION IN SULFIDE DROPLET FROM MORB GLASS

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We have determined the concentrations of chalcophile and siderophile elements by LA-ICP-MS from sulphide droplets and fresh glass in contact with them from MORB pillow rims. The aim of the study is twofold. Firstly, MORBs play an important role in the understanding of mantle petrogenesis and differentiation of the Earth, providing information on chemical fractionation of elements in the mantle. However, chalcophile and siderophile element behaviour is not completely understood, partly due to the lack of data for partition coefficients between sulphide and silicate liquids. Secondly, mass balance work on ore deposits indicates that most platinum-group elements (PGE) are present in base metal sulphides in solid solution. However, Pt and Au tend to be present as discrete minerals in association with sulphides. The origin of the Pt and Au minerals may be that they crystallised directly from a sulphide liquid, that they exsolve from base metal sulphides or precipitate from a deuteric fluid. Examination of the MORB droplets allows us to investigate how these elements behave in unaltered, quickly-cooled systems.

Some droplets have homogenous textures and some have portions rich in monosulphide solid solution (Mss) and intermediate solid solution (Iss) indicating that they have undergone crystal fractionation. For the droplets with homogenous textures, concentrations of Ni and Cu are 10 to 1%; Co and Zn 1000 to 100 ppm; Se, Te, Ag and Pb 100 to 10 ppm; Cd, Sn, Pd, Bi and Pt 10 to 1 ppm; Au, Ru and Re 1 to 0.1 ppm. For some of these elements it was also possible to obtain data in fresh glass allowing the calcu-

lation of partition coefficients. These were calculated for Ni (giving a range of  $745 \pm 252$ ), Cu (giving a range of  $1219 \pm 381$ ), Co (giving a range of  $42 \pm 5.5$ ), Zn (giving a range of  $3.4 \pm 0.9$ ), Sn (giving a range of  $10.4 \pm 1.8$ ) and Pb (giving a range of  $55.6 \pm 9.3$ ). Values for Ni, Cu and Co are in agreement with literature, suggesting that values for Zn, Sn and Pb are realistic.

In both the homogenous and fractionated droplets analysed, all elements have continuous profiles like S, Fe, Ni and Cu, suggesting that there are no discrete platinum group minerals (PGM) or Au grains present. This is also confirmed by SEM analyses. All elements are, therefore, integrated inside sulphide structures. This implies that no PGMs crystallise directly from sulphide liquid before quenching.

## CONSTRAINING KIMBERLITE CO<sub>2</sub> DEGASSING

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Although the 5-9°C global warming event known as the Paleocene-Eocene thermal maximum (PETM ~ca. 56 Ma) is attributed to a massive injection of CO<sub>2</sub> (2000-7000 Pg of carbon) into the atmosphere, the source of the CO<sub>2</sub> remains unknown. Subsequent absorption of atmospheric CO<sub>2</sub> by ocean-waters is thought to have altered ocean-water chemistry. On tectonic timescales, carbonate saturation will adapt to changing climate and ocean chemistry and hence controls CaCO<sub>3</sub> preservation, however, on >10<sup>5</sup> yr timescales CO<sub>2</sub> is buffered by the balance between weathering and CaCO<sub>3</sub> burial. Ocean-water pH is governed primarily by pCO<sub>2</sub> rather than weathering, because it reflects the balance between dissolved CO<sub>2</sub> and carbonate ion concentrations. Higher pCO<sub>2</sub> lowers ocean-water pH resulting in the shoaling of the calcite compensation depth (CCD) and leading to the widespread dissolution of seafloor carbonate. Although the relationship between the required amount and rate of CO<sub>2</sub> released is neither simple nor linear, in general a faster release requires less CO<sub>2</sub>. The relative rise of the CCD constrains the required amount of CO<sub>2</sub> to 2,000-7,000 Pg of carbon, depending on release rate.

The early Cenozoic also had prolific kimberlite eruptions in the Lac de Gras region of northern Canada that have four distinct age clusters (59.1, 55.6, 53.2, and ca. 49 Ma). The 55.6 Ma age cluster correlates with the 56 Ma PETM age and the other age clusters correlate to other climate events during the early Cenozoic, suggesting that kimberlite-derived CO<sub>2</sub> may provide the positive forcing for such warming events. Studies of hypabyssal kimberlite indicate that primary kimberlite magma is CO<sub>2</sub> rich and degasses large amounts of CO<sub>2</sub> during surface volcanism. The critical question is whether the degassing of erupting kimberlite fields can provide the volume and rate of CO<sub>2</sub> required to overcome the natural buffering systems to drive a global greenhouse effect. Utilizing kimberlite magma compositions and assuming a range of volcanic eruption parameters (i.e. magma volumes, rate of eruption, etc.) we have constrained the range of volumes and rates of CO<sub>2</sub> release during kimberlite eruptions. Our results indicate that a field of multiple kimberlite pipes such as the Lac de Gras field erupted on short timescales as even relatively small volcanic eruptions (i.e. Eyjafjallajökull, Iceland – 2010), is capable of supplying the CO<sub>2</sub> required to drive the PETM greenhouse effect.

# INFLUENCE OF SOLAR FORCING ON CLIMATE AND PRIMARY PRODUCTIVITY CHANGES IN THE NORTHEAST PACIFIC: EVIDENCE FROM MID TO LATE HOLOCENE LAMINATED SEDIMENTS

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Marine-laminated sediments from fjords along the British Columbia coast (Effingham Inlet and the Seymour-Belize Inlet Complex) provide an archive of mid-late Holocene climate variability at annual to millennial scales. Deposited under primarily anoxic conditions laminated annually deposited couplets are characterized by darker clay laminae accumulated under higher precipitation conditions in winter, and diatom-dominated laminae laid down when productivity was higher in spring through autumn. The study comprised four piston cores and two freeze cores, which collectively represent the last ~5000 year of deposition. Wavelet transform and other time series analysis methods were applied to sediment color (i.e. gray-scale values) line scans obtained from x-ray images of cores and compared with global records of cosmogenic nuclides (<sup>14</sup>C and <sup>10</sup>Be), as well as the Ice Drift Index (hematite-stained grains) record to detect cycles, trends and non-stationarities in the sedimentary record. Similar analyses were carried out on diatom, dinoflagellate and fish scale records recovered from these same cores. The results indicate that the marine productivity and sedimentary record of the NE Pacific responded to abrupt changes and long-term variability in climate that can be linked to external forcing (e.g. cosmic ray flux and solar ultraviolet (UV) radiation through solar cycles). A 2-7 year and 10-12 year cycle was recognizable suggesting that both the El Niño-Southern Oscillation and Schwabe sunspot cycle influence primary productivity and sedimentation processes. There is also evidence of a strong cooling in the region at ~3550 yr BP. This event is associated with widespread regional neoglaciation that can be correlated to a weakening of high-frequency pulses at the 88 year Gleissberg solar cycle band. Episodes of low sun activity are characterized in the sedimentary record (e.g. 2350, 2750 and 3350 cal yBP) by intervals of clay-rich and thick laminae deposited under unusually wet conditions. These intervals of higher precipitation may have been related to an intensification of the Aleutian Low (AL) caused by an eastward migration of the Center of Action (COA) of the AL, which occurs during intervals of solar minima. Dryer conditions prevail in the region during intervals of solar maxima when the COA of the AL migrates westward and the COA of the North Pacific High (NPH) migrates northward. These NPH and AL COA changes impact the influence of open ocean upwelling in Effingham Inlet and estuarine circulation in the SBIC. These results suggest that solar cycles may exert a significant influence on marine primary productivity in the northeast Pacific.

# STABILIZATION OF GARNET IN METASOMATICALLY ALTERED METATURBIDITES FROM THE ST-EUGENE LEAD-ZINC DEPOSIT, SOUTHEASTERN BRITISH COLUMBIA

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The St. Eugene Ag-Zn-Pb deposit, near Moyie, southeastern British Columbia, is a Proterozoic vein deposit hosted by Lower and Middle Aldridge metaturbidites of the Belt-Purcell Supergroup on the east flank of the Purcell Anticlinorium. The regional metamorphic grade of the rocks is biotite zone. The vein system is enveloped by a metamorphosed alteration zone of increasing intensity as the vein is approached (Joncas and Beaudoin, Econ. Geol., 2002). In the inner alteration zone, garnet occurs in a variety of associations, including in the thin argillaceous tops of turbidite beds. The equivalent thin argillaceous tops of turbidite beds away from the vein are garnet-free and representative of the regional rocks. The mineralogical zoning reflects a metasomatic gradient related to fluid infiltration from the vein into the turbidites, with the argillites near the vein enriched in Fe, Mn, Pb and Zn compared to the regional rocks; other compositional differences are minor. Thermodynamic modeling of rocks spanning this compositional gradient predicts increasing stabilization of garnet with increasing degree of metasomatism, in accord with the observed mineral assemblages. Detailed comparison of predicted and observed mineral assemblages and mineral compositions, however, suggests an interplay between equilibrium and kinetic processes in the development of the mineral assemblages, with both thermal overstepping and non-reactivity of certain minerals implied. Metamorphic conditions of 3-4 kbar and 450-500°C are similar to other estimates in the region (e.g. Sullivan Mine, Depaoli and Pattison, Can J Earth Sci, 1995). The use of garnet as an 'indicator mineral' for mineralization (Joncas and Beaudoin, 2002) is most effective under conditions of relatively low grade metamorphism (biotite zone and lower), where it is only in the anomalous mineralization-related rocks that garnet grows.

# Ag-Sb-BASE METAL DEPOSITS LINKED WITH ALKALINE MAFIC MAGMATISM IN THE ORE DISTRICTS OF EURASIA

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Linked with alkaline mafic magmatism Ag-Sb-base metal deposits represented by mainly siderite-bearing veins with prevailing Ag-Sb-sulfosalts and with Cu, Fe, Pb, Zn sulfides are localized often in Sn-Ag ore districts (Erzgebirge/Germany; Cornwall/UK; Pamir/Tadjikistan; Talas/Kyrgyzia; Yakutia/ Russia; SE Altai-NW Mongolia). Some of them have no spatial relationship to Sn mineralization (Coeur d'Alene/USA; Kaltatur/Pamir; Kumysh-tag/Kyrgyzia; Spišsko-Gemerske Rudohorie/Slovakia); other Ag-Sb-base metal ores associate with Sn-W(-Mo) and Sn-sulfide mineralization in the result of multistage ore formation (Erzgebirge/Germany, Cornwall/UK; Deputatsky ore district/Yakutia).

The main geological factors which control formation of Ag-Sb-base metal deposits are:

- 1) allocation in slightly to strong metamorphosed carbonaceous terrigenous sediments;
- 2) spatial and temporal link with alkaline mafic magmatism in intracontinental environment;
- 3) localization of Ag-Sb deposits in Sn-ore districts with post-collisional granitoid magmatism;

- 4) deposits are restricted to the deep-rooted over-regional fault zones.

Temporal correlation of the Ag-Sb-base metal mineralization with alkaline mafic magmatism (U-Pb SHRIMP and Ar/Ar dating), He isotope composition and Hg contents in the ores confirm participation of a mantle source in the formation of these deposits. Fluid and melt inclusion study in minerals from Ag-Sb ores and lamprophyre dikes of the same age shows that high concentrated chloride ore-forming fluids can be considered as volatile enriched derivatives separated from alkaline mafic melt, which produced lamprophyre dikes.

The Ag-Sb-base metal deposits are polygenic in terms of sources of ore elements and fluids. Several sources of the ore matter are considered: magmatic alkaline mafic (Ag, Sb, Hg, He, Fe, Pb, Cu, C) and inherited from host rocks such as carbonaceous terrigenous sediments (Cu, Ag, Pb, Fe, S, C) as well as granitic and monzonitic intrusions (F, Bi, Ba, Sr, S, Au, Ag).

Sufficient vertical range of mineralization (~800 m) and relatively low Ag contents in the ore (300–600 ppm) result from the temperature decrease and absence of geochemical barriers. Higher temperature gradient and dilution of magmatic fluids with meteoric water was a geochemical barrier for the Ag-rich ore formation in a narrow (~400 m) ore deposition zone.

#### **ROLE OF SEDIMENTARY BASINS IN FORMATION OF Ag-Sb-BASE METAL DEPOSITS OF EURASIA**

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Metallogeny of black shale sedimentary basins is represented by several types of hydrothermal mineralization including gold (Au-As, Au-Sb) and Ag-Sb-base metal deposits. Ag-Sb-base metal deposits represented by mainly siderite-bearing veins with prevailing Ag-Sb-sulfosalts and with Cu, Fe, Pb, Zn sulfides are localized in host carbonaceous terrigenous rocks of sedimentary paleobasins (Verkhoyansk marginal depression of the Late Paleozoic passive continental margin of Siberian craton in Yakutia/Russia, Delyun-Yustid back-arc basin in SE Altai and NW Mongolia; SE Pamir depression/Tadjikistan; Erzgebirge/Germany and Talas/Kyrgyzia in metamorphosed fragments of sedimentary paleobasins). The main geological factors, which control formation of Ag-Sb-base metal deposits are:

- 1) allocation in slightly to strong metamorphosed carbonaceous terrigenous rocks of sedimentary paleobasins;
- 2) spatial and temporal link of mineralization with intraplate alkaline mafic magmatism;
- 3) deposits are restricted to the deep-rooted over-regional fault zones.

Some deposits have no spatial relationship to Sn mineralization (Coeur d'Alene/USA; Kaltatur/Pamir; Kumyshtag/Kyrgyzia; Spišsko-Gemerske Rudohorie/Slovakia); other Ag-Sb-base metal ores associate with Sn-W(-Mo) and Sn-sulfide mineralization in the result of multistage ore formation (Erzgebirge/Germany, Cornwall/UK; Deputatsky ore district/Yakutia) in Sn-ore districts with post-collisional granitoid magmatism. Sn-bearing granites were formed in the result of melting of black shale and carbonaceous terrigenous rocks of sedimentary basins.

Temporal correlation of the Ag-Sb-base metal mineralization with alkaline mafic magmatism (U-Pb SHRIMP, Ar/Ar) and He isotope composition in the ores confirm participation of a mantle source in the formation of these deposits. Fluid and melt inclusion study in minerals from Ag-Sb ores and lamprophyre dikes of the

same age shows that high concentrated chloride ore-forming fluids can be considered as volatile enriched derivatives separated from alkaline mafic melt, which produced lamprophyre dikes.

The Ag-Sb-base metal deposits are polygenic in terms of sources of ore elements and fluids. Several sources of the ore matter are considered: magmatic alkaline mafic (Ag, Sb, Hg, He, Fe, Pb, Cu, C) and inherited from host rocks such as carbonaceous terrigenous sediments (Cu, Ag, Pb, Fe, S, C), as well as granitic and monzonitic intrusions (F, Bi, Ba, Sr, S, Au, Ag). Host rocks of sedimentary basins make strong impact on formation of Ag-Sb-base metal deposits that is evidenced by the results of geochemical and isotope-geochemical data.

#### **AN ARCHEAN SUPERCONTINENT OR SUPERCRAONS? EVIDENCE FOR A LATE ARCHEAN-EARLY PALEOPROTEROZOIC SUPERCRAON**

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The potential existence of a single supercontinent in the Archean has been the subject of extensive research in the past two decades. Recently, multiple studies have suggested the existence of at least three Archean supercratons (e.g. Superia, Sclavia and Vaalbara). In this study we highlight the evidence for global orogenesis at ca. 2.5 Ga and its implications for Archean supercraton formation. Orogenesis at this time is anomalous with respect to the majority of the well-studied Archean cratons such as the Pilbara, Yilgarn, Kaapvaal, Superior, Slave and Nain Cratons which appear to either have been tectonically stable or undergoing active rifting.

Orogenesis in the ca. 2.55-2.43 Ga period is recorded in the Gawler-Adelie Craton (Australia-Antarctica), Dharwar Craton (India), Napier Complex (Antarctica), Sask Craton (Canada), Rae Craton (Canada), Hearne Craton (Canada) and North Korean Peninsula. With the exception of the Hearne Craton, these terrains did not experience extensive orogenesis in the period 2.7-2.6 Ga, commonly assigned to a period of supercraton amalgamation. Previous studies have highlighted the presence of subduction-related magmatism leading up to ca. 2.5 Ga orogenesis in a number of the terrains. Combined with new evidence for high pressure metamorphism (~14-16 kbar) at ca. 2.49 Ga in the Dharwar Craton, we suggest this is sufficient evidence to indicate that orogenesis during this time period involved lateral accretion of terrains and collisional orogenesis. The combined geological and geochronological data are used to suggest the formation of a final late Archean-early Paleoproterozoic supercraton.

#### **REDISTRIBUTION OF RARE EARTH ELEMENTS DURING SYMPLECTITE FORMATION UNDER ULTRA HIGH TEMPERATURE METAMORPHIC CONDITIONS**

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Understanding the redistribution of rare earth elements (REE) during crustal reworking is important for addressing the stability of REE-rich accessory mineral phases in metamorphic systems and also for the meaningful application and interpretation of Sm-Nd and Lu-Hf geochronology. The systematics of REE redistribution within ultra high temperature (UHT) metamorphism is of particular interest as it is inherently difficult to provide constraints on the timing, duration and nature of these metamorphic events. By using the coupled approach of LA-ICP-MS trace element imaging and metamorphic petrology we are able to provide new insights



into the mobility of REEs in the lower crust and the duration of UHT metamorphism.

In this study, samples of differing rock types from a number of UHT terrains, including the Eastern Ghats (India), Rauer Group (Antarctica) and Southern Granulites Terrane (India), have been investigated. The analysed samples contain symplectic microstructures interpreted to form from the breakdown of garnet porphyroblasts during decompression and/or cooling. We demonstrate that rapid diffusion of REEs out of the symplectite microstructure occurs during its formation. Y and HREEs are strongly partitioned into either the relict garnet at the centre of the symplectite or into relict garnet 'islands' within the symplectite. In the case of Zr, L- and MREEs it is apparent that clinopyroxene is able to act as a major reservoir and preserves zoning in these elements with concentrations decreasing away from the symplectite. Zoning profiles of MREEs and HREEs in garnet are suggestive of varying diffusion rates for these elements.

## REASSESSMENT OF ISOBARIC AND MOLECULAR INTERFERENCES IN LA-MC-ICP-MS Hf ISOTOPE ANALYSIS

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The primary obstacle to accurate and precise in-situ Hf isotope analyses is the presence of isobaric and molecular interferences on a number of Hf masses. A significant effort has been devoted to demonstrating the robustness of correction methods for isobaric interferences of <sup>176</sup>Yb and <sup>176</sup>Lu on <sup>176</sup>Hf. To date this work has largely focused on the use of standard Hf solutions doped with interferants to determine the robustness of correction methods with supporting analysis of natural zircons. We have furthered this work by producing a series of glass beads doped with the JMC 475 Hf standard and varying concentrations of Yb, Gd and Dy.

Analysis of Yb-doped glass beads has demonstrated that Yb-Hf fractionation relationships derived via solution analysis differ slightly from the relationship observed during laser ablation analysis. The ability of LA-MC-ICP-MS analysis to correct for isobaric interferences in which <sup>176</sup>Yb/<sup>177</sup>Hf ratios exceed 0.8 (i.e. approx. three times that of <sup>176</sup>Hf/<sup>177</sup>Hf ratio) is demonstrated, highlighting the robustness of the isobaric interference correction measurements.

Theoretical calculations and measurement of Gd- and Dy-doped glass beads demonstrate that REE-oxides are also able to bias Hf-isotope data, potentially explaining a number of observed correlations between REE content of zircon and measured Hf isotope ratios. This effect is most apparent in high REE zircons and leads us to recommend monitoring of REE levels and oxide interference corrections.

## AVIAT DIAMONDS: A WINDOW INTO THE DEEP LITHOSPHERIC MANTLE BENEATH THE NORTHERN CHURCHILL PROVINCE

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The northern Churchill Province has become a region of avid diamond exploration activity in Canada. However, little is known about the mantle sources and residence history of diamonds in this area. We studied diamonds smaller than 1.1mm (-1DTC) from the ES-1 kimberlite sheet on the Aviat property, Melville Peninsula. The diamonds were analyzed for their carbon isotopic composi-

tion, nitrogen content and aggregation state to characterize their sources and residence history in the lithospheric mantle beneath the northern Churchill.

Carbon isotopic composition in some instances can be used to differentiate between peridotitic and eclogitic source parageneses for diamond. Both conventional and SIMS techniques were used to obtain  $\delta^{13}\text{C}$  values for the Aviat diamonds. Combining both techniques, the diamonds yielded  $\delta^{13}\text{C}$  values ranging from -29.7 to -0.7‰. A pronounced mode is present at -5‰, the value for mantle derived carbon, and this mode is characteristic for both peridotitic and eclogitic diamonds worldwide. The large range of  $\delta^{13}\text{C}$  values below -5‰ is indicative of at least a partially eclogitic paragenesis for Aviat diamonds. One diamond recovered from an eclogite xenolith, and hence of proven paragenesis, produced  $\delta^{13}\text{C}$  values around -5‰, perhaps indicating that the mode at -5‰ is made up of eclogitic diamonds.

Zonation was observed in several of the diamonds, with two trends in  $\delta^{13}\text{C}$ : (1.) Highly negative  $\delta^{13}\text{C}$  values in diamond cores and rim values around -5‰ with evidence for a stage of diamond resorption between the two growth stages. (2.) Core compositions with a  $\delta^{13}\text{C}$  around -5‰ and slightly (0.7-2.0‰) more negative values for the rims, again with evidence for resorption between the two growth events.

Nitrogen aggregation, quantified as the %B (relative percentage of fully aggregated B component), was measured using FTIR, and nitrogen content was measured using both FTIR and SIMS techniques. Aviat diamonds display higher than average nitrogen contents with point analyses ranging from 10-1700 at.ppm and %B components (from FTIR) ranging from 0-98%. A plot of nitrogen vs. %B (FTIR data) reveals that the diamonds span a range of time averaged mantle residence temperatures from ~1050-1300°C, indicating derivation of diamonds from sources of various depths at Aviat.

In concert, the nitrogen content and aggregation state and the carbon isotopic composition of the Aviat diamonds advocate for multiple growth events involving multiple fluid sources beneath the northern Churchill Province.

## HOW EVOLUTION CAN AFFECT SULFUR ISOTOPE FRACTIONATION

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Microorganisms produce characteristic isotopic depletions and enrichments in their substrates and waste by-products which can be preserved in the rock record. The current interpretation of the Earth's sulfur isotopic record is based on the isotopic signatures produced by modern microorganisms. An assumption however underlies biogeochemical studies of early Earth; that the fractionation of sulfur by modern microorganisms is of the same magnitude as microorganisms at any time in the past given the same environmental conditions.

Our experiments test this assumption by quantifying changes in sulfur isotope fractionation associated with documented changes in the sulfate reducing bacteria metabolism. The model organisms used are *Desulfovibrio Vulgaris* strain Hildenborough (Dvh) as well as a mutant of this strain (JW9019) which has a unique DNA barcode allowing us to track it in mixed populations of sulfate reducers. Competition experiments between ancestral and descendant strains track relative changes in the microorganism's growth rate, thus allowing quantitative tracking of evolutionary trajectories. Through precise growth assays, we can assure consistency and reproducibility of isotopic variations which are then correlated to variations in the microorganism's growth rate.

The overall results expected from this experiment are (1) sulfur isotopic fractionation might remain unchanged throughout the experiment; (2) isotopic fractionation might initially be affected by the new environment, but migrate back to its initial values during evolution, or even surpass its initial value; (3) Isotope fractionation may be affected by the stress and stay in its new fractionation regime indefinitely. Result 1 suggests that isotope fractionation is unaffected by evolutionary history. Result 2 and 3 would put into question the use of modern microbial metabolisms to directly transform isotopic variation of ancient rocks into environmental signals of early Earth.

#### **THE ANATECTIC PEGMATITIC URANIUM DEPOSITS OF THE UNGAVA BAY, NORTHERN QUÉBEC: GEOLOGY AND PETROGENESIS**

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A new major uranium district has been recently discovered in the Ungava Bay by AREVA and Azimut, following regional bottom lake geochemistry by the MNRF. Numerous uranium showings occur near the contact between the Achaean basement (zone Noyau, or Churchill zone) and the Proterozoic cover. Whereas in the northern zone, Cage U-rich skarns and pegmatoids are hosted in the Paleoproterozoic metasediments of the Lake Harbour Group, in the southern zone, the Daniel Lake and North Rae pegmatoids are hosted within the Achaean gneissic basement but most of them are located at less than 100 m from the unconformity with the Proterozoic cover. Pegmatoid sills reach hundred of meters in length on up to 10 m in thickness and are nearly concordant with the regional schistosity. They are deformed by large NW-SE trending folds and shears. With a very heterogeneous global composition consisting of variable proportions of mainly feldspars, quartz and biotite, with glomeroporphyritic texture, they correspond to the abyssal pegmatite type of London (2008).

Large facies variations are encountered, reflecting various degrees of fractionation, crystal inheritance or accumulation, reaction with enclosing rocks, and setting, with numerous evidences of multi-injection process. Barren pegmatites display tourmaline, garnets and apatite as key minerals. Large concentrations of uraninite, reaching several percent, are associated with biotite, molybdenite, and magnetite, with local uranophane.

Geochemical analysis on >500 samples, using Debon et Lefort (1983) parameters, show that the pegmatites are slightly peraluminous (A parameter <40), reflecting the quasi-absence of aluminous silicates, and suggesting a genesis by partial melting of the most felsic Achaean gneisses, with a relative stability of the biotite. Large variations of the B parameter reflect the mixing between the quartz-feldspathic eutectic magma and largely residual biotite. Most of the uranium appears to be related to the magmatic crystallization, with few evidence of post-solidus alteration.

#### **THE TAIHANG GIANT MAFIC DYKE SWARM AND XIONG'ER TRIPLE-RIFT VOLCANIC PROVINCE: PRODUCTS OF A 1780 Ma PLUME BENEATH THE SOUTH EDGE OF THE NORTH CHINA CRATON?**

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The 1780-1770 Ma Taihang dyke swarm is one of the most significant and best-preserved Precambrian swarms with a scale of over 1000 km across the central part of the North China Craton

(NCC) following the final amalgamation of the craton. This giant dyke swarm is interpreted to have a radiating geometry that is compatible with the Xiong'er triple-junction rift, which has north to south and east-south to west-north extensions of both about 500 km. In this triple rift, the Xiong'er volcanic province is dominated by mafic to intermediate rocks, and is proposed to be the extrusive counterpart of the swarm. The Taihang dyke swarm and the Xiong'er rift resulted in significant extension, uplift and magmatic accretion of the NCC, and it is comparable with the Phanerozoic Large Igneous Provinces (LIPs) in areal extent (~0.3 Mkm<sup>2</sup>) and estimated volume (~0.3 Mkm<sup>3</sup>), short lifespan (10-20 Ma), and intraplate setting. There are significantly more basaltic andesites to andesites than basalts in the Xiong'er volcanic province, indicating more crustal melts being erupted on the ground. This North China LIP is unique in that it comprises large volumes of both mafic and intermediate components. It could have resulted from extensive mantle-crust interaction, probably driven by a large-scale mantle upwelling. A plume tectonic model is favoured by several lines of supporting evidence (i.e. massive volcanic flows correlated over large areas and a giant fanning dyke swarm with plume-affinitive chemistry). It could be responsible for massive sulphide (Pb-Zn) and gold (Au-Ag) ore deposits in the Xiong'er volcanic province. Dismembered remnants of this magmatism in other block(s), with potential candidates in South America, Australia and India, could identify other cratonic blocks that were formerly connected to the south edge of the NCC. After this break-up, the south to southeast side of the NCC was never connected with other blocks till Triassic, when it collided with the South China Craton.

#### **GABBRONORITE-CHARNOCKITE-S-TYPE GRANITE-VOLCANIC SUCCESSION AND ULTRA-HIGH TEMPERATURE METAMORPHISM IN THE CENTRAL-NORTHERN MARGIN OF THE NORTH CHINA CRATON: IMPLICATION FOR A LATE PALEOPROTEROZOIC RIDGE SUBDUCTION**

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There is a 1930-1880 Ma gabbro-norites-charnockites-S-type granites-volcanic succession in the northern margin of the North China craton, where a 1930-1920 Ma ultra-high temperature metamorphic event is distinguished in the aluminous-rich sediments (deposited at 2000-1950 Ma). The Xuwuja gabbro-norites occur as dykes, sills and small plutons, and as numerous entrained bodies and fragments of variable scales in the Liangcheng charnockites and S-type granites. The Xuwuja gabbro-norites are tholeiitic and can be divided into a high-Mg (6-23 wt% MgO) and a low-Mg group (<6 wt% MgO). The Liangcheng granitoids are dominated by 1930-1890 Ma garnet-bearing peraluminous granitoids, and compose of two major garnet-bearing phases, i.e., initially a porphyritic coarse-grained phase (charnockites) and secondly or lastly a medium- to coarse-grained phase (S-type granites). The occurrence and chemical variations of the Xuwuja gabbro-norites and Liangcheng granitoids can be interpreted to have resulted from crust-mantle interaction, with mingling and different degrees of partial mixing of mantle (gabbro-noritic) and crustal (granitic) melts. The Xuwuja gabbro-norites originated from a mantle region with high potential temperatures (~1550°C), and could have had extremely high primary intrusion temperatures (up to 1400°C). Emplacement of these magmas was likely responsible for the extensive crustal anatexis (Liangcheng granitoids) and the local ultra-high-temperature metamorphism. The Halaqin volcano-sed-

imentary succession comprises greenschist- to amphibolite-facies schists, quartzites, marbles and amphibolites, which were originally pelites, pebbly sandstones, sandstones, limestones and volcanic rocks. The volcanics comprise basalts to basaltic andesites and dacites to rhyolites. The basalts to basaltic andesites divide into a high-Mg group and a low-Mg group, and are chemically similar to and likely extrusive counterparts of the two groups of the Xuwujia gabbro-norites, respectively. The dacites to rhyolites also have two chemically different groups and are possibly upper-crustal equivalents of the Liangcheng charnockites and S-type granites, respectively. We suggest that the above gabbro-norites-charnockites-S-type granites-volcanic succession and the regional ultra-high temperature metamorphism were most likely generated by ridge subduction just prior to the final amalgamation of the North China Craton.

#### THE ROLE OF MINERALOGY IN GEO-ENVIRONMENTAL ORE DEPOSIT MODELS

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To exploit an ore deposit with the least possible environmental impacts and risks, it is important to understand how its mineralogy may affect the local environs, both physically and chemically. Characterization of the quantity, texture, grain size, composition, crystallinity and alteration history of minerals gives insights as to how the minerals will react in processing and potentially impact the environment as waste products. The host rock, ore and gangue minerals can behave differently and thus may have detrimental or beneficial effects on the environment. For example, it is well known that carbonate gangue minerals associated with sulphide-rich ore bodies can help to minimize impacts from acid rock drainage upon oxidation of the sulphides. Secondary minerals formed in the surficial environment can act as a sink, or a source of contaminants such as metal(loids), sulphate, and acidity. At the Cobalt, Ontario mining camp, alteration of primary niccolite and cobaltite produces annabergite and erythrite, respectively, on the tailings surfaces. These secondary arsenate minerals form by efflorescence enhanced by wetting and drying cycles. These soluble phases can be flushed during rain events, thereby providing an ongoing source of Ni, Co and As to the local watershed. In comparison, the formation of relatively insoluble minerals such as scorodite in lode-gold mine tailings, provides a longer-term sink for contaminants in the mine environment. However, if environmental conditions change over time through depletion of sulphides or remediation efforts, these secondary minerals can become unstable and act as new sources of contaminants. With current technologies, minerals can be studied at the macro- to the nano-scale, in the field or in the laboratory, to determine how their surfaces may react to natural (hydrothermal alteration, diagenesis, pedogenesis, weathering) and man-made processes (mineral extraction) over time. This paper will examine the role of minerals as indicators of environmental change through case examples from several mining camps with different commodities (e.g. U, Ag, Au and Cu). It will focus on how mineralogy can be used in geo-environmental ore deposit models to anticipate potential environmental challenges during mining and reclamation activities.

#### 4D RADIO-WAVE GEOELECTRICAL MAPPING OF INTERWELL SPACE: SEARCHING AND MONITORING OF DEEP-SEATED MINERAL DEPOSITS

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Production technology development makes deep seated mineral deposits cost-effective. In order to provide necessary resolution of exploration of the deep seated areas, surface geophysical methods must be supported with borehole and crosshole geophysical studies. Crosshole radio-wave technique offers ample scope for exploration of such geological objects if they possess the resistivity contrast to bedrocks. The radio-wave technique is based on harmonic signal dependence from electrical resistivity of formations situated on a radio wave spreading route from a transmitter to a receiver. The crosshole measurements are carried out according to the "fan-shaped" pattern

Based on this method we have developed a new technology of 3D and 4D geoelectrical mapping. The new technology allows:

- the control and further account of the borehole transmitter characters;
- the adaptation of acquisition to various environments, by means of adjustment of radiation frequency and antennas (e.g. acquisition between distant wells, or in the low resistivity medium);
- the combined processing of several borehole-to-borehole sections, which permits to plot 3D resistivity maps, and to analyze diachronous observations.

The technology advantages are demonstrated by four examples of industrial application in various environments:

1. Search of the buried kimberlite pipes in the Yakutia region by means 400×400 m well grid. The area of 26 km<sup>2</sup> was examined. The 72% of the area was proved to be barren, that narrowed further investigation to the remaining 28% of the area. Main geological features were delineated.
2. Assessment of morphology and tectonics of the sulphide ore deposit in the Karelia region within 100×100 m well grid. The area of 1.1 km<sup>2</sup> was explored. Three ore zones were delineated by applying the radio-wave technology. The previous conception of the ore field morphology was changed.
3. Monitoring of the leaching process in the uranium field in the Ural region within 35×35 m well pattern. Block of 120×120 m was examined. The radio-wave observation, carried out before and after the leaching process start, permitted to determine the temporal and spatial distribution of the leaching solutions along the pay bed of the extremely low resistivity (<20 Ohmm). Morphology model of the ore block was corrected.
4. Monitoring of the artificial air body in the bearing formation of the uranium fields in the Uzbekistan region within 20×40m drilling grid. The area of 140×100 m was examined. Spatial distribution of air pumped into the pay bed was studied. The technology is therefore may be used for monitoring of the subsurface gas storage.

#### CRANSWICKITE MgSO<sub>4</sub>·4H<sub>2</sub>O, A NEW MINERAL FROM CALINGASTA, ARGENTINA

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Cranswickite is a newly recognised mineral of composition MgSO<sub>4</sub>·4H<sub>2</sub>O from Calingasta, San Juan Province, Argentina (IMA2010-016). Cranswickite is monoclinic, space group C2/c, a = 11.9236(3)Å, b = 5.1736(1)Å, c = 12.1958(3)Å, β = 117.548°(2), V = 667.0(1) Å<sup>3</sup>, Z = 4, d<sub>obs</sub> = 1.917 g/cm<sup>3</sup>, d<sub>calc</sub>

=1.918 g/cm<sup>3</sup>. The mineral occurs as a soft white vein filling in a metasedimentary rock. The atomic structure has been determined by direct methods and refined by Rietveld analysis of powder diffraction data. The atomic structure consists of chains of corner-sharing magnesium-containing octahedra and sulfate tetrahedra similar to the structure of pentahydrate. All the water molecules directly coordinate magnesium in the structure. The five strongest lines in the powder X-ray diffraction data are [*d*<sub>obs</sub> in Å (I)(hkl)]: 5.259 (100) (200), 3.927 (46) (1 1 -2), 3.168 (45) (1 1 -3), 4.603 (29) (1 1 -1), 2.570 (23) (3 1 1). Infra-red and Raman spectra are very similar to the spectra measured from starkeyite. The chemical composition of cranswickite is the same as starkeyite MgSO<sub>4</sub>•4H<sub>2</sub>O but starkeyite has an atomic structure where two sulfate tetrahedra and two Mg(H<sub>2</sub>O)<sub>6</sub> octahedra share corners to form a four-membered ring and not a chain as in cranswickite. The new mineral is named in honor of Lachlan M.D. Cranswick (1968-2010) an Australian crystallographer who helped to develop and maintain the Collaborative Computational Project No. 14 in Powder and Small Molecule Single Crystal Diffraction (CCP14).

#### U-Th-REE RICH SYENITES IN SOUTHERN NUNAVUT

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The presence of syenitic rocks in the region between Baker Lake, Dubawnt Lake, and Enekatcha Lake, that are enriched in U, Th, REE, Zr, and Y has been known for about 30 years. Potassic, microsyenitic (bostonite) dykes and coarse plutonic syenite (shonkinite) are rich in zircon, thorite, and monazite. Recent field work within the GEM-Uranium program has identified similar bostonite dykes transecting the Amer Belt at 125°-180°. Background field spectrometer readings are 500-700 cps, maximum reading 9000 cps, with eU/eTh = 239/23 ppm. The bostonite contains abundant monazite in syenite plus disseminated U-Th oxides, secondary U silicates, and REE carbonates associated with carbonate-rich central zones of meter-scale dykes. At the time of writing, rock analyses are pending.

Field relationships and petrography are consistent with all these intrusions being part of the extensive ultrapotassic volcanic province associated with feeder dykes and lavas of the Christopher Island Formation (lower Dubawnt Supergroup, ca. 1.83 Ga), and of being strongly fractionated from mantle-derived olivine-phlogopite-clinopyroxene (minette) magma. Rocks of similar bulk composition occur as flows in the upper portion of the Christopher Island Formation at Dubawnt Lake and Baker Lake. These lavas, also enriched in incompatible elements, commonly have compositional and petrographic characteristics more typical of lamproite than minette (e.g. groundmass leucite and tetraferriphlogopite).

Primary carbonate is common in the mafic minettes and has been described in cognate xenoliths interpreted as entrained samples of mantle source material. We interpret the carbonate portions of the bostonite dykes as a carbonatite phase, exsolved after extreme fractionation of minette magma. No outcrops of carbonatite have been described within the minette province, but we speculate that many enriched syenitic intrusions are present in the region, and are partly responsible for the numerous, anomalously radioactive regions seen on gamma ray maps east and south of Dubawnt Lake. We present detailed descriptions of the recently discovered occurrences, plus regional U-Th-REE data in the context of other Proterozoic igneous rocks (mainly granite) of the Dubawnt Supergroup.

#### VISUALAGE: A NOVEL APPROACH TO U-Pb GEOCHRONOLOGY

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VisualAge, a new tool for reducing U-Pb geochronology data, has been developed as an add-on for Iolite, the freely available ICP-MS data analysis tool. VisualAge consists of two main components: an Iolite data reduction scheme (DRS) and Igor Pro visualization routines. The VisualAge DRS improves upon the original Iolite U-Pb geochronology DRS by calculating <sup>207</sup>Pb/<sup>206</sup>Pb ages and common lead corrected ratios and ages for each point of an ICP-MS intensity versus time signal. More importantly, VisualAge can display a "live" concordia diagram as integrations are selected in Iolite, thus providing immediate visual feedback as to data discordance, error, and common lead contamination for different regions of the ICP-MS signal. This feature is particularly useful for LA-ICP-MS zircon data, where the signal from a single grain can consist of zones of concordance, disturbed or metamict areas, as well as inherited cores or younger overgrowths.

#### EVOLUTION OF THE LITHOSPHERE BENEATH THE WESTERN CHURCHILL PROVINCE: U-Pb GEOCHRONOLOGY OF ZIRCON FROM KIMBERLITE-HOSTED LOWER CRUSTAL XENOLITHS

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Zircon recovered from lower crustal xenoliths can preserve unique geodynamic records of relatively unexplored levels of diamondiferous lithosphere. We present the first such data from two Archean crustal blocks located within the western Churchill province, Nunavut, Canada. Zircon U-Pb geochronology and trace element analysis were conducted using a SHRIMP II (Geological Survey of Canada) on four mafic granulites (grt-cpx-plg) from the Chesterfield block, Hearne province and five mafic granulites (grt-cpx-plg±hbl±opx) and three felsic granulites (plg-cpx-plg±hbl±opx) from the Repulse Bay block, Rae province. SEM-CL(colour) imaging of zircon revealed a complex range of morphological and textural features. Mottled or oscillatory-zoned cores mantled by uniformly zoned metamorphic rims are a ubiquitous characteristic of both suites. For the Rankin Inlet xenolith suite, oscillatory-zoned, igneous zircon cores from two xenoliths record <sup>207</sup>Pb/<sup>206</sup>Pb ages of ca. 2.85 to 2.75 Ga, whereas mottled textured, metamorphic zircon cores from one xenolith yield ages of ca. 2.00 to 1.90 Ga. Metamorphic zircon rims from all four xenoliths record ages of ca. 1.75 to 1.65 Ga. Mottled textured and oscillatory-zoned zircon cores from the Repulse Bay xenolith suite yield minimum ages between ca. 3.50 and 2.60 Ga. Metamorphic zircon rims were recognized in all eight xenoliths and yield ages of ca. 1.80 to 1.65 Ga. The trace element compositions of the metamorphic zircon rims from both xenolith suites differ from those of older zircon cores, with the former characterized by lower HREE contents and low (Lu/Gd)<sub>N</sub>, suggesting garnet crystallization syn- to pre-zircon growth at ca. 1.80-1.65 Ga. The Archean ages of zircon cores correspond broadly to the upper crustal ages of the two blocks; however, prevalence of ca. 1.80-1.65 Ga metamorphic zircon rims suggests regional-scale thermal reworking of the lower crust during the Paleoproterozoic. Although both areas experienced significant Paleoproterozoic tectonic reworking between 1.90 and 1.83 Ga, and subsequent intracratonic extension up to 1.75 Ga, the lower crustal xenoliths record the influence of a much younger process that occurred as much as ~100 Ma after

termination of these upper crustal events. Previously unrecognized regional magmatic underplating and/or remobilization of mantle lithosphere may account for this terminal stage in western Churchill cratonization.

#### **A SOIL-LEAD BIOACCESSIBILITY ASSESSMENT OF RESIDENTIAL PROPERTIES IN ST. JOHN'S, NEWFOUNDLAND AND LABRADOR**

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The primary goal of this study is to map soil lead bioaccessibility levels by housing age and location on residential properties in order to better understand exposure risk for young children in St. John's and to test the hypothesis that there is a strong spatial dimension to soil lead bioaccessibility related to lead sources. For St. John's, a largely non-industrialized city, former lead sources include leaded paint and gasoline and the products of coal combustion. This study forms part of a larger project to investigate children's blood lead levels in relation to environmental lead concentrations across the city.

Two approaches to the determination of soil-lead bioaccessibility are pursued in this study: direct measurement and estimation based on soil characteristics. A total of 417 soil samples from 201 residential properties across six housing age categories were collected as part of the study. In the first approach, a subset of 48 samples underwent three digestion methods: a water leach, an in vitro bioaccessibility digestion (EPA method 9200.1), and a 1M nitric acid digestion. Results from the three methods will be compared against soil sample type – dripline or ambient – a proxy for lead source in this study and across housing age categories. In the second approach, soil characteristics related to lead bioaccessibility were analyzed for each sample: pH, cation exchange capacity, grain-size and organic matter content. A predictive model will be constructed by combining results from both approaches on the sample subset.

#### **CHARACTERIZATION OF SHOCK IN THE IMPACT-MELT-BEARING BRECCIAS OF THE MISTASTIN LAKE IMPACT STRUCTURE, LABRADOR**

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The extremely high temperatures and pressures that result from hypervelocity impacts generate a unique suite of rock-types, many of which are still poorly understood. Through the study of shock effects and clast variation we hope to place constraints on the formation and source material of one of these rock types, commonly referred to as "suevite" but referred to here as impact-melt-bearing-breccia. The ~28 km diameter, ca. 36 Ma Mistastin Lake impact structure presents an excellent opportunity to understand the genesis of impact melt-bearing breccias as these lithologies are well preserved and are found in a variety of stratigraphic sections. At Mistastin, impact-melt-bearing breccias occur both underlying and overlying coherent impact melt rocks, and in a dyke-like intrusion into metamorphosed basement rocks; this variation in stratigraphic location suggests an extremely dynamic mode of emplacement. Fieldwork and sampling was conducted at various locations around the Mistastin Lake impact structure during the 2010 field season. Thin sections have been examined to quantify and compare shock effect variation between the lithic matrix and the mineral inclusions in the glass clasts. Examination of the shock effects sustained by the different components of the breccia will

provide clues to its origin and emplacement mechanism. Additionally, this investigation will quantify the number of glass clasts and variations between them including what fraction appears to have been solid before incorporation into the breccia and what fraction exhibits flow and partial mixing with the matrix.

#### **LOWER PALEOZOIC ALKALIC BASALT VOLCANISM IN THE SELWYN BASIN AREA, SOUTHEAST YUKON**

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Recent revision bedrock mapping in Coal River map area (NTS 95D) in southeast Yukon has improved understanding of the stratigraphic position and chemistry of Lower Paleozoic volcanism in the area. Volcanism occurs in several stratigraphic intervals ranging from Lower Cambrian to Lower Ordovician. Previously these horizons have been informally termed the Toobally, Gusty, and Coal River volcanics.

Interbedded massive, pillowed and autobrecciated flows, volcaniclastic debris, and tuffs ranging from a few metres to more than 1300 metres-thick were mapped in Lower Cambrian and Lower Ordovician siliciclastic and carbonate successions. Locally dykes and sills occur below and within the volcanic packages.

The flows consist of plagioclase, rare clinopyroxene and olivine phenocrysts in an aphanitic matrix containing plagioclase microlites, iron oxides and chlorite. Typically the olivine phenocrysts are altered to a chlorite. Primary textures are clearly visible in samples from the east side of the Coal River map sheet. With increasing metamorphism and/or alteration in a westward direction, plagioclase is replaced by sericite and/or calcite and/or epidote. Western exposures in the map sheet have an incipient to pervasive deformation fabric overprinting and destroying primary textures.

The oldest exposed volcanic horizon occurs within the Proterozoic to Lower Cambrian siltstone and silty phyllite of the undivided Vampire-Narchilla formations. This horizon is intruded by a medium-grained, hornblende-plagioclase diabase with similar chemistry. Conodont age determinations from adjacent carbonate beds constrain the younger volcanic horizons to Tremadocian and Floian stages of the Ordovician period.

Chemically the volcanic rocks and associated intrusions have an overall Oceanic Island Basalt signature. Discriminant diagrams indicate they are alkali basalts with within-plate or rift-related tectonic affinities. The oldest Lower Cambrian horizon has significant depletions in zirconium, hafnium and titanium. This depletion pattern is consistent with incipient partial melting of a source containing hornblende or garnet.

These exposures are part of a regionally-extensive belt of Lower Paleozoic basaltic volcanic rocks within, and adjacent to, Selwyn basin (including Menzie Creek volcanics near Faro, Marmot volcanics on the NWT-Yukon border at 64°N, and southern Ogilvie Mountain volcanics north of Dawson City). They reflect episodes of submarine eruptions possibly related to rifting after the formation of the passive margin of northwest Laurentia (present orientation).

## ZIRCON FROM ALKALINE PEGMATITES IN THE LARVIK PLUTONIC COMPLEX, OSLO RIFT VALLEY, NORWAY – IMPLICATIONS FOR PETROGENESIS FROM TRACE ELEMENT GEOCHEMISTRY

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On the basis of textural, mineralogical and geochemical characteristics, six distinct alkali-feldspar syenite pegmatite types have been defined in the Larvik plutonic complex (LPC), Norway: (1) Stavern (S)-type; (2) Stålaker (ST)-type; (3) Tvedalen (T)-type; (4) Langesundsfjord (L)-type; (5) Bratthagen (B)-type; and (6) external (EX) pegmatites found intruding earlier alkali basalts. A detailed EMPA and laser-ablation ICP-MS study of the REE composition of zircon in these six pegmatite types shows the following characteristics. Primary zircon from miaskitic S-, T- and ST-type pegmatites have REE = 704 ppm, are depleted in LREE, have a moderately-steep LREE slope (Sm/La = 484-650), steeper HREE slope (Lu/Gd = 23 – 43), significant positive Ce anomaly (Ce/Ce\* = 44 – 67), and negative Eu anomaly (Eu/Eu\* = 0.15-0.18). Secondary T-type zircon are REE-enriched (REE = 5035), with a flatter REE pattern (Sm/La = 0.13; Lu/Gd = 30), Ce/Ce\* = 0.97 and a Eu anomaly similar to primary T-type zircons (Eu/Eu\* = 0.21). Secondary zircon from agpaite L-type pegmatites display a distinctly different REE pattern characterized by overall REE enrichment (REE = 967), a flat profile with Sm/La = 10, Lu/Gd = 9, Ce/Ce\* = 1.92, and a minor negative Eu anomaly (Eu/Eu\* = 0.37). Zircon from agpaite B-type pegmatites occurs as both a primary and a secondary phase and are strongly enriched in REE relative to other zircon (REE = 4178 and 8388, respectively). Primary B-type zircon have a similar REE pattern to miaskitic zircon, with a steeper HREE profile (Lu/Gd = 20), and reduced Ce and Eu anomalies (Eu/Eu\* = 0.73; Ce/Ce\* = 6.22). Secondary B-type zircon are strongly enriched in LREE compared to primary zircon, do not display a positive Ce anomaly with Eu/Eu\* = 0.56. Both primary and secondary B-type zircons have elevated Th/U ratios (631 and 2114, respectively, versus 0.21 – 0.71 for all other zircon), suggesting a different melt source for B-type pegmatites. Pegmatites external to the LPC have similar trace element signatures as S-, T- and ST-type primary zircons with Ce/Ce\* = 214 and Nb/Ta and Th/U ratios that are more akin to those of secondary L- and B-type zircons. It is suggested that these external pegmatites have the same parental melt as the miaskitic pegmatites, but have undergone alteration by hydrothermal fluids derived from the host basalt or post-magmatic F-rich fluids which mobilize Nb and Th.

## ON THE FORMATION OF THE LITHOSPHERE IN THE EARLY AND MIDDLE ARCHEAN

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At the time of the magma-ocean the early Earth atmosphere was very dense (with minimum pressure ca. 35 MPa) and composed of compounds mostly in supercritical conditions, which formed atmospheric layers separated by density. The main layers of the early Earth atmosphere were sulfur, carbon and water. Formation of the early lithosphere started with the stratification of the magma-ocean by density and iron content and starting solidification of the magma-ocean. First the "Forsterite layer" was formed, having the highest solidus temperature among silicates, then surface layers of felsic magmas followed by solidification of inter-

mediate magmas below the felsic layer, mafic magmas below the intermediate layer and ultramafic magmas below the mafic layer of the forming lithosphere. The presence of Hadean zircons of up to 4.4 Ga shows that solidification of the felsic layer started by this time and the surface temperature dropped below ~1173°K, the temperature of resetting zircon ages. Appearance of significant amounts of basalts and komatiites in Pilbara and Kaapvaal cratons points to the solidification of both felsic and intermediate layers by that point. Negligible amounts of sediments prior to the start of Warrawoona Gr. and Onverwacht Gr. deposition at ca. 3.55-3.52 Ga shows that the water-ocean had most likely not yet formed, and temperature of layers of the formed lithosphere at that point was just below the solidus temperatures of dry rocks. However, formation of numerous chert layers of regional significance in both Warrawoona Gr. and Onverwacht Gr. indicate the beginning of direct interaction of water with surface rocks, marking the beginning of water-ocean formation. This is also supported by sharp change of Nb/Th and Th/U ratios at ca. 3.6 Ga. Formation of numerous barite deposits in both Pilbara and Kaapvaal cratons during 3.55-3.20 Ga indicate the complete redistribution of the sulphur-layer of the atmosphere and drop of surface temperature below ~700°K, making the density of water greater than that of CO<sub>2</sub> and giving the water-layer direct contact with the surface, leading to formation of water-ocean. Formation of barite deposits also shows that the surface temperature dropped below 610-611°K (the boiling point of H<sub>2</sub>SO<sub>4</sub>). Appearance of significant amounts of rhyolites and dacites in the Mid-Archean Fig Tree Group (3.26-3.23 Ga) of Kaapvaal craton and Kangaroo Caves Fm. (3.24 Ga) of Pilbara craton mark the beginning of water penetrating into crustal layers, significantly dropping solidus temperatures (wet solidus) and starting to rework the entire lithosphere formed by then.

## GOLD POTENTIAL RESOURCES IN ECUADOR, SOUTH AMERICA

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Ecuador is a small country of 264,000 square kilometers, with a great Geo-biodiversity. The new Constitution and the Mining Law, gives expressly rights to the nature, and this is an innovation at the global level, the State may not earn less than the mining enterprise and requires the application of technologies with low environmental impact and benefits to surrounding communities and local governments.

Ecuador is part of the fire Pacific ring and is affected by the triple interaction of the Cocos and Nazca plates with South America and the Caribbean, where active subduction zone of Peru-Ecuador-Panama plays an important role in the formation of favorable geologic environments for the generation of mineral deposits.

For the estimation of gold bearing potential, we used the data base with geological, mining, geochemistry, structural, ores, etc., located in the Library "BOB RIBERA" by FUNGEOMINE, besides the experience and work for more than 30 years working in gold exploration of the author, and data from websites of public mining companies, have allowed these valued mineral resources.

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The gold bearing potential is evidenced by the presence of 637 mineral occurrences, classifieds in 153 geochemical anomalies, 51 old gold mines, 17 deposits, 203 evidences, 96 small scale gold mines in operation, and 117 gold prospects, which are located

in the both flanks of the Andes ridge, plus 6500 kilometers of line rivers with evidence of alluvial gold.

These data correlated with the lithology and structural geology of Ecuador, helped to identify 14 highly favorable litho tectonic belts to contain gold deposits, and 13 metallogenic bands identified.

To evaluate the gold potential, was plotting between deposits and prospects: 13 occurrences of high epithermal sulphidation, 56 low epithermal sulphidation, 48 undifferentiated epithermal, 9 mesothermal, 21 porphyry Cu-Au, 35 porphyry breccias Cu-Au, 10 occurrences of skarn type, 5 massive sulphide, and 3 Cu-Mo with low Au.

In these instances, it is determined a resource potential for primary gold in 94 million ounces.

#### **NOBLE GASES, STABLE ISOTOPES ( $\delta^2\text{H}$ , $\delta^{18}\text{O}$ , $\delta^{37}\text{Cl}$ , $\delta^{81}\text{Br}$ ) AND $^{87}\text{Sr}/^{86}\text{Sr}$ OF GEOTHERMAL WATERS OF THE LOS AZUFRES FIELD, MICHOACAN, MEXICO**

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Los Azufres is a Pleistocene volcanic caldera hosting the second most active geothermal field in Mexico. Volcanic activity began 18 Ma ago, producing andesite that constitute the main aquifer of the field. Andesitic volcanism lasted until 1.0 Ma ago, followed by silicic volcanism up to 0.15 Ma and represented by rhyolitic and dacitic domes. Three different fault systems (NE-SW, E-W and N-S) confer secondary permeability to these formations. Geothermal manifestations (fumaroles, solfataras and mudpits), and location of significant energy production zones are related to the E-W fault system. Despite extensive investigations, the functioning of the recharge zone with respect to fluid circulation and the effects of reinjection of used water on the enthalpy of the field are not completely understood. Here, we present preliminary results of an extensive survey of noble gases (He, Ne, Ar, Kr and Xe), stable isotopes ( $\delta^2\text{H}$ ,  $\delta^{18}\text{O}$ ,  $\delta^{37}\text{Cl}$ ,  $\delta^{81}\text{Br}$ ) and  $^{87}\text{Sr}/^{86}\text{Sr}$  in order to reconstruct past fluid circulation in these formations. Twelve wells and eight hot springs and fumaroles were analyzed. Three hot springs from the Araro locality, located 30 km northwest of the field, outside the caldera rim were also analyzed to ascertain whether or not the fluid circulation extends beyond this area. Noble gases are mainly atmospheric except for He. Helium shows a strong magmatic  $^3\text{He}$  signature with  $^3\text{He}/^4\text{He}$  ratios (R) normalized to that of air ( $R_a$ ) ranging from 4.5 to 7.0  $R_a$ , where  $R/R_a$  of the upper mantle is 8 $R_a$ . Some geothermal wells and hot springs display higher  $^{40}\text{Ar}/^{36}\text{Ar}$  values with respect to that of the atmosphere (295.5), which are accounted for by mass fractionation during boiling and steam separation. However two wells (AZ-62 and AZ-13) display high  $^{40}\text{Ar}/^{36}\text{Ar}$  values ( $429 \pm 3$  and  $366 \pm 2$ , respectively) that might result from incorporation of in-situ radiogenic  $^{40}\text{Ar}^*$ . The heavier noble gases are all atmospheric and  $^{20}\text{Ne}/^{36}\text{Ar}$ ,  $^{84}\text{Kr}/^{36}\text{Ar}$  and  $^{132}\text{Xe}/^{36}\text{Ar}$  ratios are clearly fractionated due to boiling and steam separation. Stable isotopes of water are directly correlated and deviate from the GMWL, pointing to mixing between a young freshwater recharge component and magmatic water component. This is supported by a positive correlation between  $\delta^2\text{H}$  and  $^3\text{He}/^4\text{He}$  ratios. Interestingly, a direct correlation between  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^3\text{He}/^4\text{He}$  ratios is observed with the magmatic component displaying  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios between 0.7048 and 0.7050, similar to those measured in the rhyolitic and dacitic rocks.

This suggests that the source of heat (and  $^3\text{He}$ ) is related to the last silicic volcanic episode.

#### **TEMPORAL TRACE METAL DYNAMICS OF FRESHWATER FLOC**

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Suspended floc is a significant metal sequestering compartment in aquatic systems. Results to date indicate floc microbes and associated extracellular substances act as templates for accumulation of metal reactive amorphous Fe oxyhydroxides, while hydrologic energy-regime significantly influence overall floc metal behaviour by facilitating exchange of Fe oxyhydroxides with surficial bed sediments. Metal retention of floc Fe oxyhydroxides is likely to be temporally dynamic in shallow wave-dominated beach environments. This is due to diel variations in water-column physico-chemistry (e.g. photosynthetic driven pH changes), constantly changing hydrological energy-regimes and the potential existence of floc associated microbial Fe metabolisms (i.e. facilitating formation/dissolution of Fe oxyhydroxides). Characterizing the combined role of the diel-linked physical and biogeochemical parameters on floc metal dynamics would further understanding of contaminant cycling directly relevant to water management needs for freshwater beaches.

The objectives of this field-based study were to investigate: 1) metal distributions between suspended floc, bed sediment and water-column aqueous compartments; 2) reactive solid phases for metal sequestration and 3) potential floc associated Fe metabolisms as they influence floc metal behavior under diel variations in water-column physico-chemistry and hydrologic conditions within an urban freshwater beach. Water, floc and bed sediments samples were collected at Toronto Sunnyside Beach during a 12-hour sampling campaign (July 21, 2010) for trace metal analysis (Ag, As, Cu, Co, Ni and Pb). Floc and bed sediments metal partitioning were determined by sequential extraction. Laboratory enrichments targeted potential floc associated microbial Fe metabolisms (e.g. heterotrophic Fe reducing bacteria, acidophilic Fe oxidizing bacteria). Flocs and their associated microbial consortia were visualized for internal structure (TEM), elemental analysis (TEM-EDS) and internal geochemical gradients (fluorescent pH probes). These results, characterizing diel-linked floc metal partitioning with physico-chemical, hydrologic, microbial metabolic-regimes and their implications for metal cycling in aquatic systems will be presented.

#### **LAB TO FIELD SCALE EFFECTS ON CONTAMINATED NEUTRAL DRAINAGE PREDICTION FROM MINE WASTE ROCKS**

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Minerals within the mine wastes, particularly sulfides like pyrite and pyrrhotite, may oxidize upon contact with oxygen and water from atmospheric conditions to produce sulfates and metals which may be released into the environment through mine drainage. The acidity generated by sulfide oxidation may lead to acid mine drainage (AMD), characterized by acidic pH and high levels of sulfates and dissolved metals, when neutralization by other minerals cannot maintain near-neutral conditions. Contaminated neutral drainage (CND) conditions are obtained if the neutralizing minerals are able to maintain near-neutral conditions but metal levels still exceed the accepted levels. The quality of mine drainage water is often predicted with laboratory prediction tests. However, many



factors controlling the release rates of chemical elements, such as the pH, the liquid to solid ratio, the secondary mineral precipitation, and the grain-size distribution and related surface phenomena (sorption, ion exchange, etc.) may show significant variations between the laboratory and field scales. Moreover, mechanisms such as surface kinetics, liquid transport mechanisms or thermodynamic equilibrium between substances exert influence over reaction rates. Consequently, laboratory and field results sometimes show considerable differences in release rates or contaminant concentration in drainage waters. Understanding the scale influence on the different factors that affect the geochemical behaviour of mine wastes is necessary in order to extrapolate results from the laboratory to the field. No model or general equation is available which enable to predict field weathering rates from laboratory-derived weathering rates. The present study focuses on CND-generating waste rock from the Tio mine (Rio Tinto), in Québec, Canada, where Ni concentrations in the drainage waters of some of the waste rock piles sometimes exceed the regulated limits. The main objectives are to compare prediction results obtained at the laboratory (humidity cells) and field scales (field test pads and actual waste rock pile), and to understand the scale factors involved. Kinetic prediction testing with humidity cells on Tio mine waste rock samples generate contaminant concentrations in drainage waters that are 3-4 orders of magnitude lower than those observed in the piles. To the author's knowledge, this is the first study to focus on scale effect on drainage prediction for CND generating waste rocks with low sulphide levels. Results should enable a more accurate CND prediction for mine wastes from laboratory results.

#### **HUMAN-INDUCED CLIMATE CHANGE: WHY I AM SKEPTICAL**

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Climate cycles are of galactic (143 my), orbital (100,000, ~41,000 and ~21,000 yr), solar (1,500, 210, 87, 22 and 11 yr), oceanic decadal (~30 yr) and lunar tidal (~18.6 yr) origin. Sporadic climate changes are caused by super volcanoes, supernoval eruptions, tectonism and possibly impacts. Since the Hadean, Earth has been degassing CO<sub>2</sub> and CH<sub>4</sub> from plutonism, volcanism and metamorphism, before, during and after volcanic eruptions from gas vents, hot springs and craters. Submarine degassing occurs from at least 3.4 million off-axis basaltic volcanoes and from the 64,000 km strike length of mid ocean ridges. Submarine CO<sub>2</sub> dissolves in cool high-pressure bottom waters for degassing to the atmosphere thousands of years later.

Ice on Earth is rare. Planet Earth has been warmer and wetter than at present >80% of time and, since late Archaean, atmospheric CO<sub>2</sub> has decreased from ~30%v to 0.039%v. The decrease in CO<sub>2</sub> results from the long-term biota-assisted sequestration into carbonate rocks and altered rocks. In former times of high atmospheric CO<sub>2</sub>, oceans were not acid, there was no runaway greenhouse and the rate of change of temperature, sea level and ice waxing and waning was no different from the present. Doubling or quadrupling of CO<sub>2</sub> will have very little effect on temperature unless atmospheric CO<sub>2</sub> residence times increase by two orders of magnitude. To argue that temperature and sea level are increasing depends on when measurements first started. Since 1842, it has been known that coral atolls rise with rising sea level. Coastal planning based on 'global sea level rise' ignores compaction, sedimentation and tectonism.

Six major ice ages since the Palaeoproterozoic were all initiated when atmospheric CO<sub>2</sub> was higher than now. CO<sub>2</sub> increases follow temperature rises during deglaciation. Temperature decreases (1880-1910, 1940-1976, 1998-present) show no correlation of temperature with CO<sub>2</sub> increase, therefore no causation.

Ongoing Milankovitch, solar and PDO cycles will lead to another glaciation as part of the present ice age that started at 34 Ma.

Humans have adapted to live on ice, in mountains, in the desert, in the tropics and at sea level and can adapt to future changes. During interglacials, humans have created wealth; populations grow; glaciation is heralded by famine, starvation, disease, depopulation. Humans, although not the dominant biomass of Earth, have changed the surface of the planet. Pollution kills, CO<sub>2</sub> is plant food, H<sub>2</sub>O vapour is the main greenhouse gas. Climate models throw no new light on climate processes.

#### **THE BROKEN HILL Zn-Pb-Ag DEPOSIT, AUSTRALIA**

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The world's largest Zn-Pb-Ag deposit (Broken Hill) has produced some 300 Mt of high-grade ore. The nine masses of 1685 Ma sulphide rocks have undergone multiphase coeval high-grade metamorphism and intense deformation in the Olarian Orogeny (1600 Ma) and coeval lower grade metamorphism and deformation in the Delamerian Orogeny (500 Ma).

Metasediments hosting sulphide rocks show four upward coarsening cycles. At 1685 Ma, high Fe-high Ti tholeiitic basalt sills (Unit 4.4) intruded wet sediments and crystallized at a buoyancy front. Pelite-capped psammite units constrained sulphur-poor geothermal systems that leached evaporites (Unit 4.2). Reactive minerals in volcanics and felsic metasediments were preferentially altered. Metasediments below the Broken Hill orebody (Unit 4.5) show extensive hydrothermal alteration and now comprise blue quartz-manganooan garnet-ferroan gahnite-plumbian orthoclase assemblages with minor sulphides.

Sudden deepening (Unit 4.6) coeval with felsic pluton intrusion at 1685 Ma resulted in breaching of an extensive pelite cap. Oxidised sulphur-poor geothermal fluid precipitated an iron formation now comprising a finely laminated quartz-magnetite-spessartine-fluor apatite ± hyalophane-sphalerite-gahnite-plumbian orthoclase rock. Repeated intrusion of felsic and mafic rocks occurred after deposition of a thick sequence of overlying shallow water psammites stratigraphically equivalent to thin distal sub-aerial felsic pyroclastics (Unit 4.7).

A transgressive sulphide-bearing footwall alteration zone (C Lode) operated as a conduit for the episodic release of fluids for the stratiform zinc lode B Lode, upper and lower A Lode, upper and lower No 1 Lens. The Western Mineralisation comprises all six zinc lodes and formed by replacement of psammites and minor pelites beneath the water-sediment interface. The zinc lodes and the Western Mineralisation are enveloped by a large quartz-manganooan almandine-gahnite alteration assemblage.

Psammitic metasediments overlying the zinc lodes contain the stratiform No 2 and No 3 Lenses (lead lodes). Much of the galena in the zinc lodes overprints earlier sphalerite-rich horizons. Spessartine- and gahnite-bearing rocks stratigraphically equivalent to the Broken Hill orebody are exhalites whereas strike equivalent tourmalinite and possibly some quartz-gahnite rocks may have formed from stratal flow and metal precipitation in psammite aquifers. The sequence was covered by a pelite sequence (Unit 4.8) that contains minor quartz-spessartine-magnetite-fluor apatite, quartz-gahnite, magnetite and quartz-tourmaline horizons.

During the Olarian and Delamerian Orogenies sulphide rocks reacted with enclosing metasediments to form spessartine- and gahnite-rich rocks, sulphide rocks moved as cataclastites along axial plane cleavages, into fold hinges and into dilational jogs. During the Olarian Orogeny, manganooan garnet rocks at the edge of the lead lodes were overprinted by a Cu-As-Au-U assemblage.

## AN OVERVIEW OF EARTHQUAKE LOSS ESTIMATIONS FOR THE CITY OF OTTAWA: PAST, PRESENT AND FUTURE

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For many Canadian cities, earthquakes are one of the only city-wide hazards with crippling physical, social and economical losses. Advancements have been made with respect to earthquake loss estimations in Canadian settings but a generalized model for engineering and social risk assessment for Canadian cities is required. Ploeger (2010) demonstrated the vulnerable and unsafe pre-conditions existing in the city of Ottawa using earthquake loss estimations via HAZUS (Hazards United States). As a compliment to the HAZUS model, we present our efforts to develop engineering and socially based seismic risk assessment tools for the Canadian context. Using GIS concepts and geophysical/geological information, a seismic site class map of Ottawa was published in 2009 by the Geological Survey of Canada (GSC) and the Canadian Seismic Research Network (CSRN) depicting the variation of expected ground shaking across Ottawa based on the type of surficial materials. We briefly outline the production of this map and its use within a GIS—based software application used for earthquake loss estimations and risk assessment called arcCanRisk. The ArcGIS-based CanRISK software developed at the University of Ottawa's Hazard Mitigation and Disaster Management Research Centre, integrates site specific spatial information from the 2010 seismic site class map with seismicity from the 2005 edition of the National Building Code of Canada, using a probability of 2% in 50 years. In addition, this tool allows for various levels of engineering risk assessment with detailed user-input that includes building-specific data that establishes the damage level and seismic risk for different structures. Finally, we provide a proposed multidisciplinary seismic disaster management framework that builds on recommendations presented in Ploeger (2008). This new framework and its integration with arcCanRisk will fill a much needed gap in the translation of earthquake loss estimations into management principles including decision-making in mitigation, response, and recovery.

## PALIMPSEST GLACIAL DISPERSAL TRAINS AND IMPLICATIONS FOR MINERAL EXPLORATION

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A glacial palimpsest dispersal trains is defined as a pre-existing train deposited in a given sense of ice movement that has escaped destruction or been modified by subsequent ice movement(s) of different direction(s). Such dispersal trains have been identified in glaciated regions of the Keewatin and Labrador Sectors of the Laurentide Ice Sheet, in the Appalachian Ice Complex, and the Cordilleran Ice Sheet. More are being discovered as complex ice-flow histories are deciphered through detailed and regional studies. The palimpsest dispersal patterns are defined by till components such as clasts, mineral grains, or geochemical concentrations of elements or compounds of known provenance. In some cases, the first dispersal train is only partly modified by a subsequent ice movement which implies that the till associated with the first ice movement was not completely eroded and redeposited or buried by the younger ice movement(s). A parallel can be made between palimpsest glacial dispersal trains and palimpsest glacial landforms in which case an earlier formed set of glacial landforms is partly reworked, deformed or overprinted by a subsequent ice movement. Palimpsest dispersal trains and landforms attest to the complexity of the erosional and deposi-

tional environment at the base of glaciers which is influenced by parameters such as topography, sediment load, substrate composition, ice physical conditions (e.g. temperature, velocity), and duration of ice-flow events. Correct interpretation and recognition of palimpsest dispersal trains must rely on a complete understanding of the ice-flow history which can be achieved by interpreting ice-flow indicators present at all scales from micro-features on bedrock outcrops to landforms interpreted from digital elevation models. Implications for mineral exploration activities using drift prospecting techniques, must take into account the complete ice-flow history of a region because glacial dispersal patterns detected will be the net result of all ice movements.

## IRON-OXIDE-COPPER-GOLD ± URANIUM DEPOSITS IN THE GREAT BEAR MAGMATIC ZONE

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Under the Northern Uranium for Canada project (GEM-Energy Program), the nature of uranium in iron oxide copper-gold (IOCG) systems is being investigated using examples from the Great Bear magmatic zone (GBMZ). Hypotheses being addressed include: Can uranium and thorium serve as vectors to multiple-metal endowments in IOCG systems? What is the potential for IOCG systems to contain recoverable energy resources? How can we maximise geological vectoring to ore with geochemical information from hand-held gamma-ray spectrometers?

Fieldwork focused on known IOCG alteration systems with anomalous uranium (U) and thorium (Th) showings at Lou, Cole and Fab lakes. At Lou Lake, two U-Th-bearing breccias were discovered west and south of the NICO deposit. The more significant discovery consists of a 2 km long, northwest-southeast trending, U-Th-arsenopyrite breccia corridor (eU = 0.01-1%, eTh = 0.2%). This corridor comprises syn- to post-tectonic hydrothermal iron oxide (magnetite to hematite) breccias and U-Th-arsenopyrite ± molybdenite anomalies within either sodic-, potassic- or silica-altered metasedimentary rocks. This new corridor is spatially distinct from the NICO ore zone (which does not contain U), corresponds to the inferred apical part of the ideal IOCG system, and may have been a pathway for both incoming and outgoing fluids that formed the NICO deposit.

At Fab Lake, several new Th and one U anomalies were discovered and the timing amongst the various generations of porphyries and IOCG alteration better constrained. On the northeast and northwest shoreline, several Th-bearing amphibole-magnetite veins brecciate feldspar porphyry and are sharply cross-cut by younger, two-feldspar porphyry dykes. Although both porphyries contain late biotite alteration, the two-feldspar porphyry dykes lack the amphibole-magnetite-K feldspar assemblage and subsequent brecciation characteristic of the older porphyry. Variable Th enrichment in these brecciated zones (Th/U = ~4-10) records decoupling of U and Th during formation and may be a vector to ore.

Discovery of the significant U-bearing zone near the NICO deposit was predicted by the IOCG alteration to brecciation and mineralization model developed by the project. Predictions were made by analysis of regional metallogenetic and geological data compiled by the Geological Survey of Canada and Northwest Territories Geoscience Office. Follow-up field studies in 2010 provided further constraints on the structural, magmatic and hydrothermal events which led to documentation of the IOCG-porphyry continuum in the GBMZ. These results also highlight the

potential of the GBMZ to host undiscovered IOCG-type ore deposits.

### **STABLE ISOTOPE EVIDENCE FOR LOST CITY-TYPE HYDROTHERMAL DEPOSITS IN THE ca. 3.0 Ga NORTH SPIRIT LAKE GREENSTONE BELT, NW ONTARIO**

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The ca. 3.0 Ga North Spirit Lake greenstone belt in NW Ontario is thought to represent, in part, an oceanic spreading center composed of basal tholeiitic and komatiitic basaltic lavas with NMORB-type affinities. These are overlain by a volcano-sedimentary succession that, near the base, includes BIF composed of sulphide- and Fe-oxide-cherts succeeded by banded ferruginous-carbonate-cherts and carbonate deposits. The banded sulphide-, Fe-oxide and carbonate-cherts consist of pyrite-quartz, magnetite-quartz and siderite-quartz, respectively. The carbonate deposits are predominantly ankerite in composition.

Oxygen-isotope results for quartz are +17‰ in sulphide-chert, +11‰ in magnetite-chert and ~+17‰ in siderite-chert. Oxygen- and carbon-isotope results for siderite and ankerite range from +15.5 to +18.0‰ and -4.3 to -2.3‰ and +13.7 to +16.2‰ and -1.6 to +4.2‰, respectively. The  $\delta^{18}\text{O}_{\text{qtz}}$  values of the cherts are within the  $^{18}\text{O}$ -depleted range recorded in other Precambrian chert deposits. This is also the case for the carbonate oxygen-isotope compositions, which are depleted in  $^{18}\text{O}$  by 1 to 10‰ relative to Precambrian BIF carbonate deposits in Australia, Africa and southern Ontario. These  $\delta^{18}\text{O}$  values indicate carbonate and chert deposition at higher temperatures than usually invoked for BIF-type deposits, suggesting an association with seafloor hydrothermal vents in a ridge-type setting. Assuming an Archean seawater oxygen-isotope composition of 0‰, calculated precipitation temperatures for both cherts and carbonates fall in a narrow range between 125 and 135°C. Exceptions are the magnetite-chert, with a calculated temperature of 210°C and a carbonate pod and siltstone sample with calculated temperatures between 135 and 150°C.

The carbon-isotope compositions of the carbonates are similar to previously reported results for other BIF deposits. The  $\delta^{13}\text{C}_{\text{sid}}$  values are consistently lower than  $\delta^{13}\text{C}_{\text{ank}}$  values but do not show the excessively  $^{13}\text{C}$ -depleted values, down to -13‰, observed in large basal BIF deposits and attributed there to organic activity. The siderite  $\delta^{13}\text{C}$  values measured here (-4 to -2‰) most likely reflect a mixture of marine DIC and magmatic carbon. The values from the ankerite deposits, alternatively, may indicate a predominantly marine DIC source.

REE patterns for these deposits have positive Eu anomalies, suggesting a strong hydrothermal influence. The stable isotope results support this interpretation, for they also indicate high precipitation temperatures and possible magmatic carbon input. Therefore, we propose that these deposits were formed in environments similar to those found at modern day mid-oceanic ridges, transitional between high temperature, sulphide-rich black smokers (e.g. Rainbow) and low temperature, carbonate-dominated white smokers (e.g. Lost City).

### **METAL ENRICHMENTS IN LAKE SEDIMENTS: A HISTORICAL RECORD OF THE INDUSTRIALIZATION AND REMEDIATION EFFORTS OF SUDBURY, ONTARIO**

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The emission of metals from industrialization within the last century has caused significant effects on the chemical composition of

soil and water bodies within the Greater Sudbury area. The occurrence and accumulation of elements in lake sediment layers can be used to provide an accurate record of the local agriculture, mining and urbanization history. Sediment cores from Vermillion Lake were sampled to the depth of 40 cm. The core was subsequently sectioned into 470 samples of less than 1 mm in thickness. The water content of all samples was measured and plotted versus depth. Twenty selected samples were analysed for major and ultra-trace elements, as well as for the Pb isotopes 204, 206, 207 and 208, using ICP-MS. The water content data indicated water loss at a depth of roughly 24 cm and an increase at a depth of roughly 11 cm, in conjunction with a change in grain size from silt to sand and sand to silt, respectively. These two key depths are synchronous with large increases and decreases of metal enrichment factors within the core, associated with the beginning of mining activities and the building of the Superstack, respectively. The largest metal enrichments within the core are those of Ni, Cu and associated metals (e.g. Pb, Cr, Co). The enrichment factors of Cd and Zn do show the same trend as other metals, since they increase towards present. This observation indicates that the concentrations of these metals are not affected by recent efforts to reduce metal emissions. Major element enrichment and Nb/Ta ratios remained constant through the core, indicating that the detrital sediment composition remained constant. Manganese and P are more enriched within the top 10 cm of the core. The enrichment of Mn is likely attributed to an increase in organic content, whereas the enrichment of P is interpreted to be the result of increased activities in remediation and agriculture. The Pb isotope ratios indicate that the Pb within the sediment originated mainly from the local smelting activities and the combustion of gasoline. The enrichment of metals measured from this lake sediment core provides for the first time a sensitive chronological record of mining activities, industrialization and, remediation efforts within the Sudbury area.

### **SEISMITES: PROXY FOR SYNSEDIMENTARY TECTONIC ACTIVITY IN INTRACRATONIC BASINS**

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Traditionally considered quiescent, intracratonic basins often turn out to have had regions of active tectonics during sediment deposition, and the Ottawa-Bonnechere graben is an example. This activity is typically manifested by varying thicknesses over short distances which point to differential subsidence about normal faults. Much can be learned about the specific activity and location of such faults based on the stratigraphic and geographic distribution of deformed horizons, termed 'seismites'. The Mesoproterozoic Belt Supergroup, for example, is riddled with seismites especially in the lower and middle portions. This should come as no surprise given the extraordinary subsidence rate of that basin, which may have averaged 0.5 mm per year and considerably exceeded that during its early phases. Seismites are far less common in other Proterozoic platform successions from less tectonically active basins.

The Late Ordovician Red River Group of subsurface southeastern Saskatchewan is a good place to test the value of seismite stratigraphy, because that part of the Williston Basin is known through geophysics and drilling to have an underlying pattern of NE/SW- and NW/SE-oriented orthogonal normal faults that were intermittently active. Bioturbated fossiliferous limestones of the Yeoman Formation comprising the lower unit have a uniform thickness, but in any case the shallow-water environment was not conducive to preservation of deformation horizons. By contrast, the overlying Herald Formation consists of lower energy dolomudstone-anhydrite cycles that were affected by differential subsidence. The kinds of seismites indicate a range of rheological

responses from soft-sediment deformation to brittle failure, and include millimetre- and centimetre-scale folds, veins, dikelets, microfaults, breccias, and smeared laminae and loop-bedding, due to variably-directed stresses and varying intensity of ground motion imposed on shallow-buried sediments below wave-base.

Although the database is biased because drilling has been focused traditionally on structural plays, the distribution of seismites corroborates the activity of known faults. Because seismites are observed in cores from outside the study area, it is possible that hitherto unrecognized faults are present. This approach is thus particularly relevant for petroleum exploration strategies in general.

#### **CHARACTERIZATION AND SPATIAL DISTRIBUTION OF THE ALTERATION FACIES FOR THE MAFIC TO ULTRAMAFIC POTTER MASSIVE SULPHIDE DEPOSIT, ABITIBI GREENSTONE BELT, ONTARIO**

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The Potter Cu-Zn-Co VMS deposit located in the eastern part of the (2720-2710 Ma) Kidd-Munro assemblage of the Abitibi greenstone belt, is somewhat unique among Archean VMS deposits, in that it is hosted in mafic volcanoclastic units that are enclosed entirely within a dominantly ultramafic succession. The mineralization consists of eleven stacked tabular lenses of semimassive to massive sulphides mostly composed of pyrrhotite, sphalerite and chalcopyrite.

The hydrothermal footprint is essentially recorded within the volcanoclastic rocks where the matrix and juvenile fragments were preferentially replaced. The alteration typically occurs as irregular stratabound zones that surround the ore lenses. Three alteration facies were recognized based on the matrix mineralogy, from proximal to distal: 1) chlorite, 2) albite-calcite, and 3) chlorite-clinopyroxene. The proximal chlorite facies is characterized by an increase in chlorite abundance and locally talc, both within the matrix and the fragments, and by the first appearance of Fe-rich chlorite. The albite-calcite facies is characterized by widespread replacement of the matrix by albite, calcite and minor Mg-rich chlorite and by a partial chloritization of the fragments. The distal chlorite-clinopyroxene facies, developed within the matrix, is composed of Mg-rich chlorite, clinopyroxene and albite, the clinopyroxene being a product of metamorphism. Fragments are not chloritized in this distal alteration facies. The high permeability of the volcanoclastic rocks allowed significant ingress of heated seawater-dominated fluids, which formed the distal and transitional Mg-rich chlorite, albite, and calcite alteration facies (facies 2-3). The proximal Fe-rich chlorite alteration (facies 1), associated with a maximum water/rock ratio and peak temperature, is developed only close to the sulphide lenses due to the lack of focused fluid pathways in the footwall (e.g. discrete synvolcanic faults).

Despite deformation and a patchy, diffuse, and gradational contacts between the alteration facies, the original geometry of the hydrothermal system can be illustrated along a mineralized section: the proximal alteration is developed within 10m of the ore lenses, the near-proximal to distal facies is developed between 10m and 80m away from the ore lenses, and the distal facies is present at least 35m away from the ore lenses. This study shows that the stacking of ore lenses has resulted in a complex geometry of overlapping alteration facies. Moreover, synvolcanic dykes and sills were responsible, at least in part, for the distribution of the alteration by controlling fluid pathways. Therefore, the nature of the volcanoclastic rock and the geologic environment are the main

factors controlling the primary distribution and mineralogy of the alteration.

#### **TEMMI: A THREE-DIMENSIONAL EXPLORATION MULTISPECTRAL MICROSCOPIC IMAGER FOR PLANETARY EXPLORATION**

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A microscope represents one of the most basic tools required for geology and astrobiology, and it is anticipated that most, if not all, future surface missions to the Moon and Mars will carry one. TEMMI (a Three-dimensional Exploration Multispectral Microscopic Imager) has been developed through a collaborative initiative, spearheaded by the Canadian Space Agency, involving two industrial partners – MacDonald, Dettwiler and Associated Ltd (MDA), and National Optics Institute (INO) – and three academic science partners – The University of Western Ontario, The University of New Brunswick and York University – to conduct geological and astrobiological investigations in Lunar and Mars analogue environments. In the fields of geology and astrobiology, the ability to capture a visual record of the terrain – from the regional (km) to outcrop (m to cm) to microscopic (mm to micrometre) scale – and of sites visited, is invaluable. Microscopy, in particular, provides the fundamental context and empirical information required to fully understand the origin and significance of samples.

TEMMI can be used to study the physical and structural properties of surfaces, both of rocks, minerals and the dusty regolith to contribute to the geophysical analysis of an area and to the overall geological and mineralogical interpretation of the sites of interest. Past environmental conditions can be constructed, weathering effects on different lithologies studied, and the transportation of particles across the planetary surface mapped. Specific objectives are to

- Investigate the physical properties of minerals;
- Recognize common minerals and identify unknown phases;
- Understand the relationships between the internal (composition and structure) and external properties of the minerals;
- Identify traces of reactions and physical conditions that affect the stability and occurrence of minerals;
- Interpret the broader significance of mineral compositions and structures;
- Investigate the effects of heat pressure on properties of minerals;
- Constrain the sizes and shapes of regolith particles on the surface or particles precipitating out of the atmosphere.

This instrument can also be used to study the morphology of a potential biological sample and identify structures that may be characteristic of past or present biological activity. TEMMI can utilize the interaction of visible and IR light with the crystalline and non-crystalline materials to detect possible biogenic material such as kerogen or fatty acids and proteins preserved within the rocks and minerals. It can also be used to identify biomolecules through UV fluorescence, create 3D images, and aid in identification of a sample return site.

## **AN ISOTOPIC BASELINE FOR THE MARINE SULFATE RESERVOIR PRIOR TO THE CRYOGENIAN SNOWBALL GLACIATION**

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Atmospheric oxygen concentrations figure prominently in models for early animal evolution but are difficult to quantify in the Precambrian. The size of the marine sulfate reservoir, along with the net sulfur isotopic fractionation between sedimentary sulphate and pyrite ( $\Delta^{34}\text{S}$ ) are thought to respond to atmospheric oxygen levels. Broad compilations of sulphur isotope data spanning the Archean to the Recent, suggest a Neoproterozoic oxygenation event. Subsequent work has focused primarily on the Cryogenian (720-635 Ma) and the Ediacaran (635-543 Ma) periods, and current thinking suggests that the marine sulphate reservoir increased dramatically in the middle of the Ediacaran, where a large increase in  $\Delta^{34}\text{S}$  is taken to indicate the oxygenation of the environment that permitted the first animals to evolve.

Few data exist for the earlier Neoproterozoic, but carbon isotopes indicate a sustained interval of high organic carbon burial at this time suggesting that atmospheric oxygen and marine sulphate may have increased before the Ediacaran. Little deformed early- to mid-Neoproterozoic sedimentary rocks of the Shaler Supergroup in north-western Canada contain thick intervals of sulphate evaporites, which present a rare field opportunity to evaluate depositional and environmental conditions leading to the pre-Cryogenian global glaciation.

We measured 150 m-thick stratigraphic section through the Minto Inlet formation, one of the best preserved intervals of evaporites. We also logged over 400m of drill core spanning the uppermost parts of the underlying Jago Bay formation and its transition into the Minto Inlet formation. Our study focused on an ~45m thick transgressive interval at the top of the Minto Inlet formation that is dominated by bedded gypsum and anhydrite at the base and cyclical deposits of bedded gypsum and lithographic limestone nearer to the top. High-resolution S-isotope analysis of this interval is reported, in order to establish a base-line for the period preceding the Cryogenian glaciation, giving us insight into the size of the marine sulphate reservoir, and thus the level of atmospheric oxygen, during this time period.

## **PREDICTABILITY OF CLIMATE PATTERNS IN THE CENTRAL NORTHWEST TERRITORIES: IMPLICATIONS FOR THE LONG-TERM VIABILITY OF THE TIBBETT TO CONTWOYTO WINTER ROAD**

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This research documents the climate variability in the central Northwest Territories (NT) through the last 3500 years and provides an assessment of the impact of climate change on the Tibbett to Contwoyto Winter Road (TCWR).

Time series analyses of meteorological observations from the NT indicates that throughout the last 50 years there has been considerable climate variability in the central NT with winter and summer signals often becoming decoupled. There is a correspondence between the 11-year solar cycle and seasonal climate variability with higher solar activity (i.e. more sunspots) corresponding to warmer winters, whereas summer temperatures peak lag behind solar cycle intensity peaks by an average of four years. Vice versa lows in solar intensity at the 11-year cycle cor-

responds to cooler winters. The average amplitude of the winter temperature variability through a 11-year solar cycle is ~2°C, as opposed to a temperature variation of only 0.5°C for the summer months. Fluctuation of the Pacific Decadal Oscillation (PDO) and North Atlantic Oscillation (NAO) between positive and negative states has contributed to often abrupt step-wise temperature changes in the Arctic at 20-40 year time scales, representing non-linear responses with abrupt transitions between relatively stable temperature stages that are superimposed on the solar fluctuations. These patterns are superimposed on an ~1.5°C temperature increase through the last 60 years.

A novel new freeze core microtome developed at Carleton University permits subsampling of a 2 m freeze core obtained from Waite Lake, ~200 km north of Yellowknife on the route of TCWR in an age resolution of 2-4 years. Time-series analysis (cross-wavelet, wavelet, spectral analysis) shows that the sedimentation of this core is also dominated by a strong and persistent 11-40 year cyclicity through the last 3500 year BP, superimposed on a weaker 500-800 year cyclicity. At about 1300-1700 cal yr BP, a weak ~200-300 year cyclicity is replaced by a weak ~120-160 year cyclicity.

We conclude that the current, and long-term persistent influence of 11-year solar cycles, as well as PDO and NAO fluctuations, have a strong influence on Arctic climate and the stability of the TCWR. Assuming that the ratio in the sedimentary cycle amplitudes reflects linearly the ratio of temperature fluctuations, we also conclude that the general Arctic warming trend through the last century cannot be explained solely by the superposition of long-term (>100 year wavelength) natural climate cyclicity.

## **CONNECTING WITH YOUTH AND THE PUBLIC: THE UNIVERSITY STUDENT AS AN OUTREACH RESOURCE**

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As an undergraduate, and now a graduate student with the Department of Earth Sciences at Carleton University, I have participated actively with Geoscience Outreach initiatives. These include Geoheritage Day, the Enrichment Mini Course Program for high school students, Teachers' Workshops, and visits to public schools. Through my participation in these initiatives, and working with individuals in Geoscience Outreach, I have found that I am able to function equally as a peer mentor for the students, as well as a teaching assistant.

With the use of University Outreach programs, public school students and teachers are able to explore many facets of Geoscience in a very interactive way, and the presence of a University student changes the dynamic of the experience by reducing the perceived age-gap between the professional and the class. In this way a peer-relationship and mentorship between the University student and the class, teacher, or public, typically occurs. A University student currently engaged in study brings his/her life and learning experiences to the Outreach events, encourages an active connection between peers, and can help to engage the younger generation of students contemplating their future careers.

By presenting the perspectives of University students during Outreach activities and public Geoscience initiatives, I aim to show that the University student can be a useful resource; as a bridge between the teacher, the visiting specialist, and their class; as a peer to the students; and as a mentor available to the elementary-, middle-, and secondary-students and their teachers, especially regarding post-secondary education and careers.

## UPPER CRETACEOUS STRATA OF ELLEF RINGNES ISLAND, CANADIAN HIGH ARCTIC: A WINDOW INTO THE DEPOSITIONAL HISTORY OF THE BOREAL SEA

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Ellef Ringnes Island, part of the Queen Elizabeth Islands of the Canadian Arctic, exposes Cretaceous strata characterized by an unusually low degree of lithification. The study area partly represents the basin centre of the Sverdrup Basin. This study addresses the latest Albian to possibly Campanian interval including the uppermost Christopher, Hassel and Kanguk formations. The over 400 m thick measured section reveals significant paleoenvironmental changes. These are under study by addressing various fossil groups including pollen, dinoflagellates, radiolarians, diatoms and foraminifera. These data will be complemented with carbon isotope analysis in order to identify oceanic anoxic events.

Strata of the Albian Christopher Formation are only sampled at the uppermost part where silty shale gradually changes into increasing sand-rich facies of the Hassel Formation. Sedimentary strata of the Hassel Formation showcase delta progradation from a prodelta with variable silt and clay deposition to delta front settings characterized by interbedded fine sand and muds, with hummocky- and swaley-cross bedding, grading to a predominance of fine sand with little to no mud and planar-bedding. The upper Hassel Formation represents a delta plain setting with conglomeratic channel deposits, coals and possibly lake muds. The Hassel Formation is unconformably overlain by a thick section of black, organic rich shale of the Kanguk Formation. The sand/shale boundary contains no pebble bed and the transgressive system tract seems to be missing.

The Kanguk shales are rich in dinoflagellates, diatoms and radiolarians indicating high surface productivity and explaining the high organic content of these sediments. Benthic foraminifera seem to be lacking, which can be explained by two hypotheses. If bottom waters were anoxic due to stratified waters, benthic organisms are inhibited from thriving. This is supported by the platy nature of the shale in parts of the section suggesting no bioturbation and the preservation of organic matter. On the other hand if bottom waters were oxygenated and calcareous foraminifera have existed, corrosive porewaters become the result of decay of organic matter and would have caused increased CO<sub>2</sub> concentrations at the sediment-water interface which in turn causes dissolution of calcium carbonate. The biostratigraphic analysis of this study will offer the first multi-fossil framework for this area and will advance our understanding of the Boreal Sea as a complex ecosystem.

## NUMERICAL MODELING OF HORIZONTAL AND INCLINED FAULTS RESPONSES TO PUMPING TEST

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Analytical models conventionally used for the interpretation of pumping tests in discontinuous media are unable to account for a large range of multistage real signatures that combine both radial and fractional flow types. The term radial is employed here in Barker's sense, referring to the cross-flow area growth conditions during the pumping test rather than to its symmetrical geometry. It relates to the flow dimension parameter  $n$ , which is equal to 2 in conventional radial behavior (Theis aquifer) and a non-integer in fractional behavior. Previous analytical and numerical studies demonstrated that a conductive vertical fault confined in a non-impermeable matrix produces multistage signatures with the char-

acteristic flow dimension succession 1.5-2. The present study numerically investigates extensions of these models to less idealized geometries including horizontal and inclined conductive faults. Transient flow simulations are performed through single faults surrounded by a permeable matrix to characterize theoretical drawdown derivative time-series, and identify the hydrodynamics associated with several elementary behaviours. The 2- < 2-2 flow dimension sequence is shown to result from interactions between the matrix and a horizontal to weakly inclined fault. The 2-1.5-2 succession suggests a higher fault inclination and is a temporal combination of the vertically- faulted model and a generalization of the horizontally faulted model. These results allow the interpretation of previously unexplained drawdown series from long term pumping tests. They provide substantial improvements for the hydraulic characterization of faulted environments, allowing assessment of fault and matrix properties including the fault inclination. Applications are successfully tested on real datasets.

## ARCHEAN SEISMIC ACTIVITY AND GOLD MINERALIZATION ALONG THE CADILLAC-LARDER LAKE FAULT ZONE: A NUMERICAL MODELING APPROACH

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This study investigated the Archean seismic activity of the Cadillac-Larder Lake Fault Zone (CLLFZ) of the Abitibi Subprovince to determine its role in orogenic gold deposit genesis. Numerical modeling was carried out using UDEC (Universal Distinct Elements Code) to reproduce the earthquakes that induced crustal-scale hydrothermal fluid migration and gold deposit formation. Observations of active faults in modern environments suggests that hydrothermal fluids are drained from deep-level sources during the seismic cycle into 2<sup>nd</sup> and 3<sup>rd</sup> order faults located in coseismic damage zones (CDZs) near to the main fault (typically <10 km). The structural permeability enhancement sustained in these zones allows the discharge and precipitation of large volumes of mineralizing fluids for several years or decades following the earthquakes. CDZs can be identified spatially using static stress modeling, following aftershock theory, a seismological approach initially developed to study active fault seismic hazards. The Coulomb failure stress change is calculated around a ruptured fault. CDZs correspond to positive change areas brought to the critical rupture state and are characterized by increased seismic hazard and triggered earthquakes. This theory has been applied for decades by seismology researchers to active faults; its extension to gold exploration is an innovative approach, which was successfully introduced in the Australian Greenstone Belt. The recognition of late gold mineralization stages in several deposits from Val d'Or, Malartic and Rouyn-Noranda goldfields is considered to be contemporaneous with the late dextral component of movement along the CLLFZ. Postulating this dextral activity, regional static stress models achieve an excellent correlation between gold deposits and CDZs produced by recurrent earthquakes on E-W fault-segments (magnitude 7-7.5). It can also explain the heterogeneous distribution of world-class deposits around the CLLFZ, forming clusters known as goldfields. During late-orogenic mineralization stages, the CLLFZ seismic dynamics are controlled by a well-marked structural segmentation inherited from prior Archean tectonics. This architecture causes repeated main-shock rupture arrests on few structural points where the fault is folded, bent, offset and/or split, leading to repeated fluid discharge into the recurrent CDZs and permitting the accumulation of over-

whelmingly large fluid volumes that are required to generate world-class deposits. This is corroborated by ample field evidence of repeatedly attained high pore fluid pressures (crack-seal veins). The spatial correlation between large deposits and CDZs is confirmed at a district scale in the Val-d'Or goldfield. It is demonstrated that the occurrence of 2<sup>nd</sup> and 3<sup>rd</sup> order faults in the vicinity of rupture-arrest structural points, well-oriented with respect to CDZs, is an important gold exploration criterion.

#### **SEDIMENT-HOSTED BASE-METAL POTENTIAL OF THE MINTO INLIER, VICTORIA ISLAND, NORTHWEST TERRITORIES AND NUNAVUT**

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The Minto Inlier, exposed on northwestern Victoria Island, hosts the Shaler Supergroup, a 4-km thick succession of early Neoproterozoic sedimentary rocks. These rocks are interpreted to be a remnant of the Amundsen Basin, a broad epeiric sea that lay within the supercontinent Rodinia, before it began to disaggregate in the middle Neoproterozoic. The Shaler Supergroup has potential for two types of base metal concentration: 1) sandstone-hosted, red-bed copper type, and 2) carbonate-hosted, Mississippi Valley zinc-lead type (MVT).

Sandstone-hosted copper was discovered in the 1980s in northeastern Minto Inlier and several prospects were drilled by Noranda Inc. in the early 1990s. Copper occurs at several stratigraphic levels within quartzarenite of the Nelson Head Formation. The highest concentrations are hosted by the lowermost fluvial quartzarenite/conglomerate and comprise disseminations and massive matrix/cement replacements of chalcopyrite and pyrite with subordinate tennantite and enargite. Mineralization occurs over an extensive area and exhibits crude lateral zonation with increasing grade towards an inferred paleo-ridge developed on underlying carbonate rocks of the Mikkelsen Islands Formation. Precipitation of sulphides appears to have been controlled by anomalous concentrations of bitumen (now pyrobitumen) occurring in the matrix of the sandstone, along the ridge trend.

Potential for MVT zinc-lead lies in dolomitized carbonates occurring at several different stratigraphic levels within the Shaler Supergroup. Vuggy dolostone is particularly well developed in rhythmically bedded, slope carbonates of the Wynniatt Formation in the western Minto Inlier, near Minto Inlet. Vugs are filled with coarse, layered dolomite, late sparry calcite and rare pyrobitumen. Dolomitized zones are located close to a well-defined, northeast-trending fault such that mineralization could be related to channelization of hydrothermal fluids. Dolomitization and related brecciation of the carbonates is also a product of paleo-weathering (karstification) beneath overlying lower Cambrian sandstones. The age of the host rocks and the textures and structural setting of the occurrences are identical to that of the Gayna River deposit in the Mackenzie Mountains, Northwest Territories.

#### **EXPLORATION FOR GOLD MINERALIZATION IN THE EASTERN DESERT OF EGYPT: USING REMOTE SENSING APPROACH**

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In the Eastern Desert of Egypt, Landsat Thematic Mapper (TM) data and fieldwork was combined with mineralogical and geochemical investigations in order to detect and characterize alteration zones within Pan-African rocks. The processing of Landsat TM data using ratioing (bands 5/7, 5/1, 4/3 in Red, Green, Blue) showed two different types of alteration zones (type 1 and 2). Type

1 is close to the ophiolitic ultramafic rocks at the central and southern parts of Egypt, whereby type 2 is located within island-arc related metavolcanic rocks at the southern part. Both of these alteration zones are concordant with the main NE-SW and NW-SE structural trends.

The ore mineralogical studies indicate that the alteration zones of type 1 consist mainly of gold, chromian spinel, pyrite, and Ni-bearing sulphides (gersdorffite, pentlandite and polydymite). Alteration zones of type 2 are characterized by presence of native gold, pyrite, chalcopyrite and iron oxides.

Geochemically, the gold content reaches up to 5 g/t in the alteration zones, while it reaches up to 10 g/t in the quartz veins.

This study presents a mineralogical characterization of such zones and demonstrates the utility of orbital remote sensing for finding unknown alteration zones in the Eastern Desert and other arid areas with similar host rock lithologies.

#### **EXPLORATION FOR THE MASSIVE SULPHIDE DEPOSITS IN THE ARABO NUBIAN SHIELD: USING REMOTE SENSING AND AIRBORNE MAGNETIC DATA**

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Different approaches of remote sensing and airborne data were used in exploration for the massive sulphide deposits in the Arabo-Nubian Shield. Digital processing of Landsat ETM+ images for the several studied areas in the Eastern Desert of Egypt and sotjern Sinai, generated several products ranging from false colour composite images (7, 4, 2 in RGB) to ratio images (5/7, 5/4, 3/1 in RGB).

Landsat TM images (bands 7, 4, 2) were suitable for regional tectonically structure analysis and provide an excellent base map for the studied areas. Landsat TM ratioing images (5/7, 5/4, 3/1 in RGB) were used for lithological discrimination of different rock types. Otherwise the ratio image (bands 5/7, 5/4, 3/1) succeeded to distinguish the alteration zones capping the massive sulphide deposits.

In South Eastern Desert of Egypt, Landsat ETM+ imagery, combined with geological and aeromagnetic data were used for the identification of sulphide-mineralized zones. The geochemical analysis for some representative samples from the alteration zones capping these sulphide zones indicates that the copper content reaches up to 14.3% and the gold content reaches up to 3.2 g/t.

In the south eastern part of Sinai, Landsat ETM+ imagery are used to identify the location and extent of the alteration zones capping the massive sulphide deposits. Geochemically, these alteration zones recorded presence of relatively high contents of Au, Ag, Cu, Pb, Sb and Zn elements.

The gold content reaches up to 5 g/t in these alteration zones, Ag up to 5.4 g/t, Pb up 2800 ppm, Zn up to 5900 ppm, Cu up to 2%, Sb up to 700 ppm.

This demonstrates the utility of orbital remote sensing for finding unknown mineralized zones in the Arabo-Nubian Shield and other arid regions.

#### **AGE, COMPOSITION, AND PATTERNS OF FELSIC CRETACEOUS TO EOCENE MAGMATISM IN SOUTH-CENTRAL YUKON**

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We present results of a regional petrogenetic study on sub-alkalic, Cretaceous to Eocene, W±Mo±Sn and Pb-Zn-Ag±Au±Cu mineralized granitoids emplaced into the Cassiar Terrane (CT) in south-central Yukon. The CT comprises a Neoproterozoic upper plate rifted margin overlain by Phanerozoic passive margin rocks that



were formerly located south of the Selwyn Basin (SB), Yukon, along the ancestral margin of North America. Isotopic, geochemical, and field observations for Cretaceous to Eocene intrusions in the CT are the most consistent with mixed crustal melts sourced from thick, radiogenic Proterozoic supracrustal successions and interlayered intermediate to mafic sills/flows. Melt input from overlying Phanerozoic rocks or obducted oceanic terranes is possible, although unlikely to be significant. The intrusions studied were all previously classified as the Early Cretaceous 'Cassiar' plutonic suite, which we have now subdivided into four spatially, temporally, and geochemically constrained plutonic suites: (1) The redefined Cassiar suite (115-104 Ma) is a widespread, westward-younging belt of reduced biotite  $\pm$  muscovite monzogranite plutons and batholiths, with less abundant oxidized biotite  $\pm$  hornblende monzogranitic to granodioritic phases. The locus of crustal melting for the Cassiar suite moved steadily northeastward at  $\sim 1$  cm/yr, and formed in a retro-arc setting with respect to an extensive calc-alkalic arc located immediately to the west (i.e. the 123-107 Ma Teslin and Whitehorse plutonic suites). (2) The 103-94 Ma Seagull suite is composed of very small to moderate-sized, highly fractionated, reduced, biotite  $\pm$  muscovite monzogranitic and tonalitic plutons forming a long, narrow belt near the western edge of the CT. This westward shift of crustal melting contrasts with the simultaneous northeastward progression of magmatism in the Selwyn Basin (SB) to the north. Also, the Seagull suite does not correlate with widespread magmatism to the west. These observations suggest segmentation of the subducting plate between the CT and SB by 103 Ma, possibly combined with the cessation of subduction under the CT. (3) The 82-76 Ma Rancheria suite comprises small, reduced/oxidized, leucocratic biotite  $\pm$  muscovite granitic plutons in the southwestern CT. (4) The 49-47 Ma Black Lake suite is composed of two reduced, biotite  $\pm$  muscovite monzogranitic intrusions emplaced immediately southwest of the Tintina Fault. The Late Cretaceous Rancheria and Eocene Black Lake plutonic suites are coeval to probable within-in plate magmatism in northern BC and at least as far west as the Yukon-Alaska border, and are tentatively classified as within-plate granites emplaced in the vicinity of large dextral transpressional structures.

#### **PEOPLE, PUMPS, AND PARTS-PER-MILLION: ADVANCES IN URBAN GEOCHEMISTRY**

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Urban geochemistry research made significant advances in the past decade. Ingestion of indoor dust by children was identified as a key route of exposure to metals and organic contaminants, with lead receiving the greatest attention. Many areas of cities impacted by past industrial activity were identified by mapping the distribution of contaminants in urban soils. Improvements in sampling technologies have contributed to a greater understanding of personal, indoor and outdoor exposures in the built environment. Information about the quality of the indoor environment is particularly in demand, due to the fact that Canadians spend the greatest proportion of their time indoors. The penetration of vehicle emissions and airborne particles from industrial sources can introduce outdoor contaminants into the home. In addition, there are many indoor sources of metal and organic compounds, including consumer products, carpets and furnishings, paints, building materials, cooking processes, cigarette smoke, crafts and hobbies. Results of residential monitoring studies show that airborne metals inside Canadian homes are typically very low, and difficult to measure, compared to outdoor air. Interestingly, settled dust often shows the opposite trend: in urban areas not heavily impacted by industry,

concentrations of lead and other metals such as copper, nickel and zinc may be many times higher in house dust compared to garden soil. An important future direction is metal speciation and metal bioaccessibility research, as information about the biological availability and toxic action of metal compounds is considered essential for identifying risks to human health that arise from ingesting or inhaling dust and soil particles.

#### **RE-EVALUATING AGE AND PALEOMAGNETISM OF CALLANDER COMPLEX: TESTING HIGH-LATITUDE MID-EDIACARAN LAURENTIA**

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Several syenitic intrusive phases of Callander complex and at least three petrologic generations of associated mafic dykes are relatively easier-accessible and better-exposed than most Ediacaran alkali complexes of the Ottawa-Bonnechere precursor-rift arm. Extant paleomagnetism of Callander syenite and dykes suggests extremely high paleolatitude for Laurentia at the time of intrusive cooling. Some aspects of this magnetization, and the precise age of intrusion and cooling, however, remain ambiguous; and new development in the western Lake Nipissing corridor presented opportunity to address these issues with fresh exposure of dykes cutting both fenitized and unaltered basement in roadcuts. We report U-Pb crystallization, Ar-Ar cooling, and revised paleomagnetic results from Callander complex and discuss their context in a broader rapid, multiple Ediacaran true polar wander-versus-nonuniformitarian geomagnetic field interpretive scheme.

#### **EARLY "WHIFFS" OF ARCHEAN OXYGEN AS METASOMATIC ARTIFACTS**

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Stratigraphic evidence for the first appearance of atmospheric oxygen – hypothetically a direct result of the first evolution of oxygenic photosynthesis – straddles a "necessary" versus "sufficient" interpretive gap. Primary paleomagnetism of laterized paleosol breccia and massive sedimentary manganese deposits requires significant atmospheric oxygen immediately following the youngest Paleoproterozoic "Snowball Earth" glaciation, ca. 2.22 Ga, but trace metal abundances, biomarker evidence, and sulfur and nitrogen isotopic systematics permit ephemeral "whiffs" of trace oxygen hundreds of millions of years earlier. These data are not strictly incompatible with one another; however establishing firmly the earliest date of oxyatmoversion would discriminate among hypothesis causally linking Earth's evolving Precambrian biosphere to changing tectonic styles, climate catastrophes, and/or changing biogeochemical cycle regimes. Strongest evidence for early "whiffs" of oxygen comes from ca. 2500 Ma black shales of Australia's Hamersley basin penetrated by deep scientific drillcore ABDP-9. This core never has been described in stratigraphic detail, nor its iron and sulfur petrography placed in regional context. A variety of lines of evidence suggest 2.2 to 2.0 Ga, hot orogenic fluids may have localized molybdenum and rhenium in metasomatic sulfide phases, and exogenic biomarkers in associated carbonaceous shale.

# ELEMENTAL CHANGES RECORDED IN VARIABLY ALTERED GRANITOID ROCKS IN THE VICINITY OF THE CENTENNIAL UNCONFORMITY-RELATED URANIUM DEPOSIT, NORTHERN SASKATCHEWAN, AND IMPLICATIONS FOR URANIUM MINERALIZATION

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The Centennial unconformity-related uranium deposit is located in the south-central part of the Athabasca Basin (Saskatchewan, Canada), and is spatially associated with brittle structures along the Snowbird Tectonic Zone trend. The mineralization is hosted by the Athabasca Group sandstone and the underlying basement rocks, which include quartzite, pelitic schists, and peraluminous granitoids, which are mylonitic in places. Drillcore intersections indicate that the granitoid is variably altered, with the feldspars in particular being extensively replaced up to 100 m below the unconformity by very fine-grained, unoriented chlorite. This chloritic assemblage is considered to be the end product of alteration associated with a paleoweathering profile or early diagenesis, as it is overprinted near the unconformity and near to the deposit by illite and sudoite, which are related to the main diagenetic and mineralizing events. The presence of the variably altered, but originally homogeneous granitoid, allows examination of the chemical changes that take place during its progressive alteration by determining the major and trace element composition of fresh, chlorite-replaced, and illite-sudoite-altered granitoid.

Al, Zr, and Ti appear to be relatively immobile during the early alteration of the granitoid, but changes in concentration would suggest that there was a ca. 20-40% volume/mass loss. Chlorite-replaced granitoid normalized to the fresh granitoid show that Li, Be, Mg, Fe, Ni, Co and HREE are enriched, whereas Na, K, Rb, Sr, Ba, Pb and LREE are depleted. Si depletion is subtle, but as Si comprises ~70-75 wt% of the fresh granitoid, the observed depletion is likely responsible for the majority of the volume reduction observed. The later mineralization-related event associated with the development of illite-sudoite alteration led to gains in K, Sr, LREE, and B, and loss of Fe, Mg, Mn, Ni and Co relative to the chlorite-replaced granitoid.

The elemental changes that occurred during the early chlorite alteration, namely the removal of mobile elements and enrichment of metals, such as Fe, Mg, and Ni, is interpreted to represent the signature of intense chemical weathering of the basement. These elements were likely captured originally by vermiculite and smectite, prior to conversion to chlorite during early diagenesis, and this represents the "green zone" observed in the paleoregolith under most of the Athabasca Basin. The deposition of uranium in the basement, or the formation of a reduced fluid, may thus be linked to locations where basinal fluids can access this previously altered and now more porous ferrous iron-containing rock, along structures.

## COMPOSITION AND TIMING OF CHLORITES AT THE CENTENNIAL UNCONFORMITY-RELATED URANIUM DEPOSIT, ATHABASCA BASIN, SASKATCHEWAN

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The Centennial deposit, located in the south-central part of the Athabasca Basin (Saskatchewan, Canada), is spatially associated with brittle structures of the Snowbird Tectonic Zone. Mineralization forms a narrow, northeast trending body along the faulted, northwest dipping contact between variably altered granitoid (footwall) and metasedimentary rocks of the Virgin River Schist Group (hanging wall). In the footwall both distal and proximal to

the deposit, primary granitoid mineralogy is replaced by a very fine-grained green matrix of chlorite, and fresh granite is not intersected in drill core until depths of 70-80m below the unconformity. An illite-sudoite clay assemblage forms a funnel-shaped bleached halo around the mineralization and overprints both adjacent pelites and altered granitoid. Diabase, which post-dates the mineralization-related alteration, intrudes along unmineralized and mineralized brittle structures in the basement and is locally observed in the sandstone. The association of various types of chlorite with unconformity-related uranium deposits has been identified by many previous workers, and has allowed constraints to be placed on the composition of fluids associated with diagenetic, alteration and mineralization events. This study provides details on the composition and relative timing of chlorite based on petrography and electron microprobe analysis of chlorites associated with the Centennial deposit.

The chlorites present in the basement rocks outside the mineralization-related alteration zone are interpreted to pre-date the mineralizing event. The pelitic schist contains chamosite ( $\text{Fe}_{2.70-3.11}\text{Mg}_{1.64-1.16}\text{Al}_{1.58-1.58}(\text{Si}_{2.55-2.79}\text{Al}_{1.45-1.21})\text{O}_{10}(\text{OH})_8$ ), which forms fine- to medium-grained laths that grow across the peak metamorphic foliation defined by biotite and muscovite, suggesting it is of retrograde metamorphic origin. Granitoid rocks have been variably altered, probably during the development of the sub-Athabasca paleoweathering profile. In both fresh and altered rocks, the biotite has been altered to a Fe-Mg clinocllore ( $\text{Fe}_{2.25}\text{Mg}_{2.28}\text{Al}_{1.44}(\text{Si}_{2.75}\text{Al}_{1.25})\text{O}_{10}(\text{OH})_8$ ). Chlorites related to the replacement of feldspar porphyroclasts exhibit a complex gradational composition change from olive-green sudoite on the margins to dark green-black clinocllore in the cores ( $\text{Fe}_{0.27-0.60}\text{Mg}_{2.11-2.61}\text{Al}_{3.52-2.76}(\text{Si}_{3.70-3.26}\text{Al}_{0.30-0.74})\text{O}_{10}(\text{OH})_8$  which grade to  $\text{Fe}_{1.21-0.76}\text{Mg}_{3.04-3.09}\text{Al}_{1.80-2.11}(\text{Si}_{3.02-3.14}\text{Al}_{0.98-0.86})\text{O}_{10}(\text{OH})_8$ , respectively).

Chlorites in the intensely bleached zone adjacent to the orebody, interpreted to be related to the mineralization, are intergrown with, or replacing fine-grained illite, and have a sudoite composition ( $\text{K}_{0.17-0.17}\text{Fe}_{0.09-0.14}\text{Mg}_{1.59-1.82}\text{Al}_{4.13-3.83}\text{Si}_{3.94-3.82}\text{Al}_{0.06-0.18}\text{O}_{10}(\text{OH})_8$ ). This alteration is cut by a fracture-controlled Na-bearing sudoite ( $\text{Na}_{0.16}\text{K}_{0.03}\text{Fe}_{0.21}\text{Mg}_{1.26}\text{Al}_{4.32}\text{Si}_{3.88}\text{Al}_{0.12}\text{O}_{10}(\text{OH})_8$ ). The latest generation of chlorite is spherulitic clinocllore ( $\text{Fe}_{1.03-1.21}\text{Mg}_{3.30-3.05}\text{Al}_{1.63-1.68}(\text{Si}_{2.88-3.01}\text{Al}_{0.99-1.12})\text{O}_{10}(\text{OH})_8$ ) in veins that are observed cross cutting all earlier chlorite generations proximal and distal to the deposit. Paragenetically the vein clinocllore appears to be related to hydrothermal fluid flow associated with the intrusion of the diabase.

## PRELIMINARY STUDY ON SOLUBILITY AND STABILITY OF SCORODITE IN THE PRESENCE OF SCHEWANELLA SP. CN32 AND SCHEWANELLA SP. ANA-3

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The presence of arsenic in mine effluents leading to the contamination of soils and drinking water is a major health and environmental concern worldwide. A method of countervailing this problem is to form a stable arsenic compound of low solubility and low toxicity. The synthetic mineral scorodite ( $\text{FeAsO}_4 \cdot 2\text{H}_2\text{O}$ ) is a potential candidate. In addition to factors such as pH, temperature and solution composition, it has been determined that the presence of bacteria can have a significant influence on the stability and solubility of minerals such as scorodite. In this study, the rate of dissolution of scorodite in the presence of *Schewanella putrefaciens* CN32, an iron and arsenic reducer, was compared to

that of *Schewanella putrefaciens* ANA-3, a known arsenic reducer. In addition, the required minimal amount of phosphate required to maintain the cells' reproduction was also tested.

Preliminary results indicate that both *Schewanella* survived at comparatively low phosphate concentration, 50 microM and lower. The As(III) and Fe(II) concentrations measured in microcosm experiments containing the low phosphate concentrations were about three times the concentrations of As(III) and Fe(II) found in experiments conducted at phosphate concentrations of about 400 microM, the phosphate concentration typically used for similar experiments with *Schewanella*. Initial findings indicate that the *Schewanella* sp. ANA-3 yields higher concentrations of As(III) and Fe(II) than the *Schewanella* sp. CN32.

#### **PRELIMINARY RESULTS ON THE PHYSICAL VOLCANOLOGY OF KOMATIITES OF THE PRINCE ALBERT GROUP WITHIN THE PRINCE ALBERT HILLS, MELVILLE PENINSULA, NUNAVUT**

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Komatiitic rocks represent a significant component of the Prince Albert Group (PAG) that form a semi-continuously, northeast trending Archean supracrustal succession of metavolcanic and metasedimentary rocks on each side of the Committee Bay within the Rae Craton, Nunavut. Two major coherent greenstone belts occurred on Melville Peninsula and have been interpreted as part of the PAG, the Roche Bay greenstone belt to the east and the Prince Albert greenstone belt (PAGB) to the west. The present study is part of the Geo-mapping for Energy and Minerals (GEM) project of the Geological Survey of Canada, and focuses on one of the best-preserved komatiitic sequence within the southwest portion of the PAGB on Melville Peninsula.

The komatiitic succession in this area is bordered on its western margin by tonalitic intrusions, whereas to the east it is overlain by mafic and felsic volcanics, and massive gabbroic dykes are prevalent throughout the succession. Both undifferentiated and differentiated komatiites units were recognized. The well-exposed and well-developed differentiated units with an upper spinifex-textured zone (A-zone) and lower cumulus-textured zone (B-zone) are located within the eastern part of the study area. This textural layering is accentuated by weathering where the spinifex layers are grey-green in color and generally 0.3-0.6m thick, and the cumulate layers are orange-brown in color, typically 0.5-1 m thick. Locally, the A-zone may be further subdivided into an A2 (randomly oriented spinifex), and A3 (coarse platy spinifex) zones whereas the B-zone may be further subdivided into the B1 (aligned skeletal olivine), and B2 (medium-grained cumulate). However, the uppermost part of the A-zone, the fractured upper chill zone and flow top breccia containing microspinifex (A1), was rarely observed. The komatiitic succession is interpreted to be slightly overturned with an eastward younging direction based of fining upward of spinifex textured and rare polyhedral jointing at the contact between units. The komatiites have been altered and metamorphosed hence the primary mineralogy are rarely preserved and replaced by an assemblage of serpentine, chlorite, tremolite-actinolite, magnetite, talc and carbonate minerals.

The mode of emplacement of those komatiitic units is currently being investigated but the lack of volcanic features, especially of the rarity of polyhedral flow top breccia within the differentiated units, suggests that some of the komatiitic units might be intrusive. Furthermore, a new Ni-Cu occurrence discovered within this komatiitic succession to the north (Adamson River

occurrence grades up to 7.9% Ni) indicates that this succession may have economic potential.

#### **POST-SUBDUCTION METALLOGENY**

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There is growing recognition of a class of porphyry Cu-Au and porphyry-related epithermal Au deposits in post-subduction tectonic environments, which include arc-continent and continent-continent collision, arc reversal or migration, and arc rifting. Common to these deposits is a magmatic signature ranging from calc-alkaline to moderately alkaline, but mostly retaining arc-related trace element signatures, suggesting at least an indirect input from subduction sources. Alkaline-type epithermal gold deposits (e.g. Porgera, Lihir, Emperor, Cripple Creek) may represent an extreme mafic end-member to this range of deposits, whereas calc-alkaline porphyry Cu±Au deposits in the Neo-Tethyan collided arcs of the Balkans, Turkey, Iran, and Tibet may represent another end-member, barely discernible from normal arc porphyries.

Key to the formation of this suite of deposits is a source in subduction-modified, amphibole-rich, upper-plate lithosphere, or rarely in residual metasomatized asthenosphere (although such asthenospheric sources can be expected to be rapidly dissipated by convection after subduction ceases). The heterogeneity of this lithosphere, and the wide range of lithologies and geochemistry (including metals) left behind from a protracted phase of arc magmatism gives rise to the wide variety of observed magma types and metallogenic associations. Dehydration melting of such amphibolitic sources during any number of later tectonic events (e.g. crustal thickening, lithospheric mantle delamination, rifting) will generate relatively small volumes of partial melt, which, although they may share the general geochemical signature of their subduction-related parentage, may shift to more alkaline compositions relative to the original calc-alkaline arc magma flux from which the amphibolites were derived.

Subduction-modified lithosphere may be an important source for a variety of other mineral deposit types that are not obviously related to subduction activity in time or space, because such lithospheric sources can be expected to be preserved until affected by some later tectonomagmatic event. Although events such as arc collision commonly occur shortly after arc magmatism, and are therefore more obviously related to subduction, re-heating can conceivably occur at any later time, where the connection to earlier subduction may be obscure. It is tempting to speculate that other types of intra-continental ore deposits related to alkaline magmatism may have such an origin in previously subduction-modified lithosphere.

#### **STRUCTURAL GEOLOGY OF THE ARCHEAN PRINCE ALBERT GROUP, MELVILLE PENINSULA, NUNAVUT**

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The purpose of this study is to characterize the structural geology of the Prince Albert Hills on Melville Peninsula, Nunavut. This study will build on previous geological mapping done by the Geological Survey of Canada and is part of a current bedrock geological mapping program through the Federal Government of Canada's Geo-mapping for Energy and Minerals (GEM) program. The Melville Peninsula Project aims to renew the regional geoscience knowledge base, and to stimulate mineral exploration to support economic and societal development of northern communities.

This study will use detailed geological and structural mapping to provide constraints on the deformation and metamorphic history of the area. Recent dating by the Geological Survey of Canada in the Prince Albert Hills has established that volcanic sequences in the area range from 2.97 to 2.75 Ga. There are currently no constraints on the history of deformation affecting the supracrustal assemblages. This study aims to constrain the ages of deformation using U-Pb and in situ Ar-Ar dating methods. It will provide a benchmark with which to compare with other Archean supracrustal belts in the area such as the Mary River Group, Roche Bay belt, and Committee Bay belt. It will also provide key information for further mineral exploration activities in the area.

## **GEOCHRONOLOGY AND TECTONIC EVOLUTION IN THE SERRINHA NUCLEUS GRANITE-GREENSTONE TERRANE**

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The Precambrian basement of Sao Francisco Craton (SFC), north-eastern Brazil, consists of Archean cratonic nuclei surrounded by belts formed during the Trans-Amazonian orogenic episode. SHRIMP U-Pb dating of zircon provides time constraints for main tectonic events in the Serrinha Nucleus, showing that deformation was closely related to specific episodes of granitoid intrusion. Our data show that the granitoid plutons can be divided into 3 distinct age groups. Xenocryst ages of 3.6 Ga, the oldest zircon yet recorded within the SFC, are found in the Paleoproterozoic rocks, indicating the presence of buried Paleoarchean sialic basement. The formation of Mesoarchean gneisses (>3.2 Ga) was followed by group 1 granitoids (3162-2989 Ma), consisting of N-S elongated TTG plutons with gneissic borders that include enclaves of the older gneissic basement. An Archean metamorphic event is recognized at ~3070 Ma. Thus, serial additions of juvenile material over a period of several hundred m.y. led to the formation of a stable continent by 2.9 Ga. Evidence of Neoarchean activity is rare. Field observations initially suggested that these granites intrude the greenstone belts, however ages presently available for the volcano-sedimentary rocks are all Paleoproterozoic (2159-2073 Ma). Group 2 Paleoproterozoic granitoids, represented by ca. 2165 – 2130 Ma juvenile calc-alkaline plutons, intruded in a continental arc environment floored by the Mesoarchean crust, in which metavolcanic and metasedimentary rocks are also abundant. Most group 2 rocks have major- and trace-element compositions similar to magmas formed in present-day subduction zones. Metamorphism accompanied the main magmatic event, producing strong NW–SE structural trends. A group 3 suite of alkaline granites intruded later probably following ocean closure and slab break-off. Geochronology, geochemical data, spatial associations and lithostratigraphy suggest at least two stages of alkaline magmatism: a first stage (2114-2097 Ma), with intrusion of shoshonite, syenite and ultrapotassic lamprophyric rocks; and a second stage (ca. 2080-2070 Ma), with intrusion of small semi-circular peraluminous isotropic K-granites and dykes. These were the probable heat source driving Palaeoproterozoic metamorphism at 2.07 Ga, which is generally high-temperature and low-pressure in nature. Later magmatism is restricted to kimberlitic pipes, probably emplaced during the Neoproterozoic Brazilian event, which sampled older zircon from the basement. Multiple reworking has obliterated pre Trans-Amazonian structures and metamorphic assemblages, obscuring interpretation of the older events.

## **COLLAPSE OF THE MESOPROTEROZOIC GRENVILLE OROGEN: CRUSTAL ARCHITECTURE, TECTONIC PROCESS, AND SIGNIFICANCE FOR MINERAL POTENTIAL**

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The Ottawa hinterland of the Grenville Province can be subdivided into an orogenic infrastructure, composed of medium-P–high-T, mid-crustal gneisses with sub-horizontal fabrics, and an orogenic suprastructure composed of low-P–medium-T, upper crustal schists with sub-vertical fabrics and a low-P–T ( $\leq 500^\circ\text{C}$ ) orogenic lid. Juxtaposition of the Ottawa infrastructure and suprastructure is inferred to have been caused by foundering of the upper part of an orogenic plateau into the underlying mid-crustal channel, with the resultant geometry of the collapsed crust resembling a series of crustal-scale core complexes. Temporal progression of Ottawa metamorphism from granulite-facies in the mid crust at ca. 1090-1050 Ma, through amphibolite-facies in the upper crust at ca. 1050-1020 Ma, to heating to  $\leq 500^\circ\text{C}$  in the uppermost crust at ca. 1020-980 Ma, was a result of conductive heat transfer during collapse, as hot mid crust was exhumed against successively higher crustal levels. These ages imply that the collapse phase of orogenesis lasted for  $\geq 50$  Ma, comparable to the duration to the earlier crustal thickening phase. Crustal thinning and orogen-parallel stretching (i.e. flattening) of the pervasively migmatitic, melt-weakened mid crust was driven by the excess potential energy of the plateau. This in turn led to wholesale boudinage of the overlying brittle uppermost crust, with rise of ductile mid crust into boudin necks initiating core-complex formation. In contrast to the sub-horizontal fabrics and structures in the mid crust, coeval fabrics and structures in the ductile LP upper crust are upright and record vertical thickening driven by sub-horizontal tectonic traction forces. Coeval vertical thinning / horizontal spreading of the weak mid crust driven by gravity, and vertical thickening / horizontal shortening of the stronger upper crust driven by traction forces, implies that deformation in the two levels was decoupled and that collapse was a fundamentally 3-D process. Collapse was temporally and spatially associated with leucogranite emplacement, and normal-sense faults at the margins of several core complexes were the sites of hydrothermal alteration that led to the formation of IO(CG) deposits.

## **GIANT IMPACTS CONTROL THE MANTLE DYNAMICS OF MARS**

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A total of 20 giant impacts occurred on Mars within 200 Myr at around 4 Ga. A giant impact introduces a substantial amount of heat into the upper mantle of Mars, resulting in a hot and buoyant plume which rises rapidly and invigorates mantle convection. We investigate the collective effects of the 20 impacts on the mantle dynamics of Mars using the 3D spherical finite element convection code CitcomS with the extended Boussinesq approximation subject to cooling and free slip boundary conditions at the core mantle boundary (CMB) and a fix temperature and rigid conditions at the surface. The mantle viscosity is Arrhenius-style, temperature- and pressure-dependent, with activation parameters consistent with the viscosity of the Earth's upper mantle. The mantle is heated from within by time-dependent radioactive decay. We calculate several models with different initial mantle and CMB temperatures. The impact heating is parameterized as a temperature perturbation in the mantle. We find that a single impact can alter the entire flow field, causing a long wavelength upwelling beneath the impact site which sets up a persistent degree-1 con-

vective pattern in the mantle. The interval between the largest impacts is longer than the initial recovery time for a single impact. However, the changes in convective pattern of mantle due to all impacts have a greater effect than a single impact. We note that only the very largest impacts can heat the lower mantle significantly. Thus the effects of the 20 impacts can be approximated by those of the top 5.

## STRUCTURAL ANALYSIS OF THE MATOUSH URANIUM DEPOSIT, QUEBEC

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The Matoush deposit is situated 260 km north east of Chibougamau in the Otish basin. The deposit is hosted in the Proterozoic Indicator Formation, which comprises conglomerates, conglomeratic sandstones and subarkosic sandstones. The deposit is structurally controlled by the Matoush fault, which strikes 007° and dips 85°E. Mineralization is dominantly uraninite lenses that pitch 45° towards the south on the fault surface. The predominance of Cr-tourmaline and eskolaite near the mineralization indicates that there is a strong chromium association with the uranium. Structural elements were collected in order to determine the relationship between mineralization and deformation. The results indicate that the Matoush fault is the dominant control on fracture and vein orientation.

Tourmaline and eskolaite are the phases most commonly associated with the uranium mineralization. In areas of intense mineralization, the tourmaline contains varying levels of Cr (15-39 wt% oxides), Fe (up to 8.82 wt% oxides), V (up to 1.75 wt% oxides) and Mn (up to 0.43 wt% oxides) whereas the tourmaline in unmineralized areas contains Fe (with only up to 5 wt% oxides). The uranium is also strongly associated with eskolaite as well as other Cr-oxides and hydroxides which are usually intergrown with the uranium phase. 3D distribution of the mineral phases shows a strong zonation centered on the high-grade U mineralization.

Structural measurements were acquired from drillcore that was deemed adequately oriented for determination of true orientation. Measurements were collected for sets of structural elements in order to establish in detail the relationship of mineralization to deformation features, and to extend these mesoscopic observations to the macroscopic scale. Fracture, fault, slickenside and vein orientations were measured. Several kinds of fractures were observed, the most predominant being argillaceous, bleached, silicified and pyritized. The fracture orientations indicate that the Matoush fault is the dominant control on fracture orientation. Similarly, veins show a clear correlation with the Matoush fault. The mineral zonation is nevertheless strongly linked to overall fracture density.

Fault-fluid interaction has affected element transport and concentration. Cr concentration is a positive indicator of uranium mineralization. However, spatial distribution and localization of uranium mineralization as of this time defies characterization by simple geometric relationships. This is exemplified by the lack of obvious intersections of structural elements or clear development of dilatational zones that correspond with deposit orientations. However, the observation of rare U-bearing microscopic fault oversteps and linkages are suggestive of similar fault-scale structures for which exploration is ongoing.

## ULTRAHIGH PRESSURE MINERALS AND CRUST-MANTLE RECYCLING — EVIDENCE FROM OPHIOLITES

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Podiform chromitites and peridotites of several ophiolites, including the Luobusa and Donqiao bodies of Tibet, the Semail ophiolite of Oman and the Ray-iz ophiolite of Russia, contain various combinations of deep mantle minerals, such as diamond, coesite, moissanite, base-metal and PGE alloys and native elements. These are associated with a range of crustal minerals, including zircon, quartz, corundum, kyanite, sillimanite, feldspar, almandine garnet and rutile. In-situ grains of diamonds, moissanite, and corundum are hosted in chromite grains from podiform chromitites of the Luobusa and Ray-iz ophiolites. Coesite from the Luobusa ophiolite is intergrown with kyanite on the rim of an Fe-Ti alloy grain recovered from chromitite. The in situ diamonds, moissanite and corundum consist of euhedral grains about 200 µm across, growing in small patches of carbon. Both the diamonds and moissanite are characterized by having exceedingly low C isotopic values (mean  $\delta^{13}\text{C} = -28$ ), much lower than typical kimberlite diamonds. Most of the crustal minerals occur as subrounded to subangular grains, about 50-300 microns across, but some are blocky to subangular. The zircons typically have very complex internal structures, although a few euhedral to subhedral grains have concentric zoning, suggesting an igneous origin. <sup>206</sup>Pb/<sup>208</sup>U SIMS dates for the Luobusa zircons range from 549±19 to 1657±48 Ma, those from Donqiao from 484±49 to 2515± Ma, all much older than the ophiolites. Most zircons from Oman chromitites have similar ages to those from Tibet but 4 grains are essentially the same age as the ophiolite. The in situ UHP minerals in chromite grains indicates that at least some of the chromite crystallized at depth. The association of deep mantle and crustal minerals suggests subduction of crustal material to depths of 150-400 km where it was mixed with mantle material and subsequently incorporated into podiform chromitites and mantle peridotites. Based on the occurrence of these minerals in widely separated ophiolites of variable age, we suggest that diamonds and associated minerals may be widely preserved in the upper mantle.

## CHARACTERIZATION OF GLACIAL DISPERSAL FROM THE KIGGAVIK URANIUM DEPOSIT, NUNAVUT USING INDICATOR MINERALS AND TILL GEOCHEMISTRY

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Over the past 20 years, mineral exploration in Canada and Fennoscandia has successfully utilized till indicator mineral methods for diamond and gold in glaciated terrain. More recently, indicator mineral methods for base metals and other commodities have been developed, however, few published case studies have documented the glacial dispersal from uranium deposits using indicator minerals and pathfinder elements.

In the summer of 2010, a drift prospecting study was initiated at the Kiggavik uranium deposit as part of the Geological Survey of Canada's Geo-mapping for Energy and Minerals (GEM 2008-2013) program, and is a collaborative effort with Queen's University, Overburden Drilling Management Limited, and AREVA Resources Canada Incorporated. The purpose of this project is to investigate and characterize the glacial dispersal of uranium-rich debris (till) down-ice of the Kiggavik uranium deposit. Samples of sub-cropping bedrock representing hydrothermally-altered and

unaltered host rocks of mineralized zones from the Kiggavik deposit were collected for mineralogical and geochemical comparisons with till overlying, and varying distances down-ice from, the sub-cropping mineralization.

The deposit is located within the zone affected by the migration of the Keewatin Ice Divide of the Laurentide Ice Sheet. Landforms, striae, and clast dispersal provide a record of simple to complex net transport. Multiple ice-flow trajectories had been documented in the area and this knowledge was used to plan the surface till sampling survey. The oldest ice-flow phase observed was a subtle E-SE trajectory, possibly during the onset of the Laurentide Ice Sheet. A powerful NW-NNW ice flow, assumed to have occurred during the Last Glacial Maximum, is dominant, with most landforms conforming to this trajectory. Lastly, a westward ice flow direction related to the Dubawnt ice stream is commonly observed in striations on outcrop and is believed to have been the last ice flow that eroded the deposit. Surface till samples (n=71) were collected from active mud boils up-ice from the deposit, overlying the deposit, and at specific distances in a fan-shaped pattern down-ice of the deposit (10 m, 100 m, 200 m, 500 m, 1 km, 2 km, 3 km, 5 km, 10 km) with respect to the NNW, NW and W ice flows.

Both till and bedrock samples were processed to recover heavy mineral concentrates from which indicator minerals were picked. The <0.063 mm and <0.002 mm size-fractions of the till were analyzed geochemically and were compared to geochemical signatures of the mineralized and unmineralized rocks to identify glacial pathfinder elements. Further geochemical analyses will be conducted to illustrate the preferred partitioning of uranium in the till.

#### **POTENTIAL FAULT REACTIVATION IN THE OTTAWA-BONNECHERE GRABEN BASED ON APATITE FISSION-TRACK ANALYSIS**

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The Ottawa-Bonnechere graben (OBG) along the southern Quebec-Ontario border, the St. Lawrence rift system (SLRS) and the Saguenay River graben (SRG) are major brittle fault zones along which reactivation of Iapetus-related structures is believed to occur. Both the OBG and SRG are bounded by WNW-ESE trending faults and are considered to be Iapetan aulacogens. Their NW-trending structures are linked by the half-graben formed by the NE-SW trending SLRS. In June 2010, a magnitude 5.5 earthquake occurred in the OBG about 60 km from Ottawa suggesting ongoing tectonic activity in the region.

During the summer of 2010, 24 samples of Grenville basement rocks and Potsdam Sandstone were collected along several transects across the OBG faults for apatite fission-track analysis (AFT) in order to constrain the timing of potential fault reactivation in the graben. AFT age determinations for these samples are in process.

Apatite fission-track (AFT) ages from the SLRS and SRG determined from Grenville basement rocks have shown Mesozoic age discontinuities suggesting fault reactivation. Along the SLRS, AFT age offsets exist between the footwall (200-184 Ma) and hanging wall (152-149 Ma) samples at Sault-au-Cochon, Cap-aux-Oies and Montmorency Falls and suggest that Early Jurassic normal faulting was followed by Late Jurassic fault inversion. Five new AFT ages from the Shawinigan-Trois Rivières region along the southern part of the SLRS also show comparable AFT age offsets between the footwall (216-211 Ma) and hanging wall samples

(165-162 Ma) of the St-Cuthbert fault, extending the area affected by Late Jurassic fault inversion ~130 km farther south.

Along the SRG, AFT age offsets have been determined between the hanging wall (430-280 Ma) and footwall (220-180 Ma) samples along the Lac Kenogami and Rivière Ste-Marguerite faults suggesting normal faulting at ca. 200 Ma. The AFT age discontinuities across faults in the SLRS and SRG suggest that Mesozoic fault reactivation may have also occurred in the OBG but the timing and sense of motion of this potential faulting have yet to be determined.

#### **MULTIPLE SULFUR ISOTOPES AS A PROXY FOR MESOARCHAEOAN ATMOSPHERE**

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The geologic sulfur isotope record can be broadly divided into two parts that reflect the binary history of atmospheric oxygen. In rocks younger than ca. 2.5 billion years old (Ga) relationships among the isotopic ratios <sup>33</sup>S/<sup>32</sup>S, <sup>34</sup>S/<sup>32</sup>S and <sup>36</sup>S/<sup>32</sup>S are predictable on the basis of their relative isotopic mass difference. In rocks older than 2.5 Ga sulfur isotopic ratios do not follow these predictable relationships reflecting anomalous isotopic separation known as mass independent fractionation (MIF). Currently, the only known mechanism for producing significant MIF in sulfur involves ultraviolet photolysis of sulfur dioxide gas in an oxygen-poor atmosphere. Therefore, the disappearance of MIF at 2.5 Ga has been interpreted as a significant increase in atmospheric oxygen concentrations. Large MIF values prior to 3.2 Ga and between 2.7 and 2.5 Ga supports very low atmospheric oxygen levels at these times.

However, the large MIF that characterize these time periods is lacking in the current S isotope record between 2.8 and 3.0 Ga. The decrease in MIF at this time has been attributed to atmospheric changes ranging from oxygen fluctuations, variations in volcanic SO<sub>2</sub>:H<sub>2</sub>S, and high-altitude methane haze. An alternative, but unexplored, possibility to atmospheric influences is that the published sets of multiple sulfur isotope analyses from 2.8 to 3.0 Ga rocks reflect a sampling bias. Most of these analyses from 2.8 to 3.0 Ga rocks are from organic matter-poor clastic sedimentary rocks, in which the ratio of detrital to authigenic pyrite is deemed to be high. Deposition of these clastic rocks represents the end product of physical weathering rather than a direct record of the biogeochemical environment. In order to evaluate this hypothesis, we collected organic matter-rich clastic rocks (e.g. black shale) and chemical sedimentary rocks (e.g. iron formations, sedimentary carbonate and massive sulfides) from three greenstone belts in Northwestern Ontario around Red Lake, Finlayson Lake, and Lumby Lake that contain sediments deposited between 3.2 and 2.7 Ga. We will present preliminary multiple sulfur isotope results from these samples and examine the possibility of sampling bias in the published dataset of multiple sulfur isotope analyses.

#### **EXTRAPLAC: ORGANIZATION AND IMPLEMENTATION OF THE FRENCH CONTINENTAL SHELF PROGRAM**

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In 2002, the French government started the scientific and technical program for the extension of the continental shelf, offshore the

French mainland, and its overseas territories. This program, baptized EXTRAPLAC for *Reasoned Extension of the Continental Shelf*, has since affected 14 scientific cruises, for a total of over 220 days of ship time in the Atlantic, Pacific and Indian oceans. The technical and scientific team produced numerous reports, and participated in the preparation of 5 partial submissions, one in 2006, one in 2007, the remainder submitted to the CLCS in 2009. The first partial submission, concerning the Bay of Biscay, was elaborated and presented jointly with neighboring states Spain, United Kingdom and Ireland. The second partial submission is dedicated to French Guiana and New-Caledonia. Followed a submission concerning the French Antilles, and the Kerguelen Islands, a joint submission with South Africa in the area of the Prince Edward Islands and the Crozet Archipelago, and finally a submission concerning Reunion Island and the islands of Saint-Paul-et-Amsterdam, in the Indian Ocean. These extensions imply new maritime boundaries with around 10 different countries. With a total budget of ~ 20 Million€ Extraplac has had to accept compromises during the preparation of the different submissions. Concerning the data acquisition, this resulted, for example, in the use of a rapid seismic acquisition system (600 m streamer towed at 10knts), preferred over a conventional multi-channel seismic system four times more expensive, and with respect to multi-beam bathymetric mapping, no systematic mapping was performed, but only discrete profiles in strategic parts of the French continental shelf. In this presentation we will focus on the organization of the program and on the technical solutions that have been used up.

#### **HYPERSPECTRAL SENSING IN SUPPORT OF MINERAL EXPLORATION IN NORTHERN LATITUDE REMOTE REGIONS: EXAMPLE FROM THE CAPE SMITH NICKEL BELT, CANADA**

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Regional geologic mapping in the Arctic is time intensive and costly, primarily owing to poor accessibility, but it is essential for subsequent geologic investigations and to guide mineral exploration activities. Along with established geophysical exploration technologies (e.g. magnetic and radiometric surveys), hyperspectral imaging is a promising avenue to facilitate detailed continuous regional mapping in the Arctic, if issues such as low illumination and lichen cover on bedrock can be addressed. This study investigates AISA optical airborne hyperspectral imagery (~2500 km<sup>2</sup>) acquired over the Proterozoic Cape Smith greenstone belt of northern Quebec (Nunavik), Canada. The belt is host to Nickel-Cu (PGE) mineralization occurring within a series of thick (50-200 m) mafic-ultramafic complexes that outcrop discontinuously. The objective of this study is to demonstrate the capability of producing detailed maps from such imagery to highlight ultramafic rock units associated with mineralization in the presence of lichen coatings.

Lichens are predominant on bedrock surfaces, adding to the challenge of remotely mapping packages of mafic rocks with inherently low spectral contrast. Within flight line, and between flight line calibration issues result in significant inconsistencies between lines impeding the continuous mapping of spectrally significant lithologic units. A leveling algorithm was developed that effectively minimizes these differences providing a near seamless mosaic of flightlines for the full spectra range (0.4-2.5  $\mu$ m). The similar mineralogy of the basalt-gabbro-pyroxenite-peridotite-dunite units and the extensive lichen cover complicates their discrimination. However, the spectra of lichen are similar in the short wave infrared, and thus, variability in spectral shape for lichen

covered bedrock samples can be principally attributed to the contribution of minerals.

Spectral and mineralogical analysis of field samples was completed first to determine spectral features associated with key index minerals that could be used to discriminate between rock types and lichen. A series of normalized multi-band ratios were developed from key spectral features of minerals present in field samples. When applied to airborne imaging this resulted in effective discrimination and mapping of rock units, including the subtle spatial compositional variations related to the zoning of ultramafic bodies. The predictive map distributions of dunite, peridotite, pyroxenite and gabbro/basalt emulate the detailed ground mapping conducted for a subset of the region as part of on-going mineral exploration efforts. Valuable mineralogical information can thus be captured from airborne imaging spectroscopy despite extensive cover by rock encrusting lichen.

#### **SERGIPANO BELT MAFIC-ULTRAMAFIC ENCLAVES, NE BRAZIL**

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The Sergipano belt, on Northeastern Brazil, is characterized by a Neoproterozoic granitic (s.l.) association. On the central area of the belt, so called the Macururé Domain, these granites preserves mafic-ultramafic enclaves. The Macururé granites show a wide range of granite compositions (muscovite-granites, muscovite-mica granites, mica-hornblende granites, and hornblende-monzonites), all with a consistent volcanic-arc signature. Their contacts with metamorphic rocks are sharp, usually cut by dykes. On the core, these granites show magmatic foliation, and even tectonic foliation was seen in some outcrops. On many of the investigated plutons muscovite-granites grades, smoothly or sharply, to biotite or hornblende granites, and in rare cases to monzonites, which suggest some zoned distribution still not completely understood. The enclaves seem to be less abundant in less differentiated rocks. Meta-sedimentary xenoliths were occasionally also found. The studied granites have medium to coarse granulation, prevalence of allotriomorphic textures, sometimes porphyritic on the less differentiated rocks. The mafic-ultramafic terms occur as micro-granular enclaves of assorted sizes, with or without biotite or amphibole borders, as well as sin-plutonic dykes. It is common to observe structures suggesting co-existence and mixing processes at varied intensities between the felsic and mafic magmas. The mineralogy of the enclaves is essentially composed by plagioclase, hornblende, biotite, opaque minerals, diopside and, as accessory, apatite, titanite and sometimes zircon. The chemical composition of these enclaves (44lt; %SiO<sub>2</sub><56) allows classifying them as clinopyroxinite, gabbros, monzonites and quartz-diorites with metaluminous alkali-potassic to ultrapotassic signature. The Harker diagrams for these samples, despite the pluton in which they were collected, show linear patterns that suggest the existence of mixing process. By the other side, most of the studied samples show negative anomalies of Eu (0.5 a 0.9) with SiO<sub>2</sub>, impoverishment. The fractionated ETR pattern (7<La<sub>N</sub>/Yb<sub>N</sub><23), and the relationships shown by the trace elements indicate a volcanic arc source, similar to that observed on the granites in which they occur. The present data suggest these enclaves are evidence for the interaction between mafic-ultramafic and crustal-riolitic magmas, and indicate that they can be responsible by the generation of the diversity of granites and enclaves found at the Macururé Domain. [Acknowledgements: We thank the financial funds from FAPITEC – Universal 2008 and CNPq to the development of this project. This is the contribution from LMP-UFS.]



## PRELIMINARY STRATIGRAPHY AND PHYSICAL VOLCANOLOGY ASSOCIATED WITH THE PALEOPROTEROZOIC BACK FORTY VMS DEPOSIT, MENOMINEE COUNTY, MICHIGAN

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The most recently discovered volcanogenic massive sulphide (VMS) deposit within the Paleoproterozoic Wisconsin Magmatic Terrane is Aquila Resources' Back Forty Deposit, located approximately 35 km north of Menominee, Michigan. Aquila Resources' recent press releases indicate this deposit contains a measured plus indicated resource of 18.1 million tonnes, grading 1.63 g/t Au, 20.04 g/t Ag, 0.19% Cu, and 2.48% Zn (October 15, 2010). The deposit occurs within a structurally deformed sequence comprising felsic volcanic breccias, tuff-breccias, lapilli-tuffs and tuffs. Stratigraphic correlation to this point has been based largely on lithogeochemical characteristics, which have determined three chemically distinct units. Detailed field mapping (varying from 1:500-1:5000 scale), diamond drill hole logging of approximately 10,000 meters of exploration diamond drill core, and petrographic and lithogeochemical studies are currently being utilized to evaluate the detailed volcanic stratigraphy, volcanic facies, and volcanological environment associated with the mineralization. The felsic volcanic units are being further distinguished based on 1) bedding vs. massive lithofacies, fabric and grading; 2) crystal composition, size, shape, abundance and distribution; 3) fragment composition, size, shape, abundance and distribution; and 4) grain size. Detailed physical volcanological environment is under investigation. Thick sequences of felsic volcanic rocks may be consistent with a caldera setting; however, more widespread regional stratigraphic studies will be needed to evaluate this.

## AN LA-ICP-MS INVESTIGATION OF GARNETS WITH UNUSUAL REE PATTERNS

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Many garnets of non-crustal origin (peridotitic or eclogitic) exhibit rare earth element (REE) patterns with elevated middle (M)REE concentrations. This feature is not readily explained by the widely accepted crystal lattice strain model, which predicts that the trivalent REE occupy the garnet x-site. This site is smaller than even the smallest REE (Lu). Substitution of REE into this site yields the positive sloping REE pattern commonly observed among crustal garnets, essentially representing the left limb of an Onuma diagram.

When unusual garnet REE patterns were first discovered with secondary ion mass spectrometry it was not possible to establish whether only the MREE or also the light (L)REE were enriched, owing to the very low LREE concentrations ( $La = 274 \pm 128$  ppb). It was therefore proposed that the mechanism for enrichment was re-equilibration with – or metasomatic alteration by – a melt highly enriched in LREE.

The purpose of this study was to investigate how LREE could substitute into the garnet crystal lattice. As a first step, garnets were analysed with a New Wave 213 nm laser ablation system coupled to an XSeries2 ICP-MS. These analyses used a large 100  $\mu$ m spot, to obtain the best possible count rates. The modern analyses, in agreement with many other recent LA-ICP-MS analyses of mantle garnets, revealed that the CI-normalized REE pattern is not LREE enriched but sinusoidal in shape, suggesting enrichment in the MREE superimposed on a typical garnet REE pattern. This

observation strongly argues against metasomatic re-enrichment, which should yield strongest LREE anomalies.

Selected garnets exhibiting sinusoidal REE patterns were later revisited with a higher efficiency Resonetics M-50 Excimer LA system. Traverses of 2 cm length using a 10  $\mu$ m spot size and a speed of 2  $\mu$ m/s were carried out. The analytes were restricted to key masses, namely Ce, Sm, Gd, Dy, Er, and Yb to define the REE pattern with the minimum of analytes with best counting statistics. The very small spot size of the laser beam coupled with the sub-ppm detection limits of the system revealed that MREE are not homogenous across a grain but that <10  $\mu$ m areas are encountered with much higher MREE than others. This observation suggests either a heterogeneity in REE chemistry in otherwise chemically homogenous garnet or the presence of MREE-enriched inclusions. Etching experiments revealed the presence of <5  $\mu$ m inclusions that more readily dissolve in HF vapour than the host garnet, favouring the second hypothesis.

## A MULTI-SENSOR LOGGER FOR ROCK CORES

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Throughout Canada, the cores from thousands of exploration diamond drill holes sit in repositories, often unsheltered from the weather. Typically, after the initial visual log by the geologist and assays of mineralized intervals, nothing much happens to these very costly cores. Yet a lot more information could be extracted out of drill cores before their containers eventually rot, such as the physical properties of the rocks, their mineralogy, and their lithogeochemistry. Quantifying these parameters could help reaching goals such as

1. planning or interpreting geophysical surveys;
2. modelling the geology or physical properties of rocks in three dimensions;
3. documenting hydrothermal alteration.

Various devices are available for measuring each property at a time, but this approach makes it unrealistic to build a large multi-parameter database for a certain region given the high cost of data acquisition, the time involved, and the destructive nature of several conventional analytical techniques.

The multi-sensor core logger at INRS-ETE is an automated system that measures all the parameters near-simultaneously on rock cores, in a non-destructive manner. The system is part of a mobile laboratory funded by the Canadian Foundation for Innovation and designed to physically, mineralogically and chemically characterize rocks. Currently, the logger can measure the density and magnetic susceptibility of rocks, quantify several chemical elements by XRF methods, and characterize mineralogical assemblages by infrared spectrometry. The system can also acquire a high-quality continuous image of the core using a linescan camera. Electrical conductivity and natural gamma radiation measurements may be added in the future.

The mobile laboratory will be used in applied research projects in collaboration with industry and governments. The first such project, a two-year study funded by Ministère des Ressources naturelles et de la Faune du Québec, is currently underway in the Matagami area, in collaboration with Xstrata Zinc. The Matagami mining camp in the northern Abitibi Subprovince contains numerous volcanogenic massive sulphide deposits and has good potential for additional discoveries. Measurements of physical properties in drill core will make it possible to convert geophysical models into geological models. Moreover, high-resolution geochemical and mineralogical measurements on volcanic and intrusive rocks will lead to a better understanding of the volcanic

stratigraphy, volcanic architecture and hydrothermal alteration in the Matagami area.

#### **NOBLE GASES IN FLUID INCLUSIONS FROM THE TILLY PORPHYRY MOLYBDENUM SYSTEM, JAMES BAY, CANADA**

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Noble gases are increasingly applied to hydrothermal-related ore deposits to quantify the contribution of mantle and crustal fluids to mineralization and temperature of the system, being Ar, Kr and Xe easily fractionated by fluid boiling. Archean porphyry systems are not well documented and remain poorly understood compared to their Phanerozoic counterpart. However, their economic importance has been substantially increased with the development of major systems such as Boddington Au and Spinifex Ridge Mo (Yilgarn), Young-Davison and Malartic Au (Abitibi). Intensification of exploration lead to recent discoveries of mineralized plutonic system North of the Abitibi belt. The Tilly porphyry Mo ± Cu system is located in the La Grande geological Sub-province, James Bay area, Superior Craton. Hosted by a tonalite-granodiorite pluton dated at 2746-2740 Ma, porphyric intrusions of calc-alkaline affinities form dykes and irregular bodies and display limited potassic and phyllic alterations. Pyrite, molybdenite and chalcopyrite, with some gold and silver, are associated either in stockwork and disseminated bodies within the intrusions, or with quartz-cemented large hydraulic breccias. Noble gases were analyzed in seven quartz separates (ca. 500 mg). Four of them represent cement of hydrothermal breccias, two are veinlets and one is phenocrysts from a porphyritic dyke which is interpreted to be the source of mineralized fluids. The gases were extracted under vacuum and  $^4\text{He}$ ,  $^{36-40}\text{Ar}$ ,  $^{84}\text{Kr}$  and  $^{132}\text{Xe}$  measured by quadrupole mass spectrometry. Fluid inclusions contain variable amounts of  $\text{H}_2\text{O}$  (76-89% v/v) and  $\text{CO}_2$  (0.9-4.5% v/v). Noble gases amounts were:  $^4\text{He}$  ( $1.9-8.8 \times 10^{-9}$  ccSTP/g);  $^{36}\text{Ar}$  ( $0.47-2.3 \times 10^{-10}$  ccSTP/g);  $^{84}\text{Kr}$  ( $1.6-5.6 \times 10^{-12}$  ccSTP/g);  $^{132}\text{Xe}$  ( $0.5-1.1 \times 10^{-12}$  ccSTP/g). The argon isotopic ratio  $^{40}\text{Ar}/^{36}\text{Ar}$  ranges from  $1634 \pm 187$  to  $15550 \pm 1753$  indicating radiogenic  $^{40}\text{Ar}^*$  production from  $^{40}\text{K}$ . The radiogenic  $^4\text{He}/^{40}\text{Ar}^*$  ratios range from 0.003 to 0.010, much lower than the crustal or mantle typical values of 2.5 to 5, indicating a massive loss of helium from the quartz, probably by diffusion. The heavier noble gas ratio  $^{84}\text{Kr}/^{36}\text{Ar}$  plotted against  $^{132}\text{Xe}/^{36}\text{Ar}$  is very well correlated. The linear array suggests a mixing between an atmospheric component and a component slightly enriched in  $^{132}\text{Xe}$  and  $^{84}\text{Kr}$ . Similar patterns have been observed in high-temperature hydrothermal fluids preserved in gold veins from the Allegheny district and in amorphous silica precipitated from geothermal waters in Japan. This suggests that the fractionation of the  $^{84}\text{Kr}/^{36}\text{Ar}$  and  $^{132}\text{Xe}/^{36}\text{Ar}$  ratios could be related to the temperature of quartz precipitation from the hydrothermal fluids.

#### **FAULT ROCKS (MELT OR GOUGE) INJECTING INTO CRACKS IN WALL ROCK DURING EARTHQUAKES PRESERVES CO-SEISMIC OVERPRESSURES**

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Injectons where fault rock has been emplaced into cracks in the wallrocks off the fault surface are common in brittle faults. Their geometry depends on the overpressure in the fault and fault rock rheology at the time of mobilization. Therefore the preserved

geometry of fault rock injections in ancient exhumed faults can be used to estimate the in situ stress and viscosity during slip.

Pseudotachylyte injections in the Santa Rosa Mylonite Zone, Palm Desert, California, formed during earthquakes, so slip rate is constrained, and the time scale of melt quenching constrains the time scale of injection to ~10-100s.

The veins show two general shapes: for injection lengths < ~2 cm, the width is unpredictable. Above a length of ~2 cm, the veins follow a constant length : width ratio, suggesting that a simple model of a penny-shaped, fluid-pressure driven crack in elastic media describes the system. Using melt viscosities calculated from the composition and estimated temperature, we determined that the overpressure in the melt at the time of quenching was ~10MPa.

We then examined a range of granular injections from thrust and normal faults in different continental settings, at different depths of activity, in different lithologies.

The Badwater Detachment, Death Valley, CA has ~20 cm long gouge injections into semi-consolidated alluvial fans hanging wall, essentially at the surface. The Muddy Mountain Thrust, a Sevier-age low-angle thrust fault in southern Nevada, contains both centimeters-scale upward-directed gouge dikes and metres scale upward-directed ~1 cm clast breccia injections. These inject into pristine and brecciated carbonates in the hanging wall and poorly consolidated aeolian sandstone in the footwall. The depth of preserved fault activity is unknown but probably ~100s metres. The Naukluft Thrust, central Namibia has coarse gouge -3 cm-clast breccia injections into shales, limestones, dolomites and quartzites, enabling an examination of the role of wall rock fabric and lithology in the same fault. The depth of activity is less than 5 km.

The granular fault rock injections are unconstrained with respect to viscosity during mobilization, or the time-scale of injection. However, preliminary results show that the granular examples approach the same aspect ratio as the pseudotachylytes, requiring similar viscosity and overpressure. This may be the first direct measurement of in situ conditions during coseismic pressurization of fault gouge.

#### **THE TROILUS Au-Cu DEPOSIT: A DEFORMED ARCHEAN PORPHYRY OF THE REDUCED VARIETY**

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The Archean Troilus Au-Cu deposit in the Frotet-Evans greenstone belt of northern Quebec is a low grade, high-tonnage resource hosted in Archean calc-alkaline intrusive rocks. In 2009 it produced 135,200 oz Au and 5,900 t Cu from 6 Mt milled @ 0.83 g/t Au & 0.11% Cu. Classification of the deposit has been contentious since production commenced in 1997. Several models have been proposed including porphyry Au-Cu, orogenic Au, and plutonic-associated disseminated Au. Using published geochronological data and new field observations, it can be demonstrated that the main orebody is a deformed Archean porphyry Au-Cu deposit, albeit of the reduced variety (i.e. abundant hypogene pyrrhotite and a lack of primary hematite and sulphate minerals). The possibility remains that a second Au mineralizing event (orogenic Au overprint?) unrelated to the main Au-Cu event occurred, but it is considered unlikely. The rare and areally restricted auriferous quartz veins/veinlets probably represent minor reconcentration and redistribution of existing Au during deformation and metamorphism at ca. 2.7 Ga. The minor offset of the Cu and Au zones in the deposit likely reflects the underlying asymmetry of the original Cu-Au orebody. The formation of the Troilus deposit may be separated into seven sequential stages: (1) Intrusion of a large diorite pluton into the greenstone sequence at 2791 Ma; (2) Formation

of sodic (albite) alteration in the diorite; (3) Intrusion of felsic dykes at ca. 2782 Ma; (4) Pseudobreccia formation, potassic (biotite) alteration, and Au-Cu mineralization; (5) Tilting of the Troilus deposit and intrusion of peraluminous granite dykes; (6) Intrusion of granite pegmatite dykes; and (7) Emplacement of the Parker granite at ca. 2698 Ma and further pegmatite formation. The difficulty in understanding the genesis of the Troilus deposit has 3 main causes: (1) the deposit has experienced regional deformation and metamorphism, plus contact metamorphism; (2) the reduced nature of the porphyry ores; (3) Intrusion of the Parker granite has removed the porphyry system below 700 m. There are several seemingly intractable problems with the application of an orogenic Au model to the Troilus deposit. These include the large amount of copper in the deposit, the absence of a regional deformation zone associated with the mineralization, and the disseminated nature of the sulfide mineralization. Troilus is one of the oldest (if not the oldest) Au-Cu deposits in the Superior Province and our ongoing efforts to date the Au-Cu mineralization will help identify whether it represents a discrete Archean Au-Cu event.

#### **SCROLL BARS IN THE ANABRANCHING PATTERN OF THE MIDDLE AMAZON RIVER**

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The Amazon River between the confluences with the Negro and Madeira rivers has been classified as a type 1 anabranching river, commonly termed anastomosing. This classification is based on the sedimentary record, geomorphologic features as well as the evaluation of channel change between 1978 and 2009. Evidence is provided here for a widely distributed scroll bar floodplain in the islands as well as parts of the right bank of the Amazon River and the margins of the confluence of the Madeira River. The ridge-and-swale morphology is characteristic in these areas with the development of narrow lakes and minor secondary channels that follow the swales. Individual sets of lateral accretion can reach up to 7.5 km wide. These deposits consist of silty, fine-grained, moderately to well sorted sand and greyish clay that form inclined heterolithic stratification. The strata generally dip up to 10° without a preferential direction. Subaerial exposure periods are indicated by bioturbation features associated with rather high organic detritus in the form of leaves and trunk fragments. The scroll bars follow present day migration of the main and secondary channels, are truncated either by these channels or between scroll bar sets, recording migration without a preferential direction. This indicates an active meandering behavior of individual channels in an overall anabranching pattern. Present day migration of the main and secondary channels was studied by a temporal analysis of the river system over the last 32 years. Maximum migration rates of 59 m/yr were found for the main channel, and of 42 m/yr in secondary channels. In both cases, scroll bars follow the direction of the present day migration. Optically stimulated luminescence dates indicate that scroll bars have developed at least since  $7.5 \pm 0.85$  ka in the secondary channels and  $4.6 \pm 0.58$  ka in the main channel. Scroll bar floodplains are also observed in other reaches of the Amazon River and they seem to be a common feature in this type of anabranching river.

#### **A DISCUSSION ON THE LOCAL AND REGIONAL GEOLOGY OF THE FOXE FOLD BELT NUNAVUT WITH EMPHASIS ON THE IMPORTANCE OF STRUCTURES RELATING TO GOLD MINERALISATION**

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The Paleoproterozoic Foxe Fold belt in Central Baffin Island, Nunavut, is along the western flank of the Trans-Hudson Orogen. The belt consists of a Proterozoic cover sequence overlying Archean domes. The Piling Group comprises a lower platformal basin margin sequence of siliciclastic, carbonate rocks, (Dewar Lakes, Flint Lake Formations) through to shallow marine (rift related) mafic volcanics, metasediments and iron formations (Bravo Lake formation), graphitic shales (Astarte River Formation), and a turbidite sequence (Longstaff Bluff Formation). The Foxe fold belt underwent four deformation events. D<sub>1</sub> is characterised by a regional, bedding-parallel, transposition foliation (S<sub>1</sub>) and by rare intrafolial isoclinal folds in the metasediments and calc silicates of the Bravo Lake formation. During D<sub>2</sub>, S<sub>1</sub> was folded by nappe scale F<sub>2</sub> folds that formed either during thrusting or extensional thinning and shearing of the belt. During D<sub>3</sub>, NE–SW compression produced reverse faults and refolded the nappe scale F<sub>2</sub> folds into a series of en echelon NW–SE trending F<sub>3</sub> folds associated with a regional axial plane S<sub>3</sub> cleavage and a penetrative stretching lineation parallel to the fold axes. Finally during D<sub>4</sub>, F<sub>3</sub> folds were crossfolded by roughly north-trending F<sub>4</sub> folds which produced the dome and basin map interference pattern that dominates the architecture of the belt. Gold mineralisation is typically associated with strong silicification at contacts between sedimentary formations and Bravo Lake formation or within the Bravo Lake formation itself, and is associated with post D<sub>2</sub> fractures, faults and shear zones that cut across the iron formations. One of the main goals of the project is to examine the effects of deformation on the multiple iron formation horizons that host gold prospects.

#### **A TALE OF TWO CRATONS**

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The deep-seated processes of the Tanzanian and North China Cratons have been explored through the study of mantle and lower crustal xenoliths carried in kimberlites and basalts and reveal two contrasting histories. The Tanzanian Craton has been an island of stability within eastern Africa, despite the fact that it was surrounded by continent-continent collision belts during the East African Orogeny and is currently surrounded by the East African Rift. Archean crust within the Mozambique Belt to the east of the craton underwent high-grade metamorphism associated with the Pan-African amalgamation of Gondwana, yet ancient craton-like mantle lithosphere presently underlies this belt, and there appears to have been no loss of mantle lithosphere associated with the orogeny. This may be due to the fact that the Tanzanian Craton lies in the footwall of the collision (much like India in the present-day Himalayan orogen). The presence of thick, strong Archean mantle lithosphere below the Mozambique Belt may be the reason that the rift changes from a well-defined rift valley in southern Kenya to a region of widespread extension in northern Tanzania. The East African Orogeny had little affect on the present-day craton, where thermochronology of lower crustal feldspars shows that even the deep crust remained below ~600°C since the Late Archean. By contrast, complete metamorphic recrystallization occurred in the Archean crust of the Mozambique Belt during the East African Orogeny, where crustal thicknesses of up to 80 km were attained. Thermochronology of deep-seated xenoliths from

the Mozambique Belt show that the crust cooled differentially following the East African Orogeny, with the lowermost crust cooling extremely slowly ( $\leq 1^\circ\text{C}/\text{Ma}$ ), whereas the middle crust of the orogen (present-day upper crust) cooled more quickly ( $\sim 7^\circ\text{C}/\text{Ma}$ ). This differential cooling is likely related to the westward emplacement of nappes onto cratonic lithosphere.

By contrast, the eastern block of the North China Craton underwent a fundamental transformation from a thick, stable craton to a thinned, tectonically active region during the Mesozoic. Not only did the lithosphere thin, but the original Archean cratonic lithospheric mantle was removed and replaced with more fertile lithosphere. The composition of unusual high Mg andesites and high Mg# basalts and picrites suggest a role for foundered cratonic lower crust in their formation. While the mechanism for lithosphere replacement beneath the North China Craton is the subject of debate, the fact that the craton was on the hanging wall during multiple collisions (Yangtze Craton to the south, Solonker Suture to the north) may explain the fundamental difference in behavior compared to the Tanzanian Craton.

### **THE 'ENIGMATIC MOUNDS' OF ORPHAN KNOLL: A DIAPYRIC WINDOW ON PALAEOZOIC BASEMENT SEDIMENTS**

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A bathymetry compilation in 1969 first suggested the continental nature of Orphan Knoll 550 km northeast of Newfoundland in 1800 m of water. Drilling in 1970 from the Deep Sea Drilling Project's GLOMAR CHALLENGER confirmed its continental nature when the last sample at Site 111 pulled up a 1 m core of a black, anthracite-rich, non-marine, Bajocian (Jurassic) sandstone of ca. 175 Ma age. The 250 m sediment section on top of Orphan Knoll bears a much closer relationship to Europe than to eastern North America.

Orphan Knoll is marked by a pronounced field of more than 250 mounds running along its northeast margin over a distance of about 70 km. The mounds protrude through the blanketing Bajocian to Pleistocene sediments and rise 115 to 320 m above the upper surface of the Knoll. Some of the partially-buried mounds exceed 600 m in height and basal widths are about 3 km or less. There is a second set of lower, or totally buried, mounds along the southwest margin of the Knoll.

A 1971 dredge attempt and two 1978 dredge hauls have provided intriguing evidence that the mounds are bedrock-cored and reflect Ordovician to Devonian shelf-depth sediments from the deeper parts of the Knoll. It is not believed that the mounds are actively growing, living, or former, bioherms but rather are the result of diapiric activity that has carried evidence of the deeper Palaeozoic geologic section to the present seabed surface. This implies that the Ordovician-Devonian marine intracratonic platform sediments had a broader geographic extent than has been previously recognised. This leads to the conclusion that a marine re-entrant must have penetrated 'The Old Red Sandstone'.

### **AN EMERGING PARADIGM FOR SURFICIAL MAPPING OF ARCTIC CANADA AT THE GEOLOGICAL SURVEY OF CANADA**

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Aerial photographic interpretation has been the cornerstone of surficial geological map production at the Geological Survey of Canada for 80 years. Developments in the past 20 years in computing technology, remote sensing, and digital elevation models is affording the opportunity for increased automation of the mapping process. This technological evolution has occurred at the

same time that the mapping capacity of the GSC has been decreased by half of the 1970-1980's capacity. Consequently, to continue to meet the demand for map products new mapping methods are required.

Traditionally, surficial mapping in arctic Canada has been undertaken at a scale of 1:250,000 that incorporate a genetic surficial material legend, landform mapping and iceflow history defined by landform analysis and field measurements (striations). Traditional maps based on stereo aerial photographic interpretation rely on analysis of tone, relief and spatial arrangement (pattern) in concert with field observations. This analysis relies on three elements, whereas traditional spectral image classification (Landsat) has been analysed based only on spectral response alone (tone). Within the Remote Predictive Mapping (RPM) project of Geo-Mapping for Energy and Minerals Program (GEMS) a methodology and data handling framework is being developed to enhance the GSC's mapping capabilities within the traditional field based 1:250,000 scale mapping framework and also to provide improved synoptic scale mapping. With respect to RPM research, a variety of experiments are being undertaken using optical radar and topographic datasets to produce predictive surficial material maps over the Shultz Lake NTS 66A mapsheet, which is functioning as a test area for RPM. At regional scales mapping is reliant on public domain data and the emphasis within RPM is on improving classification and modelling approaches using this public domain and easy accessible data such as Landsat and MERIS complemented by topographic (CDED) data. A variety of statistical approaches are being experimented with to produce predictive surficial maps including advanced pixel and object based classification methods that rely on training areas of representative surficial material types. Legacy data are being employed as training datasets to advance landform analysis. Progress has been made in the quantitative analysis of eskers in Keewatin using topographic (CDED) data. The GSC is developing a RPM research network involving College GIS programs, university researchers, provincial agencies, and federal government labs to assist in developing methods and protocols for producing predictive geological maps of broad areas of Canada's North.

### **EVIDENCE FOR SULFUR LOSS IN THE MARATHON PGE-Cu DEPOSIT, ONTARIO**

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The Marathon PGM-Cu deposit is hosted by the Coldwell alkaline complex, which consists predominantly of gabbro and syenite and was emplaced at 1108 Ma as part of the Mid-Continent Rift System.

Mineralization at the Marathon PGM-Cu deposit is hosted by the Two Duck Lake gabbro which is a fresh olivine-bearing gabbro. A high-grade PGE horizon, termed the W Horizon, located above the Main Zone mineralization is characterized by a low sulfur content (average  $\sim 0.3$  wt.% S), low Cu/Pd and high Cu/Ni. The dominant sulfide mineral is chalcopyrite, but bornite is also common. This contrasts with the Main Zone which has higher S and higher Cu/Pd and the dominant sulfide minerals are chalcopyrite and pyrrhotite. In general, zonation within the main zone shows a decrease in Cu/Pd and pyrrhotite/chalcopyrite from base to top.

Four drill holes were selected for detailed analysis to explain the differences between the W Horizon and Main Zone styles of mineralization. Chalcopyrite grains within the W Horizon are

commonly mantled by magnetite, which differs from primary magmatic magnetite in that it lacks ilmenite exsolution lamella and has nearly a pure end-member composition. This texture has interpreted as evidence of S loss. Whole rock S and Se contents were determined to further investigate S loss. Sulphur and Se are both siderophile elements and incompatible in silicate melts. During crystallization of a silicate melt or the formation of a sulfide liquid it is expected that the S/Se ratio will remain constant. The removal of S through desulfidization to a gas or liquid is expected to lower the S/Se ratio as S is more mobile than Se when oxidized. Average S/Se values are ~800 for the W Horizon, ~1980 for the Main Zone and ~1700 in unmineralized samples. The very low S/Se found within the W horizon is evidence that desulfidization has occurred. Electron microprobe analysis of olivine grains shows that there is an increase in forsterite content in the W horizon relative to the unmineralized samples.

These data suggest that, in the W Horizon, a sulfur undersaturated basaltic magma interacted with an immiscible sulfide liquid in a magma conduit, and that this resulted in the dissolution of sulfide into the basaltic melt and consequently in PGE enrichment.

#### **QUATERNARY GEOLOGY AND ICE FLOW HISTORY IN THE NORTHWEST PART OF THE MCLEOD LAKE MAP AREA (NTS 093J), CENTRAL BRITISH COLUMBIA: IMPLICATIONS FOR MINERAL EXPLORATION**

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The McLeod Lake map area in central British Columbia has potential for economic mineral occurrences. Mineral exploration has previously been hindered by the extensive cover of surficial deposits. This hindrance has been overcome through a media-specific sampling program of basal tills, whose geochemical signature is influenced by the composition of up ice bedrock. Knowledge of the Quaternary geology and the ice flow history are essential to the collection and interpretation of till geochemical data.

The surficial geology of the area is dominated by late Wisconsinan till, glaciofluvial and glaciolacustrine sediment with some areas of paraglacial eolian deposition. Six 1:50 000-scale terrain maps are being produced that depict the distribution of surficial materials and their morphology, providing a guide for till sampling. The ice flow history and thus sediment transport direction was investigated using both macroform and microform ice flow indicators. The dominant flow direction was to the northeast. However, local variations occurred in the northwest of the study area where flow was more northerly, and in the south where flow was more easterly. Till fabric data support these flow patterns and combined with striation data and cross-cutting streamlined features, suggest a more easterly flow direction in the later stages of glaciation. Lateral melt water channels suggest ice retreated to the southwest while hummocky gravel and esker complexes indicate some local ice stagnation. Organic samples from a peat deposit provide a minimum glacial retreat age of  $8775 \pm 30$  (ICAIMS 83989) radiocarbon years. Another minimum deglacial age of  $7000 \pm 600$  years was determined with a pilot experiment using optically stimulated luminescence dating on postglacial eolian sediment. This must be considered a preliminary date, as a full experiment has not yet been conducted. Exposed stratigraphy along the McLeod River typically illustrates retreat phase glacial successions. One section containing multiple thick diamict units may be the result of several glaciations or oscillations of the ice front during the advance or retreat phase. Analysis of the regional scale trace-element till geochemical data suggests potential economic

mineral occurrences in the area. For example, concentrations of Au, Cu, As and Ag suggest porphyry Cu-Au style mineralization. These findings, combined with spatial correlations with known mineral showings, demonstrate that despite the extensive cover of surficial materials, till geochemical surveys are effective in locating anomalous mineral concentrations in areas covered with thick surficial deposits.

#### **LA-ICPMS ANALYSIS OF THE CHEMICAL COMPOSITION OF CALCITE, DOLOMITE AND BORATE MINERALS WITH SILICATE GLASS CALIBRATION**

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This study addresses the accuracy of measurements on the concentrations of minor and trace elements in natural calcite, dolomite and borate minerals by laser ablation-inductively coupled plasma mass spectrometry (LA-ICPMS) using synthetic silicate glass reference materials for external calibration. LA-ICPMS is less time consuming compared to dissolution-based analytical methods for elemental analysis, and may be a reliable technique for the quantitative analysis of calcite, dolomite and borate, provided calibration procedures do not introduce matrix effects that bias the accuracy of results. Discrete grains of calcite, dolomite and borate (ulexite- $\text{NaCaB}_5\text{O}_9 \cdot 8\text{H}_2\text{O}$ ) from drill core samples of the Miocene Kirka volcanosedimentary basin, Gocenoluk area, Eskisehir, Western Anatolia, Turkey, were picked under an optical microscope. Electron microprobe analyses indicate that the calcite contains 55.9% CaO; the dolomite contains 29.7% CaO and 22.3% MgO; and the borate contains 14.8% CaO, 3.75%  $\text{Na}_2\text{O}$  and 40.4%  $\text{B}_2\text{O}_3$ . Most of the grains were dissolved in acid and analyzed in solution by ICPMS using a PE Elan DRCII quadrupole instrument with calibration against synthetic, multi-elemental standard solutions. Remaining grains were mounted in epoxy, polished and analysed by LA-ICPMS, using a Finnigan ELEMENT XR, high-resolution double-focusing magnetic sector ICPMS coupled to a GEOLAS 193 nm ArF excimer laser ablation system. A 40-micron diameter laser spot was used for the analyses. Laser energy was approximately 4 J/cm<sup>2</sup> and the laser repetition rate was 10 Hz. Elemental concentrations were calibrated against the NIST 612 silicate glass. Calcium, as measured by solution-ICPMS analyses, was used as an internal standard for the LA-ICPMS analyses. Although there is significant micron-scale heterogeneity in the distribution of minor and trace elements in the natural minerals, we find that, on average, the results determined by LA-ICPMS compare favorably to those measured by solution-ICPMS. For calcite, results for the two techniques agree to within 10% for Li (60 ppm), Al (2300 ppm), Ti (70 ppm) and Fe (2300 ppm) and to within 15% for Mn (60 ppm), Rb (10 ppm) and Cs (6 ppm). For dolomite, results agree to within 10% for Mn (40 ppm), Rb (9 ppm), La (0.3 ppm) and Ce (0.6 ppm). For borate, the results agree to within 10% for Sr (1300 ppm), La (0.1 ppm), and Ce (0.1 ppm), and to within 20% for V (2 ppm). This suggests that large matrix effects do not exist between silicate glass and natural calcite, dolomite and borate minerals for LA-ICPMS analysis.

## GEOMAPPING FOR ENERGY AND MINERALS (GEM) OF CUMBERLAND PENINSULA, BAFFIN ISLAND, NUNAVUT

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Cumberland Peninsula, NU has long been considered to expose the eastern extension of central Baffin Island's Paleoproterozoic Piling Group, a continental margin succession deposited on Mesozoic to Neoproterozoic Rae basement between ca. 2.16-1.9 Ga. Gold-bearing strata of central Baffin (ca. 1.93 Ga Bravo Lake formation) highlighted the potential for this style of mineralization across Cumberland Peninsula. New mapping as part of NRCan's GEM initiative, has resulted in a vastly improved understanding of eastern Baffin Island's lithological associations, crustal architecture and mineral potential, allowing insight upon which regional crustal correlations can be more accurately based.

It is now recognized that Archean (3.0-2.7 Ga) tonalite-dominated basement underlies about 60% of Cumberland Peninsula, thus enhancing its prospectivity for diamonds, with exploration activity also stemming from the similarity of plutonic rocks with those to the south on Hall Peninsula where diamond-bearing kimberlites were recently discovered. Strands of Archean semipelite, amphibolite, rare pillowed volcanic rocks and ca. 2.91 Ga porphyry form a minor, yet significant component of the basement complex.

Younger supracrustal strata of the Hoare Bay group form a northeast-trending, topographically and structurally high belt across central Cumberland Peninsula. Minor components include marble, calc-silicate and orthoquartzite, whose distribution may reflect remnants of a shelf succession in the west-central part of the peninsula, whereas mafic to ultramafic volcanic rocks associated with black shale, ironstone, chert and thick successions of psammite-semipelite suggest basinal facies in the east. Elevated concentrations of multiple metals in the basinal facies present an exploration target for polymetallic zinc-copper-nickel-gold. Where exposed, the Hoare Bay group is in contact with plutonic mylonite gneiss, indicating a mid-crustal tectonic basement-cover contact. Although lithologically comparable to the Piling Group, preliminary ages for the Hoare Bay basinal facies appear ca. 30 m.y. younger than central Baffin counterparts.

A NE-trending belt of ca. 1.9 Ga felsic plutonic rocks extends over 200 km from Pangnirtung to Qikiqtarjuaq. This granodiorite-charnockite-quartz diorite suite, ca. 30 m.y. older than Cumberland Batholith, cuts and has thermally overprinted basement and some cover strata.

Cumberland Peninsula records at least two penetrative deformation events which have resulted in tight to isoclinal inclined to recumbent  $F_2$  folds of basement and cover rocks. West-striking  $S_1$ + $S_2$  transposition fabrics dip gently to the north reflecting widespread south-vergent  $D_2$  structures. U-Pb age constraints, including in situ monazite data, all support penetrative tectonometamorphism between 1873 Ma and 1836 Ma, consistent with north-directed convergence during an early stage of the Hudsonian orogeny.

## GEOLOGICAL SETTING OF THE MOSQUITO HILL (HUXTER LANE) GOLD DEPOSIT, EXPLOITS-SUBZONE – MOUNT CORMACK SUBZONE BOUNDARY AREA, CENTRAL NEWFOUNDLAND

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The Mosquito Hill gold deposit in central Newfoundland, discovered in 1998 through prospecting and sampling of arsenopyrite-bearing quartz-feldspar porphyry float, occurs in an area characterized by extensive Quaternary cover. Extensive industry work has provided an NI 43-101 compliant resource of 11.18 Mt averaging 0.546 g/t gold for 196,257 ounces gold and an inferred resource of 38.76 Mt averaging 0.457 g/t gold for 569,496 ounces gold (0.3 g/t Au cutoff). The host rocks are ophiolitic rocks of the Coy Pond Complex and marine volcanic and sedimentary rocks of the Baie d'Espoir Group, occurring in a series of thrust-bound slices marking the boundary between the eastern Exploits subzone (Dunnage Zone) and the ellipsoid Mount Cormack subzone (Gander Zone). Mineralization is hosted by a southward-dipping, thrust-bound slice, of quartz-veined and sericite-altered quartz-feldspar±hornblende porphyry (QFP) along with similar volcanoclastic tuffs and epiclastic sandstones. The mineralized zone is bounded by tectonized black shales. At the base, the shale tectonite contains: polymictic conglomeratic horizons (lenses?) having altered QFP, ultramafic, jasper and shale clasts; large metre-scale clasts of ultramafic rocks; and a graphitic matrix characterized by fuchsite. In drill core this tectonic zone passes downwards into likely fault-bounded intervals of intact, serpentinized peridotite alternating with both grey siltstone and black shale.

The sericitized and locally quartz-veined (<1 cm – 2 m thick; typically ≤20 cm) QFP is up to 225 m thick and is open at depth and to the southwest. Alteration is widespread, and of a pervasive “flooding style”, facilitated by the brittle nature of the host porphyry and epizonal fracturing and locally intense brecciation in the intrusion. Elevated gold correlates with areas of strong silicification, sericitization and ankerite alteration in the QFP, containing 2-3% and locally up to 10% disseminated arsenopyrite and pyrite. An increase in pyrite and euhedral arsenopyrite accompanies the sericitization and quartz veining but abundant euhedral arsenopyrite correlates best with elevated gold values; free gold has not been observed. The highest gold values determined from channel samples has yielded 15.3 g/t Au over 0.8 m, however, the most significant drill intersections yielded 2.21 g/t Au over 35 m and 0.67 g/t Au over 103.35 m.

The QFP has been dated by LAM-ICP-MS U-Pb methods (Zr) at  $494 \pm 7$  Ma; the age of alteration and mineralization is not known. Lithogeochemical, mineral chemical, fluid compositional and  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  thermochronological investigations are currently in progress to further understand the deposit.

## STRATIGRAPHIC FRAMEWORK OF THE POTSDAM GROUP IN EASTERN ONTARIO, WESTERN QUEBEC, AND NORTHERN NEW YORK STATE

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The presence of a major unconformity within the Potsdam Group is an important key to unlocking the geological history of this suc-

cession throughout its area of distribution in the Ottawa Embayment and Quebec Basin.

The beds below the unconformity (Abbey Dawn and Covey Hill/Ausable formations) are largely of continental origin, up to 600 m thick, and composed of a complex assortment of red and grey quartzite cobble, quartz pebble and quartzarenite deposits of assumed Neoproterozoic to Middle Cambrian age. The Covey Hill/Ausable formations have been further divided into four units of wide distribution beginning with the marine and marginal marine Jericho Member, which is confined to the Quebec Basin bordering the Oka-Beauharnois Arch on the east, and succeeded and overlapped to the west by the mostly aeolian and fluvial Hannawa Falls, Chippewa Bay and Edwardsville members. During and immediately following deposition of these members the beds were locally faulted, folded and subjected to a long period of subaerial erosion.

Above the regional unconformity are the white and grey Nepean and partly equivalent Cairnside and Keeseville formations (up to 110 m thick) composed of upper Middle and Upper Cambrian to Lower Ordovician quartzarenite and minor quartz-pebble conglomerate intercalated locally with minor evaporites. They were deposited on the floor and margins of a seaway that entered the Ottawa Embayment from the east.

Post-Nepean, Cairnside, and Keeseville deformation (folding and faulting) of Potsdam and younger Ordovician strata was widespread through the Ottawa Embayment and Quebec Basin, likely triggered by Taconian and Acadian orogenesis and by the much later rifting and break-up of continents beginning in the Middle to Late Triassic.

#### **GEOSITES ON NORDESTINA, BAHIA: FIRST STEPS TO BUILD THE “CANUDOS GEOPARK”**

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Presently, the concern regarding the biodiversity has been subject to many discussions, which attempt to minimize the harmful effects caused by the anthropogenic activities on the environment. In spite of this, the Geodiversity concept is a recent one, arising as an outstanding component of the Geodiversity – Geoconservation-Geotourism trinomial. This abstract describes features of the Nordeste region, Northeastern of Bahia State, Brazil. This area contains a natural diversified richness, comprising important geological, paleontological and meteoric aspects, beyond its typical flora and fauna of semi-arid climate and the “caatinga” typical vegetation. The studied area is inserted in Serrinha Nucleus, one of the Archaean nuclei that compose the basement terranes of São Francisco Craton. SerN geology includes a granitic-gneissic Archaean basement complex and Paleoproterozoic volcano-sedimentary basins, associated to TTGs, calc-alkaline and alkaline potassic-ultrapotassic plutonism. During this research eight geosites were catalogued (Maria Preta Lavas Pillows, Café Royal Syenite, Morro do Afonso Lamprophyres, Caracônia Inselberg, Lopes Castle Koppie, The Orange Calcite, Quijingue Dioritic Stock, Nordeste Pipe), through the use of the software application developed by the Geological Survey of Brasil (CPRM). These geosites have been classified as of regional relevance, and at least three of them have a strong tourist appeal. The progress of researches on this topic will probably lead to the discover of new geosites with geotouristic interest, which, added to the attractions already known in the studied area (historical: the Canudos War, discover of the first and most important meteorite of the Brazilian collection; paleontological: macrofossils; geologic/metagenetic:

the major producer of gold of the state and an important and increasing diamond production; and meteoritic: the location where 2 of 5 Bahia’s meteorites have been found), will contribute to amplify and diversify its present geotouristic potential, mostly in didactic and scientific aspects. This possibility represents a concrete option for the sustainable development of such region. Five municipalities on the studied area have some of the lowest values for the Human Development Index when compared to the Brazilian mean. In this regard is the responsibility of the Bahia/Brazil geologic community to protect such Geologic Heritage through Geoconservation, while developing efforts to alert and advise the other segments of our society about the fundamental importance of this question.

#### **PUTATIVE BIOALTERATION TEXTURES HOSTED WITHIN IMPACT MELT GLASSES FROM THE RIES CRATER, GERMANY**

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Impact-induced hydrothermal systems share many characteristics with submarine volcanic hydrothermal systems including the presence of chemical and thermal disequilibria for microbial metabolism. In submarine volcanic environments, bioalteration of basaltic glasses produces characteristic tubular and granular textures. Post-impact hydrothermal systems represent an understudied microbial habitat. Petrographic investigations of impact glasses from the Ries impact structure, Germany, have revealed tubular alteration textures with remarkable morphological similarity to tubular bioalteration of basaltic glass.

Tubular textures are associated with hydrated glass, concentrated along fractures or clast margins, form radiating aggregates, and have complex morphologies including spirals, and other complex curvatures. Tubules are dominantly smooth-walled while a minority display distinct segmentation. Tubules appear to be clustered by like morphology. Smooth-walled tubules typically display complex curvatures forming a morphological continuum between loose undulating curves and spirochete morphology. Curvature appears random, non-oriented and specific to individual tubules. Non-segmented tubules have diameters ~1 µm and commonly have length to width ratios >5. Segmented tubules typically display less curvature than non-segmented tubules. Individual segments have length to width ratios approximately 1:2. Segmented tubules vary in diameter from ~1 µm to approaching 3 µm. Segmented tubules appear to display bifurcation or branching. Branching is asymmetric and highly irregular, however, branches are similar in diameter and segmentation to the parent tubule. Rare segmented tubules with large (~3 µm) diameters have segments with length to width ratios approaching 1:6.

Back scattered electron imaging shows the tubules as irregular, high albedo, sub-linear, ~1 µm diameter features. Tubules often have an undulating appearance with length to width ratios approaching 100:1. The margins of the features are sharp and range from highly irregular to smooth. Tubules with irregular margins have solid, ovoid to rhomboid cross sections. In contrast, tubules with smoother margins have hollow, ovoid cross-sections.

EDX spectroscopy shows that relative to the glassy matrix the tubules are depleted in Na, K, Al, Si and enriched in Mg, Fe, Ca. The elemental chemistry is similar to that of the morphologically distinct pyroxene quench crystallites also hosted within the glass. Preliminary Fourier Transform Infra-Red spectroscopy results indicate the presence of organic carbon within the tubules.



The appearance of the tubule alteration in the Ries glasses is strikingly similar to the bioalteration of submarine basaltic glasses and lacks a parsimonious abiotic or mineralogical explanation. To the best of the authors' knowledge, bioalteration of impact materials has not previously been reported.

# **PETROGENETIC AND METALLOGENIC MODEL FOR THE Ni-Cu±PGE-BEARING INTRUSIONS IN THE PORTNEUF-AURICIE DOMAIN, GRENVILLE PROVINCE, QUÉBEC: AN EXAMPLE OF MINERALIZED INTRUSIONS EMPLACED IN A PROTEROZOIC ISLAND ARC**

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The Portneuf-Mauricie Domain (PMD), located in the south-central part of the Grenville Province, consists mainly of metasedimentary and metavolcanic rocks of the Montauban group (1.45 Ga), intruded by plutons of the La Bostonnais complex (1.40–1.37 Ga). This assemblage was formed in a magmatic arc setting. The La Bostonnais complex comprises several mafic and ultramafic intrusions hosting Ni-Cu±PGE prospects; examples include the Réservoir Blanc, Lac Matte, Lac Kennedy, Lac Édouard mine (former small mining operation), Boivin, Rochette West, Lac à la Vase (hosting the Rousseau prospect), and Lac Nadeau intrusions. The meter- to kilometer-scale, sulfide-bearing intrusions display diverse forms, such as layered intrusions, tabular intrusions with no particular internal structure, and zoned intrusions. They were injected between 1.40 and 1.39 Ga into the mature Montauban island arc, before and during accretion of the arc to the Laurentian margin.

A two-stage model is envisaged to explain the formation of the Ni-Cu±PGE-bearing plutons. In stage I, primitive, tholeiitic, hydrous, sulfide-undersaturated magmas interacted with sulfide-bearing crustal rocks during their ascent, resulting in felsification of the magmas (as indicated by major and trace elements) and addition of crustal sulfur ( $\delta^{34}\text{S}$  values up to +5.5‰). Combined with the fractional crystallization of the silicate liquids, these processes resulted in the formation of an immiscible sulfide liquid. An early loss of a small amount of sulfides occurred in lower conduits, causing depletion of chalcophile and precious metals in the magmas, as suggested by Cu/Pd modeling. However, the main sulfide saturation and separation event occurred later in a magma chamber. Liquid-sulfide formation was followed by variable magma-sulfide interactions (R factors between 100 and 100,000), which caused some enrichment of sulfides in Ni, Cu, and, locally, PGE. In stage II, sulfide melt may have been partly incorporated and upgraded into later pulses of primitive magma, and transported into shallower magma chambers to form the PMD mineralized intrusions. The parent magmas of these intrusions, derived from the later pulses, formed two families of parent magmas according to their Mg#. Those of the Lac Matte, Lac Kennedy, and Lac à la Vase intrusions were or were close to being primary magmas, whereas other intrusions crystallized from more evolved parent magmas, with an intermediate Mg#. All parent melts sustained crustal contamination and differentiation by crystal fractionation, and formed intrusive rocks with primitive to evolved characteristics (as supported by the crystallization sequences and the mineral chemistry).

# **A GEOCHEMICAL AND ISOTOPIC INVESTIGATION OF CARBONATE MINERAL PARAGENESIS IN ORDOVICIAN ROCKS FROM THE MICHIGAN BASIN IN SOUTHWESTERN ONTARIO**

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A geochemical and isotopic investigation of calcite and dolomite from the Middle Ordovician Black River and Trenton Group limestones of the Michigan Basin in southwestern (SW) Ontario, is underway to distinguish primary versus secondary mineral types and to understand the nature of fluids involved in their formation. Primary versus secondary calcite and dolomite are differentiated on the basis of cross-cutting relationships and grain size. The minerals are being characterized in terms of major cation composition and zonation (Ca, Mg, Fe, Mn and Sr), and  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios.

Representative samples of calcite and dolomite were examined optically and analyzed chemically using Energy-Dispersive X-ray Spectroscopy in the Scanning Electron Microscope (SEM/EDS). Cathodoluminescence (CL) imaging supported back-scattered electron (BSE) imaging for identifying zonation in minerals. Results of  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios will be reported.

To date, excluding biogenic forms of carbonate minerals, analysis of carbonates from Black River and Trenton Group limestones, identified two types of calcite; primary (micritic) calcite within the limestone matrix and secondary calcite infill in vugs and veins. Primary calcite is characterized by fine grain size (2–20  $\mu\text{m}$ ) and low Mn concentrations (0–1007 ppm) in comparison to Mn concentrations in secondary calcite and dolomite. All primary calcite samples contain variable Ca (201759–382362 ppm), Mg (304–44926 ppm), Fe (0–4586 ppm) and Sr (1268 – 3467 ppm) concentrations. Secondary calcite is characterized by a relatively coarse grain size (10 – 2000  $\mu\text{m}$ ) and crystal shapes range from large euhedral crystals filling cm-size vugs to anhedral vein fills. All secondary calcite samples contain variable Fe (0–4742 ppm), Mn (0–7512 ppm), Ca (356204–394655 ppm), Mg (850–19367 ppm) and Sr (311–8706 ppm) concentrations. Matrix-replacive dolomite was observed in all samples. The dolomite is typically euhedral, ranges in grain size (10–1000  $\mu\text{m}$ ) and displays varying degrees of chemical zonation. The ranges of major cation concentrations in the zoned and non-zoned forms of dolomite are similar (Fe: 622–24796 ppm; Mn: 0–6273 ppm; Ca: 216553–250858 ppm; Mg: 78196–124457 ppm; and Sr 420–2113 ppm).

# **PROVENANCE OF CAMBRIAN SEDIMENTARY ROCKS ALONG THE EASTERN MARGIN OF THE US: CONSTRAINTS FROM DETRITAL ZIRCON AGES**

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Lower Cambrian sedimentary rocks of the US Appalachian Orogen are exposed from Vermont to Georgia. In the North-Central part of the orogen these units rest nonconformably on Mesoproterozoic metagranitoid basement, while in the south they lie unconformably above at least six different Neoproterozoic metasedimentary units. Previous work has shown that these rocks were deposited as part of a fluvial-to-marine transition on the newly formed Laurentian passive margin following the breakup of Rodinia during the Neoproterozoic. This study differs from previous, more limited ones, as it is the first to analyze more than 50 samples from the same stratigraphic horizon along the 1500 km length of the orogen. To date, >1,200 detrital zircon crystals from 16 sandstone and conglomerate samples from basal lower Cambrian units were dated by LA-MC-ICPMS. Only a small percentage of grains record middle- to late-Neoproterozoic ages, thus depositional ages of the analyzed units cannot be robustly con-

strained. However, based on the youngest detrital zircon ages there is no evidence for a depositional age younger than Early Cambrian, consistent with fossil evidence. The vast majority of the detrital zircon ages have peaks at 1170 and 1050 Ma, locally consistent with published U-Pb SHRIMP crystallization ages of the underlying basement. These populations are interpreted to record, respectively, the Shawinigan and Ottawa orogenic pulses of the Grenville Orogeny. A few samples also contain detrital zircon grains with Archean-Paleoproterozoic ages (2.9-1.6 Ga).

The dominance of Mesoproterozoic zircon grains suggests that these grains are being sourced locally, thus providing insights to the age of basement along the entire length of the orogen where U-Pb studies are lacking. The reproducibility of these populations shows that the Laurentian margin in Early Cambrian time was a very homogenous sheet of clastic material, although they were assigned more than 15 different formational names. Variations from the dominant bimodal zircon population are likely due to continued fluvial input from units such as the rift-related volcanic rocks of the Mount Rogers, Robertson River, and Catocin formations for the Neoproterozoic grains and intracratonic sources such as the rocks of the Superior Province and mid-Continent rift for zircons older than 1.2 Ga.

#### **KAWAH IJEN VOLCANO, INDONESIA: AN EXAMPLE OF ACTIVELY FORMING HIGH-SULFIDATION EPITHERMAL ALTERATION**

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Kawah Ijen is an active stratovolcano located in eastern Java, Indonesia. The crater contains a presently forming solfatara characterized by intense alunite-jarosite alteration, a hyperacidic crater lake (pH ~0.5) and large area of extensive hypogene alteration (vuggy silica, alunite, kaolinite, pyrite) located immediately north of the active solfatara. Additionally, thermal springs (located lower on the edifice of the volcano) have a hydrothermal fluid component, as well as a component of crater lake water. These features make Kawah Ijen unusual in that they represent those typically associated with the formation of high sulfidation epithermal deposits.

The distribution of high sulfidation epithermal alteration at Kawah Ijen has been mapped using field observations, X-ray diffraction and electron microprobe analyses to determine its extent and the locations of potentially metalliferous zones (e.g. vein-related and massive pyrite, alunite, silicification, vuggy silica). The minerals of the alteration center comprise cristobalite, quartz, tridymite, natroalunite, alunite, kaolinite, dickite, gypsum, native sulfur, barite, and pyrite. Alunite and pyrite predominate. The presence of minerals of the same group (i.e. natroalunite-alunite, kaolinite-dickite and quartz-cristobalite-tridymite) has been used to map temperature gradients that are confirmed by sulfide-sulfate geothermometry. Pyrite veins have elevated levels of Mo, Cu, Pb, Zn, As, Bi, Se and Hg, and alunitic rocks have elevated Pb, Zn and As, as well as trace amounts of Mo, Cu, Ni and Bi.

The gases of fumaroles in the active solfatara (350 to >600°C) have been sampled using Giggenbach bottles and condensates collected. Silica tube experiments have been conducted to identify the solid phases saturating in the gases. Giggenbach sampling and FlynSpec surveys confirm that Kawah Ijen is emitting major quantities of H<sub>2</sub>O and CO<sub>2</sub>, and significant proportions of SO<sub>2</sub>, H<sub>2</sub>S, elemental S, HCl and HF. Condensate data confirm that significant Pb, Te, As, Sb, Ag and Se are fluxing daily from the volcano. Mineral sublimates from silica tubes include native sulfur, halite and a variety of sulfates (alunite-natroalunite, alunogen), sulfides (pyrite, bismuthinite), hydroxides (gibbsite, diaspore) and

metallic minerals. The results of this study confirm that vapors of magmatic origin play an important role in the formation of high sulfidation epithermal systems.

#### **NEW INSIGHTS ON THE STRUCTURAL SETTING OF THE FLIN FLON MINING DISTRICT, TRANS-HUDSON OROGEN, CANADA BY 3D INTEGRATED INTERPRETATION OF DRILL HOLE, SEISMIC AND GEOLOGIC MAP DATA**

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3D geologic modelling of the Flin Flon mining district has yielded new insights on the structural setting of the 1.89 Ga VMS-hosting Flin Flon volcanic arc assemblage and molasse cover rocks in the internal zone of the Paleoproterozoic Trans-Hudson orogen. Repeats in subsurface lithostratigraphic markers extracted by the systematic reconciliation of drill hole and geologic map data reveals E-dipping thrust imbrication (D<sub>3</sub>) of the VMS-hosting mine horizon that is truncated by N-directed brittle-ductile to ductile Railway, Catherine and Club Lake thrust faults (D<sub>4</sub>). Seismic interpretation in combination with reconnaissance drilling shows similar overprinting relationships at higher structural levels further east where an ENE-dipping imbricate of Flin Flon arc assemblage volcanic rocks that has been brought up over the Missi Group sedimentary cover is truncated by S-dipping listric D<sub>4</sub> thrust faults. Our findings are also consistent with structural studies at surface that established the truncation of N-striking imbrications of mafic volcanic rocks in the hanging wall of the VMS ore system by the N-directed D<sub>4</sub> Catherine and Club Lake thrust faults. Tentative 3D kinematic restorations using VMS ore lenses and drill hole constraints suggest 750 m of minimum tectonic transport along individual D<sub>3</sub> thrust faults. These estimates are significantly larger than the 100-300 m tectonic transport previously estimated from D<sub>4</sub> imbrication of VMS ore lenses. The E-dipping thrust sheets of basement and cover rocks, dipping parallel to bundles of E-dipping seismic reflectors on regional Lithoprobe seismic sections, suggest that D<sub>3</sub> collisional thrusts predominantly control the structural framework of the Flin Flon mining district. Since D<sub>3</sub> thrust faults are poorly exposed and as a result do not feature as prominently in the surface geological map pattern as regional N-trending D<sub>2</sub> fold structures and D<sub>7</sub> post-metamorphic faults, this new interpretation demonstrates the significant role local 3D geologic modelling studies can play in enhancing the regional understanding of intensely tectonized mineral belts. Obviously, the 3D-modelled polyphase imbricate structure has also important implications for guiding local exploration of the mine horizon and VMS ore system as well as regional exploration of its lithostratigraphic equivalents in the under-exploited subsurface volumes of the Flin Flon mining district.

## **A FRAMEWORK FOR 3D MULTI-PARAMETER MAPPING OF VMS ORE SYSTEMS ILLUSTRATED WITH A CASE STUDY FROM THE FLIN FLON MINING DISTRICT, TRANS-HUDSON OROGEN, CANADA**

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It is widely acknowledged in the hydrocarbon and mineral industries that the development of more effective exploration methods benefits from a system approach that establishes the link between critical mass and energy transfer processes and mappable targeting elements. Accordingly, 3D geologic modelling in support of deeper mineral exploration should not only focus on modelling the ore deposit and its hosting rock units, but also on the 3D spatial characterization of targeting elements that reflect mineralizing fluid transport and mineral deposition mechanisms. We present a framework for deposit to camp scale 3D modelling of strata-conformable VMS ore systems in which this process-oriented targeting objective is addressed and illustrate its application to the Flin Flon-Callinan-777 VMS ore system hosted in accreted juvenile volcanic arc terranes of the Paleoproterozoic Trans-Hudson orogen, Canada. A grid of the envelope of the VMS-hosting mine horizon has been modelled from lithostratigraphic and fault surfaces by the systematic reconciliation of drill hole and geologic map data. This 3D strata-conformable grid serves as a multi-parameter container for geostatistical modelling of volcanic and volcanoclastic lithofacies, hydrothermal alteration indices, Cu/(Cu+Zn) ore metal zoning and physical properties supporting forward modelling and inversion of geophysical data. Although fault displacements due to early layer-parallel thrust imbrication of the mine horizon can not be restored, the integrated interpretation of the lithofacies and geochemical parameters provides valuable insight in the Palaeo-submarine setting of the VMS ore system that directly benefits deep targeting strategies in the mine camp.

## **HEMATITE/MAGHEMITE TRACE ELEMENT GEOCHEMISTRY IN BASE METAL EXPLORATION**

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Maghemite/hematite concentrates of regolith samples were analysed for major and trace elements to test their suitability for geochemical exploration in areas under cover. Bulk samples are medium to fine-grained partly calcareous sand with variable amounts of clays, locally containing calcrete nodules. Extraction of maghemite/hematite was done using a RE-magnet. Petrographic studies show the intricate and small scale compositional variation of the individual grains consisting of FeOxide, mostly detrital quartz and variable amounts of illites and carbonate. Mineral composition of the maghemite/hematite concentrates as determined by XRD and Rietveld analysis is: Maghemite: 25-35%, Hematite: 10-40%, Quartz: 10-35%, Rutile: 1-5%, Illite: 1-15%, Calcite: 1-15%, Na-feldspar: 1-5%, Ankerite: <5%. In comparison to bulk sample the concentrates have distinctly higher average concentrations of base metals (conc./bulk, [ppm]): Pb: 70/6, Zn: 83/17, Ni: 43/9, Cu: 25/22. Other trace elements enriched in the mineral concentrates are: Sn: 177/35, As 104/11, Co: 18/5, Cr: 286/25, Mo.: 11/2, V: 1326/75 and total REE: 136/41. Correlation of the trace elements with major elements (Si, Al, Fe) in bulk sam-

ples as well as in the concentrates is only weak. Electron Probe Micro Analysis (EPMA) of the composite maghemite/hematite grains shows the distinct association of trace elements with the Fe-oxide phase, for example (max./average [ppm]): Cu: 1493/274, Zn: 1219/237, Ni: 790/199, Co: 610/32, As: 1017/374, Cd: 938/95, Sb: 1030/141. The results show that a large number of trace elements are mobile in the regolith environment and are selectively enriched in authigenic maghemite and hematite. This enrichment of trace elements makes the magnetically extractable maghemite/hematite concentrate a suitable sampling medium for geochemical exploration for base metals in areas of cover and may provide valuable pathfinder information for other elements. The higher concentration of trace elements in this mineral fraction allows for improved, higher resolution definition of anomalies and more accurate data processing.

## **THE MIDDLE ORDOVICIAN BASIN OF ANGLESEY (WALES) AND THE ROLE OF MONIAN BASEMENT ARCHITECTURE ON DEPOSITION AND ACADIAN SHORTENING**

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The island of Anglesey, north Wales, comprises a complex collage of Late Neoproterozoic and Palaeozoic rocks that preserve a record of accretionary tectonic processes on the outboard margin of Gondwana. Late Neoproterozoic subduction along the Panthalassic margin is recorded by the intrusion of the Coedana Granite at 615 Ma, part of an assemblage of supra-subduction zone granites that make up much of East Avalonia, and by the accretion of blueschists of the Penmynydd Zone, metamorphosed at around 560 Ma. Early Ordovician (Monian/ Penobscottian) deformation records the assembly of the Late Neoproterozoic rocks with an approximately Middle Cambrian to Early Ordovician sedimentary succession of the Monian Supergroup, considered by some authors to be comparable with Ganderian successions of central Newfoundland and New Brunswick.

Assembly of these units is constrained by overstep of a basinal succession of Middle Ordovician to Silurian age that records renewed subsidence along the Gondwanan margin of Iapetus, analogous to proposed post-Penobscottian roll-back and back-arc basin formation in the contemporary record from Atlantic Canada. The basin is strongly asymmetric in geometry. Deposits along the northern fringe record steep, unstable palaeoslopes and are characterised by debris flows and coarse clastic submarine channels. These contrast with the southern margin where supra-storm wave base marine deposits pass rapidly upward and outward into de-stratified, anoxic, basinal facies rocks of approximately Late Arenig to Early Llanvryn age. The latter facies record deepening and basinal instability interpreted as recording rapid subsidence along the basin margin. A contemporary central basinal succession is also preserved comprising an anoxic facies of thin mudstone turbidites.

These stratigraphic elements are juxtaposed and imbricated along former thrust faults with inliers of the basement Monian Supergroup and Coedana Complex that record shortening by horizontal translation during the post Llandovery phase of deformation. The strongly asymmetric morphology of the Middle Ordovician basin is here interpreted to reflect renewed-subsidence of a post Monian foreland basin and subsequent reactivation of basement thrusts during the main Acadian phase of deformation.

## VMS-TYPE ORE DEPOSITS AND PROSPECTS IN THE BARBERTON GREENSTONE BELT: EVIDENCES FROM A 3.2 GA EPICONTINENTAL RIFT SYSTEM

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The 3.2 Ga Upper Fig Tree Group of the Barberton greenstone belt, South Africa, hosts several base metal sulfide prospects and iron formations delineating a zone of epicontinental rift-related hydrothermal activity. The ore prospects include the 2.9 Mt Zn-Pb-Cu-Ag Bien Venue deposit, the M'hlati zinc prospect, associated with a distinct iron formation exhalite horizon, and a massive iron formation at Spago. Other zinc prospects (Annex Riverbank, Dunbar, N'hluimi, Maurice Dale) are attributed to the uppermost Onverwacht Group. The Bien Venue VMS deposit is associated with quartz-muscovite schists which have been derived from calc-alkaline rhyodacitic volcanic rocks. The zinc-rich massive and disseminated sulfides show an unusual Ag-Cu-Sn enrichment including minerals like jalpaite, cassiterite, freibergite, and canfieldite. The formation of the orebody is best explained by a moderate temperature, moderate to shallow seawater hydrothermal system with complex fluid-rock interaction and a fluid evolution which is characterized by steep physicochemical gradients. The M'hlati iron formation occurs in the same stratigraphic interval and is hosted by immature greywackes and carbonaceous shales. It represents a base metal-rich siliceous and ferruginous exhalite horizon. Elevated Zn, Cu and Pb values indicate a distinct potential for associated sediment-hosted base metal sulfide deposits. Geochemical and mineralogical studies indicate the formation from mineralizing fluids with temperatures in excess of 250°C. The compositions of ores and wall rocks at Bien Venue and M'hlati exhibit distinct affiliation to evolved and differentiated crust. It is suggested that the Bien Venue, M'hlati and Spago sites delineate a stratigraphic horizon with products of moderate to high-temperature hydrothermal activity in an epicontinental immature rift system.

## TEACHING THE SIGNIFICANCE OF IGNEOUS TEXTURES USING SYNTHETIC ANALOGUES

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Learning to describe the textures of igneous rocks in samples or in thin sections is a key element of all undergraduate programs in geology. Students quickly identify differences in the size and shape of minerals and assign processes to explain them (e.g. skeletal crystals in a volcanic rock = rapid cooling; coarse, equant crystals in a plutonic rock = slow cooling). The final texture of an igneous rock may evolve through a number of steps from initial nucleation and crystallization through crystal growth in a melt-dominant environment to textural coarsening at low melt fractions as the temperature approaches the solidus. As part of a graduate course in igneous petrology, we used the analog experiments of Means & Park (1994: New experimental approach to understanding igneous texture, *Geology* 22, 323-326) to provide a window into the textural evolution of crystalline phases during crystallization. Preparation involves mixing saturated solutions of ammonium thiocyanate  $\text{NH}_4\text{SCN}$  and cobalt chloride  $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$  in a fume hood, adding a drop of the resulting blue solution to a glass slide on a hot plate at 80°C, partial dehydration of the solution, and then remelting at 150°C. A second glass slide is used to cover and thin the drop of solution, the section is removed from the hot plate and allowed to cool, and then is placed on a hot plate at 50°C to coarsen. The sections can be examined on a petrographic microscope and textural evolution can be recorded with serial pho-

tomicrographs or video. Three crystalline ammonium compounds form and look remarkably like igneous minerals: a white phase that forms bladed to blocky crystals, a colourless cubic phase, and a blue acicular phase. Due to the lack of suitable temperature control after preparation of the sections, we mostly produced textures that resulted from strong temperature gradients and rapid cooling, including dendrites, swallow-tail crystals, and spherulites. We also observed the initial stage of dendrite growth and subsequent segmentation into individual grains with elimination of the smaller grains reported by Means & Park, which by analogy suggests that nucleation in silicate melts may be quite different from conventional views. A teaching highlight to performing these hands-on experiments is the ability to see crystal textures actually develop in real-time and then compare them to natural examples. Future experiments will evaluate the effects of isothermal coarsening with the aim of producing texturally mature crystalline materials that resemble plutonic rocks.

## U-Pb SHRIMP GEOCHRONOLOGY OF PALEOPROTEROZOIC GRANITE IN THE KIGGAVIK AREA OF THE NORTHEAST THELON BASIN, NUNAVUT

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Recent investigations, as part of the Geological Survey of Canada's GEM-Uranium Project, have been conducted to resolve the age of the Paleoproterozoic igneous rocks around the Thelon Basin, and investigate their potential "ground preparation" relationship to uranium deposits of the Kiggavik trend. Two major granite suites are documented regionally: the ca. 1.85-1.81 Ga Hudson suite and the ca. 1.76-1.74 Ga Nueltin suite. The former is dominated by monzogranitic compositions derived by crustal melting associated with collision of the Rae and Hearn cratons, whereas the Nueltin suite consists mainly of syenogranite and coeval rhyolite thought to have been produced by magmatic underplating of the crust, generating hot, dry melts. Zircons from six igneous units were dated via U-Pb SHRIMP techniques at the Geological Survey of Canada.

Field mapping in the area revealed the predominance of Hudson suite plutons which commonly show mingling with coeval minette magma to produce the Martell Syenite. Two large, coarse-grained granitic plutons, 18km southwest and 8.5 km west (Granite Grid) of Kiggavik, were determined to be  $1834.4 \pm 6.4$  Ma and  $1842 \pm 6.4$  Ma, respectively. The crystallization ages of two intrusive bodies immediately south of Kiggavik are interpreted to be ca. 1810 and ca. 1830 Ma, based on dating of zircon overgrowths on Archean cores. The predominance of inherited zircon cores is a characteristic of Hudson suite granites and is interpreted to reflect minimum melting temperatures and limited melt migration from the source.

Two drill core samples from the Kiggavik uranium deposit were investigated. A drill core sample of mixed granite and minette yielded a zircon age of  $1825 \pm 11$ , consistent with the age of Christopher Island minettes in the Baker Lake basin. Core of the Lone Gull granite, texturally continuous with but from just outside the highly altered mineralized zone at the Kiggavik deposit, identified two distinct zircon populations within the pluton: a Hudson suite component at  $1806 \pm 33$  Ma and a Nueltin-age component at  $1744 \pm 12$  Ma. The former indicate a previously undocumented interaction between the Hudson and Nueltin suites. Ongoing investigation of other local uranium-associated granitoid rocks may help determine if the interaction between the two suites is more widespread. The Lone Gull pluton, along with feldspathic

metawacke that it intrudes, are highly altered to clay and chlorite where they are mineralized with uraninite. Hudson granitoid and mingled minette (Martell Syenite) bodies are also clay altered but not mineralized.

#### **GEOENVIRONMENTAL MINERAL DEPOSIT MODELS: PAST, PRESENT, AND FUTURE**

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Geoenvironmental models, as originally conceived in 1992, established the link between the geological and geochemical characteristics of a mineral deposit and its environmental expression. Since then, numerous case studies have confirmed this linkage. In their simplest form, models are empirical compilations of geologic and environmental data that include mineralogy and geochemistry of mine waste, sediment, surface water, and groundwater. The concept has evolved past the exploratory stage and has now reached a point that warrants critical evaluation. The current geoenvironmental models possess the requisite characteristic of models – the provision of a testable hypothesis that provides insight into the environmental geochemistry of mineral deposits. The compilation allows similarities and differences among sites to be identified, which ultimately should lead to conclusions regarding the importance of various biogeochemical, hydrologic, and climatic processes in determining environmental features. The current model for seafloor massive sulfide deposits indicates that the classification of subtypes of these deposits is reflected in distinct Cu/Zn ratios of mine drainage associated with the subtypes. Departures from these predicted or characteristic ratios are helpful for identifying locally important atypical geochemical processes, such as cation sorption in slightly acidic to neutral anoxic settings. To advance the concept and utility of geoenvironmental models, a more systematic, consensus approach is needed. The form or forms will necessarily be driven by uses of the models. Application of models to the remediation of abandoned mine sites could be quite different from application to future mining including every stage from exploration stage through permitting to operation and closure. At abandoned mines, models can insure a comprehensive site assessment throughout all phases of activity. With growing emphasis on sustainability of future mining, geoenvironmental models can be used at the exploration stage to provide a more robust assessment of likely environmental costs to constrain the grade or total-contained-metal characteristics of a deposit that would be needed for economic viability. At the feasibility stage, decisions could be made to not mine certain deposit types, or to mine them only using certain methods to improve environmental management. For example, underground mining could minimize disturbance of large volumes of acid-generating waste rock that are unavoidable by open pit methods, particularly in the context of climatic conditions that determine water availability. Throughout the mine development process, the approach could also highlight stages where innovation in mining method, waste handling practices, or metallurgy are needed to make a marginal deposit profitable.

#### **HYBRID TILLS AND COMPLEX GLACIAL FLOW PATTERNS IN WEST-CENTRAL NEW BRUNSWICK, CANADA: IMPLICATIONS FOR SUBGLACIAL PROCESSES AND MINERAL EXPLORATION**

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Hybrid till is defined as till that was transported and deposited during one glacial phase and then reworked during a subsequent glacial phase. It has the geochemical and lithological characteristics

of the depositional phase but a fabric that reflects the trend of the reworking phase. West-central New Brunswick provides excellent examples of hybrid till. The results from two decades of near surface (~0.5 to 1 m depth) basal till geochemistry sampling, primarily based on a 2-km grid, provide a clear indication of glacial dispersal direction. Most major dispersal trains (~10 to 50 km in length) from subcropping mineral deposits or distinct lithologic units trend southeast to south-southeast. These dispersal trains reflect deposition during the Caledonia Phase (Early to Middle Wisconsinan) by the combined efforts of the Laurentide Ice Sheet and the Notre Dame Ice Divide of the Appalachian Glacier Complex. In contrast, 70% of till fabrics measured at a similar depth have a trend relating to a Middle to Late Wisconsinan phase of the Appalachian Glacier Complex: south to west (Escuminac Phase), east to northeast (Scotian Phase), northeast to northwest (Chignecto Phase), or west to northwest (Collins Pond Phase, Younger Dryas Stadial). The glaciological implication is that the complex ice-flow patterns of the Late Wisconsinan were relatively ineffective: they had the ability to locally rework the upper one to two metres of previously deposited till, but typically could move it only far enough to reorient the fabric and generate striae on bedrock surfaces that extended up into the zone of reworking. Only rarely were they effective enough to locally form an identifiable Late Wisconsinan till.

In mineral exploration it is commonly assumed that the direction of glacial dispersal is parallel to the last ice-flow direction as recorded by glacial striae or till fabric trends. Clearly, following the up-ice trend indicated by the orientation of such features in west-central New Brunswick is a good way to completely miss the source area of mineralized float or a till geochemical anomaly. For the mineral explorationist working in an area of complex glacial flow patterns and potential hybrid tills, in the absence of prior knowledge of glacial dispersal trend, there is only one clear indicator of the true direction of glacial dispersal. That is the lithological composition of the till itself, which can be compared with the bedrock geology of the area to identify those bedrock units sampled by the glacier during till formation.

#### **ACCESSORY MINERAL CONTROLS ON TRACE-ELEMENT FLUXES DURING PARTIAL-MELTING, EXAMPLES FROM THE OTTER LAKE AREA, GRENVILLE PROVINCE, QC**

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A detailed study of three suites of rocks in the Otter Lake area, Quebec, was conducted combining field and petrographic observations with geochemical data to constrain the effects of accessory mineral fractionation on trace-element fluxes during partial-melting. In addition, in situ U-Pb geochronology provides age constraints for the high-temperature processes in the study area.

The Otter Lake area lies within the Proterozoic Grenville Province of the Canadian Shield. Various rocks have been assembled into five groups based on mineralogy and microstructure, as follows. Group 1: marble and skarn, 2: felsic gneiss, mafic gneiss, amphibolite, granulite, quartzite, with combinations of sillimanite, garnet, hornblende, Ca-pyroxene, orthopyroxene, representing a sequence of interlayered clastic sedimentary rock and volcanic rock, 3: metagabbro, minor metapyroxenite, 4: K-feldspar gneiss, mainly veined gneiss, 5: granitic and syenitic rock ranging from granodiorite to nepheline syenite. The two lithological units studied include groups 2 and 4.

An age of  $997 \pm 10$  Ma from a large single titanite crystal from the Yates mine, Otter Lake, is the only age for the study area, hence obtaining an age for the area would be beneficial. The main

tectonic-metamorphic event that affected the above lithological units occurred between 1250-1190 Ma. These rocks were affected by ductile deformation during the Grenville Orogeny. Nearly uniform metamorphic grades are found across the study area at high amphibolite to low granulite facies. Estimates of peak temperature and pressure of metamorphism in the area are at 700°C and 7 kbar.

This study focuses on accessory minerals which play a large role in the incorporation of trace elements into their structures during melt crystallization. Zircon is resistant to chemical and physical breakdown with its insolubility in crustal melts and fluids making it a prime candidate for retaining geochemical tracers. The relative timing of zircon fractionation into the melt whether pre-, syn-, or post-crystallization may dramatically alter the geochemical signature of the resultant melt. Growth zoning within individual zircon crystals may represent; (i) earlier xenocrysts (including inherited crystals), (ii) overgrowths which themselves may represent several phases of crystallization, (iii) new crystals with or without complex growth zoning.

Laser-ablation inductively coupled plasma-mass spectrometry (LA-ICPMS) has been used to characterize zircon populations from the study area. Within a single grain, multiple growth zones can be observed and individually dated *in situ*. Detailed trace element patterns were also examined for the zircon grains, to document changes in chemistry and crystallization environment.

#### **RIFTING: THE MOST WIDESPREAD TECTONIC PROCESS ON EARTH**

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Rifting is the most widespread tectonic process on earth and probably always has been since the formation of a solid shell around the planet. It also seems to predominate over other kinds of tectonic processes in most other rocky planets and moons of our solar system. Rocks are about four times weaker under tension than under compression and this probably is one reason why extensional structures are so much more widespread in the lithosphere than those of shortening. However, the nature of the events taking place along plate boundaries lead to the formation of extensional structures along all three types of plate boundaries, plus plate interiors and at incompatibility junctions within the continental lithosphere in many more ways than they generate shortening-related structures. This observation behooves us to be careful while assessing the tectonic significance of various types of extensional structures.

Not all normal-fault-bounded troughs are rifts. Many normal-fault-bounded troughs are intracrustal or even intracutaneous, in the sense that they only affect the sedimentary cover. Such structures were first identified by miners and the German-speaking mining community called them grabens from the German word for trench or moat. The word rift was first employed for the East African normal-fault-bounded depressions and was derived from the root 'reve' meaning to pull asunder. It seems useful to preserve this historical precedent and call those normal-fault-bounded troughs not penetrating the lithosphere grabens and those that do penetrate the lithosphere rifts. Rifts are thus structures under or near which the entire lithosphere has thinned in extension. For rift studies it seems useful to use the peridotite solidus as the lower boundary of the lithosphere. This definition brings with it certain mechanical implications allowing flowage to be considered within the compass of rift studies.

Not every individual rift is always an independent entity. In many instances rifts crowd in regions characterised by regional extension. Such areas are called taphrogens and commonly it are taphrogens that need to be studied rather than individual rifts for understanding the tectonics of a given region. Extensional envi-

ronments form taphrogens, but extension can be brought about in divergent, convergent or transform plate boundaries, plus in regions of doming or subsidence in plate interiors. So not every rift and even not every taphrogen automatically lead us to a unique regional tectonic interpretation. Thus, it might be helpful to identify certain fingerprints of different kinds of 'rifting' to constrain our interpretations.

#### **SPATIAL-TEMPORAL VARIATION IN MODERN DEEPWATER CHANNEL-FAN SYSTEM DEVELOPMENT: PANDORA AND MORESBY TROUGHS, GULF OF PAPUA**

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The distribution and geometry of deep-water channel fan depositional systems are dictated by combined effects of local processes, ocean hydrodynamics (controlling shelf and upper slope sediment movement), and glacio-eustasy. Most studies have considered transgression and highstand as times of negligible sediment supply to deepwater. However, more recent work, including ours, suggests that the development of oceanographic processes on the flooding shelf and the shelf morphology itself influence on-shelf sediment trapping mechanisms and can also facilitate off-shelf sediment transfer.

Preliminary study in Gulf of Papua (GoP), Papua New Guinea, has shown that during Marine Isotope Stage 2 (MIS-2, 14.1-27.6 Ka) sea level was ~125 m lower than present, and the shelf was exposed, enabling fluvial systems to progress seaward, incising the shelf plain and directly feeding canyons and deeper basins with sediment.

During the Holocene sea level rise (14 Ka – recent), we observed two contrasting source to sink histories in two adjacent depocenters, Pandora and Moresby Troughs. In Pandora Trough, sea level rise drowned the shelf, promoting the clinoform development and preventing direct fluvial sediment transfer to the canyons and deeper water. In Moresby Trough, regional shore-parallel currents developed that impinge on the eastern shelf edge. These eastward currents entrain sediment from major western GoP rivers, bypassing canyons to the south, and may have created a coalesced sediment source that potentially produce a single large deep sea fan, compared to smaller deposits that would be created from isolated sources.

#### **URANIUM AND SULFIDE MINERALOGY OF THE MENQIGUER ROLL-FRONT URANIUM DEPOSIT, YILI BASIN, CHINA**

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Sandstone hosted roll-front uranium deposits are among the most significant source of uranium worldwide (Cuney, 2009). These deposits form in the direction of flow of groundwaters, as crescent or lens shaped ore bodies at an oxidation-reduction interface. The MenQiGuEr uranium deposit of the Yili Basin, Xinjiang Autonomous Region of NW China is a roll-front type uranium deposit. Two drill holes were sampled to characterize the uranium and sulfide mineralization. Drill-hole ZKP1120 intersects the nose of the roll-front, and ZK739 is drilled further updip in the oxidized region. Samples P1 and P4 were collected from locations ZKP1120 and ZK739, at depths of 443.23 m and 441.00 m, respectively. Hand samples of organic-rich subarkosic sandstones, display sub-rounded to sub-angular, fine to medium-sized sand grains, are poorly sorted, friable and light to medium grey. Sample

P1 is comprised of subhedral to euhedral pyrite that ranges in size from 2-200  $\mu\text{m}$ . Grains of pyrite are generally disseminated throughout the sample and rarely occur as clusters of pyrite. Sample P4 consists of fine-grain, anhedral pyrite that ranges in size from <1 to 10  $\mu\text{m}$ . Uranium mineralization in sample P1 largely consists of fine-grain (<1-5  $\mu\text{m}$ ), spheroidal blebs of uraninite ( $\text{UO}_2$ ) within pyrite grains and less commonly as uranophane ( $\text{Ca}(\text{UO}_2)_2[\text{HSiO}_4]_2 \cdot 5\text{H}_2\text{O}$ ). In sample P4, uranium mineralization is largely uranophane and brannerite ( $(\text{U}^{4+}, \text{REE}, \text{Th}, \text{Ca})(\text{Ti}, \text{Fe}^{3+}, \text{Nb})_2(\text{O}, \text{OH})_6$ ) that occupy spaces between grains of pyrite and quartz, and infill cellular wood structures. Electron microprobe analyses of uranium minerals from samples P1 and P4 show that uraninite has uranium, silicon, and calcium concentrations ranging from 21.0 to 82.9 ( $\text{UO}_2$  wt.%), 0.30 to 6.8 ( $\text{SiO}_2$  wt.%), and 0.37 to 6.2 (CaO wt.%). The variable chemistry is due to the fine grain-size of uraninite (<1-5  $\mu\text{m}$ ) and the larger beam size (5  $\mu\text{m}$ ) of the electron microprobe. Chemical concentrations for uranophane range from 77.4 to 83.2 ( $\text{UO}_2$  wt.%), 2.3 to 5.0 ( $\text{SiO}_2$  wt.%), and 3.4 to 4.9 (CaO wt.%), and brannerite range from 82.2 to 88.3 ( $\text{UO}_2$  wt.%), 0.69 to 1.2 ( $\text{SiO}_2$  wt.%), and 4.1 to 6.8 (CaO wt.%). Chemical Pb ages of uranium minerals were calculated based on atomic wt%. Uraninite ranges in age from 3 to 251 Ma, whereas uranophane and brannerite range in age from 16 to 82 Ma and 22 to 63 Ma, respectively. However, due to the very small grain size of uraninite in P1, the chemistry of uraninite is variable and therefore the chemical Pb ages less reliable.

#### CHROMITITE DEPOSITS IN IRAN: RELATIONSHIPS BETWEEN OPHIOLITE TYPE AND CHROMITE GEOCHEMISTRY

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Chromitites are a main constituent of mafic-ultramafic layered intrusions. Podiform-type chromitites and accessory chromites also occur within ultramafic ophiolitic rocks and have a large range of compositions reflecting their primary magmatic origin. Primary chromites can be used as petrogenetic indicators, because systematic relationships exist between chromite chemistry and compositions of melts and ultramafic residues. Studies of chromite deposits and the type of ophiolites they are associated with in Iran have mainly been limited to a few large deposits, especially chromite compositions and mode of occurrence. However systematic studies including chemical zoning, bulk-rock composition or mineral assemblage, geological setting and geological processes have not yet been done on such deposits and peridotite hosts in Iranian ophiolites. For Iranian ophiolite occurrences, we classified Iranian ophiolites into 1) Late Cretaceous Zagros ophiolite belt including Nain-Baft inner belt and Kermanshah-Neyriz outer belt ophiolites, 2) Early to Late Cretaceous Eastern ophiolite belt, the Birjand ophiolite, 3) Northeastern ophiolites, Late Cretaceous Sabzevar-Torbat-e-Heydarieh ophiolites, 4) Late Jurassic to Late Cretaceous Northwestern ophiolites, Khoy-Maku ophiolites. We separately discuss the range and mean of Iranian ophiolite spinel compositions for these occurrences.

Zagros inner belt ophiolites have chromites (both podiform and residual) with mean Cr# (=100 Cr/Cr+Al) of 65 for Dehshir (residual), 35-40 and 60 for Nain residual and podiform types respectively, 43 for Shahr-e-Babak, 52 and 85 for Baft residual and podiform chromites respectively, with podiform chromites having higher  $\text{TiO}_2$  content. Zagros outer belt ophiolites are characterized by having more refractory chromites with mean spinel Cr# ranging from 60-75 in Neyriz, 40-50 in Kermanshah and 60 in Haji-Abad.

The eastern ophiolites including Birjand have residual and small podiform chromite lenses, which are represented by spinel with mean Cr# of 40-50. Large podiform chromite deposits are found in NE Iranian ophiolites, such as the Sabzevar ophiolite, with spinel Cr# in range of 70-80.

The northwestern Iranian ophiolites have spinels with Cr# ranging from 20 to 50.

This information is to classify and to compare Iranian chromite deposits and the type of associated ophiolites and to demonstrate the usefulness of understanding differences in Iranian ophiolites and using this for finding and exploiting economic deposits of chromite.

#### FEMTOSECOND VERSUS NANOSECOND LA-ICP-MS: ADVANTAGES AND DISADVANTAGES

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The last few years have witnessed a tremendous increase in applications of LA-ICP-MS in elemental and isotopic analyses of a wide variety of samples. Developments in laser technology and ICP-MS have contributed to resolve problems that were commonly encountered since the initial applications of this technique. Matrix effects, elemental and isotopic fractionation, mass bias, and lack of matrix-matched standards were, and still are, challenging problems that can limit the applications of LA-ICP-MS.

Laser systems have been greatly improved since 1985 when the first LA-ICP-MS experiment was conducted using a nanosecond Ruby laser. For nanosecond laser systems wavelength, among other parameters, plays an important role in defining the ablation quality and performance of LA-ICP-MS. Deep UV excimer lasers (157 and 193 nm) were reported to be excellent for LA-ICP-MS since their laser pulses can be absorbed by most materials and produce small-size particles that can be easily transported by the carrier gas and efficiently atomized and ionized in the ICP. However these laser systems were expensive, not easy to maintain, required a controlled ablation environment since wavelengths < 200nm can be absorbed by air and can cause damage to the transfer optics. Recently femtosecond lasers have been introduced for ablation and have shown better ablation quality than nanosecond laser systems. The advantages of femtosecond LA-ICP-MS arise from the nature of interaction of ultrashort laser pulses with matter. During the interaction time the energy transfer to the lattice is very fast and there is not sufficient time for the material to melt. The high intensity of femtosecond laser pulses makes the ablation of transparent materials more deterministic (well-defined ablation threshold) through multiphoton ionization process. In this process bound electrons, under the high electromagnetic field of the femtosecond laser pulses, are forced to leave their atoms and form seed electrons that are necessary for absorption of the laser beam by the material. The particles generated using femtosecond laser pulses are of nanometre scale and can be transported, atomized and ionized in the ICP with efficiencies higher than those of the particles generated by nanosecond laser pulses. The absence of heating effects in fs-LA-ICP-MS minimizes or even eliminates fractionation at the ablation site which makes the ablated particles more representative of the sample.

Femtosecond lasers are ideal for applications that require high sensitivity such as isotope ratio measurements by MC-ICP-MS where large ion beams are necessary for accurate and high precision isotopic analysis. Addition of foreign gases (i.e. hydrogen and nitrogen) to Ar carrier gas has shown additional enhancement in sensitivity when used with femtosecond lasers.



## A SIMPLIFIED PROCEDURE FOR EXTRACTION OF MORPHOTECTONIC FEATURES FROM DIGITAL ELEVATION MODELS

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Tectonic deformation along faults is characterized by changes in local geomorphology e.g. drainage basin tilting, linear valleys, knick points, ridge lines, slope breaks etc. These morphotectonic features are developed over the period of time and reflect the influence of regional tectonics, erosion and climatic processes. These features can act as a reconnaissance tool to identify areas experiencing tectonic deformation. In this work, we provide a two step simplified procedure for automatic/semiautomatic extraction of these features i.e. generation of geomorphic parameter and calculation of a set of linear and nonlinear morphotectonic indices. Most of these tasks can be easily carried out in our newly released software TecDEM, which is a MATLAB based toolbox for Tectonic Geomorphology.

Geomorphic parameterization broadly includes the extraction of drainage networks, sub basins, ridge lines and other related parameters from digital elevation modes (DEMs) available in different spatial resolutions (Low, Medium and High). It consists of five sub steps i.e. filling depressions, generating flow directions, calculating upslope contributing areas, assigning Strahler orders to the drainage networks and the sub basin extraction. All those sub procedures can be executed in TecDEM. In order to prepare a set of effective morphometric maps, several automatic and semiautomatic operations are applied on the extracted geomorphological parameters. Spatially distributed streams profiles are selected for calculating concavity, steepness and Hack indices. These streams can also be used to identify the possible locations of knick points and the calculation of relative uplift rates. Similarly, TecDEM also includes automatic algorithms to prepare surface dynamics maps e.g. the relative relief, the local base level, the drainage density, the surface roughness etc. It also includes algorithms for drainage basin tilting and hypsometric analysis. Drainage basin tilting is a complex computational task, which can be carried out on the basins of different Strahler orders. The spatial distribution of different morphotectonic parameters, uplift rates and knick points, is exported into standardized GIS formats and can be integrated with other geoscientific data. We tested this procedure on DEMs from different tectonic settings worldwide and received verifiable results with other studies.

## SEDIMENT DISPERSAL PATTERNS AND THEIR SIGNIFICANCE TO MINERAL EXPLORATION IN THE EAST ARM AREA OF GREAT SLAVE LAKE

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Field mapping, sampling and analysis of glaciogenic sediment in a ~250,000 km<sup>2</sup> region near the East Arm of Great Slave was carried out to support regional mineral assessment (1 sample /~400 km<sup>2</sup>) in a proposed national park reserve.

Glacial erosion features (e.g. striae) record an east to west flow with NW and SW radial divergence across the study area. Transport of glacial sediment, till, followed a similar divergent pattern based on 40-60 km wide, fan-shaped geometries for most dispersed indicators. Sediment transport ranges from a few kilometres to >200 km, depending on the clast size and lithology reported, although transport distances from known sources within the study area range from ~1-80 km. Dispersal in till appears to be aligned with ice flow direction.

Glaciofluvial erosion (s-forms and till removal), transport and deposition, mainly expressed as esker sediment set within 0.25-3 km wide erosional corridors, show a similar divergent pattern as that of ice-flow (till) indicator distribution. This similarity in flow pattern suggests that meltwater and glacial events responded to similar directional gradients, potentially simplifying mineral tracing. The similarity in pattern, inferred close timing of events (late ice flow to meltwater flow), and lack of multiple flow phases may have contributed to the apparently simple dispersal pattern observed. Transport paths and dispersal of rock fragments and minerals is similar in till and glaciofluvial sediment, although transport distances appear to be greater (from 5 to 25 km) in some constituents in eskers and indicator minerals are more concentrated in esker sediment than in till.

The fan-shaped geometry for most dispersed indicators is interpreted to relate to either broad source-rock areas or to expanding (point source?) flow patterns often observed in glacial erosion and dispersal trains. The 40-60 km wide East Arm patterns are in marked contrast to long, linear, parallel patterns found in nearby parts of the Slave such as Ranch Lake and Snap Lake. For example, the Ranch Lake diamond indicator dispersal train is pencil-shaped with sharply-defined lateral edges and a narrow width (500 m at source, 2 km at 30 km and <5 km at 80 km down-flow). It is interpreted that these dramatically different geometries relate to either differing flow regimes, flow vectors, source dimensions or to different processes.

## IN SEARCH OF THE WORLD'S OLDEST URANINITE

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Two recent studies have shown that minerals have evolved through time. The first major era (>4.55 Ga) consists of the formation of chondrite minerals and ~250 achondrite minerals. The second, from 4.55 to 2.5 Ga, is an era of crust and mantle reworking defined by igneous processes and plate tectonics. The final era is that of biologically mediated mineralogy that resulted after the Great Oxidation Event (GOE). This era is responsible for most of Earth's 4300 minerals species.

More specifically the evolution of uranium mineral deposits can be divided into four main phases. The first, from ~4.5 to 3.5 Ga, is characterized by the concentration of uranium into magmatic-related fluids from which the first U<sup>4+</sup> minerals formed (mainly uraninite). The second phase occurred between ~3.5 to 2.2 Ga and involved the formation of large low-grade concentrations of detrital uraninite that were deposited in an anoxic fluvial environment. Earth's third phase of uranium mineral evolution (~2.2 Ga to 400 million years ago) followed the GOE and was mediated by the oxidation of U<sup>4+</sup> to the more soluble U<sup>6+</sup> species. Examples of mineral deposits that formed during phase three include unconformity- and vein-type U deposits (Australia and Canada) and the unique Oklo natural nuclear reactors in Gabon. The final phase began ~400 million years with the rise of land plants, this led to the formation of new sandstone-type ore deposits from non-marine organic-rich shales. However, one question still remains: What is the age of the oldest uraninite?

In situ U-Pb isotopic analysis of uraninite using secondary ion mass spectrometry (SIMS) shows that the uraninite from the Huron Claim are highly discordant (>5%) with an upper intercept of 2575 ± 38 Ma. Lead (<sup>207</sup>Pb-<sup>206</sup>Pb) isotope ages range from 2514 ± 5 Ma to 2573 ± 19 Ma, with an average age of 2550 ± 17 Ma. Therefore, the crystallization age of the uraninite is interpreted to be 2575 ± 38 Ma. A comparison of this age with uraninites from other deposits suggests that the Huron Claim uraninite is the oldest uraninite.

## THE LINK BETWEEN MELT STRUCTURE, VISCOSITY AND MINERAL DISSOLUTION RATES

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Assimilation has significant effects on the trace element and isotopic composition of igneous rocks. Incorporation of cations from a dissolving mineral will, unless mineral and melt have the same composition, lead to a change in the structure of the melt adjacent to the crystal and to the development of chemical potential gradients in the melt. If the added cation is silica the melt should become more viscous than the solvent. If alumina is added, the data of Toplis and Dingwell (2004, *Geochimica et Cosmochimica* 68, p5169-5188) suggest that the situation is more complex since  $\text{Al}_2\text{O}_3$  addition can lead to an increase or decrease in viscosity depending on its structural role. The degree of change needed to equilibrate the solvent with the interface melt is measured by the difference in degree of polymerization of the two as reflected in their viscosity. Since network forming cations are considered to be the slowest diffusing, by virtue of their strong bonds with oxygen, dissolution rates of minerals should be related to the resistance of the melt to structural change induced by movement of these cations. Tests of this hypothesis using literature data for olivine and quartz show that there is a correlation between the experimentally determined dissolution rate constant and the difference in viscosity, and therefore structure, between the solvent melt and the melt at the dissolving crystal interface. For dissolution of olivine in andesite and quartz in synthetic melts in the CMAS / CAS systems, the dissolution rate constant increases as the viscosity difference between interface and solvent melt decreases. In the case of  $\text{Al}_2\text{O}_3$  addition to the solvent melt, although calculated viscosities for melts at the interface of dissolving sapphire are an order of magnitude or more lower than expected from experimental data, the rate constant for dissolution of alumina in simple melts in the CAS system is still correlated with viscosity such that as the structural difference between interface and solvent declines, the dissolution rate increases. Taken as a whole, these data indicate that there is a maximum possible dissolution rate when the viscosity difference is zero and no structural rearrangement is required. This should correspond to the rate of interface reaction. Furthermore, the observed relationships suggest that this is a promising approach to a method for calculations of dissolution rates which might mirror the recent advances in calculation of melt viscosity.

## THE ELUSIVE SECOND BEND OF THE CANTABRIAN ARC

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The Variscan orogen of NW Iberia doubles back on itself through a 180-degree hairpin-like bend, the Cantabrian arc. Coupled structural and paleomagnetic analysis have shown that the bend developed by vertical axis rotation of an originally linear orogen. However, palinspastic restoration of the orocline has proven difficult owing to (1) an unusually great orogenic width of over 700 km in strike across Iberia and (2) exposure of shallow water strata of the Gondwanan margin in both the northern and southern portions of the orogen, a hindrance in determination of the original direction landward toward the Gondwanan foreland. Here we present new paleocurrent data collected from Lower Ordovician (Arenig) shallow marine clastic sedimentary rocks across the Variscan of Iberia. Our aim was to further constrain palinspastic restoration by using the collected paleocurrent data to determine the oceanward facing direction throughout the orogen. Our data reveal the Variscan orogen of Iberia to be deformed through a second and more southerly orocline, less conspicuous than its north-

ern counterpart. Together, the Cantabrian and Central Iberian arcs define an s-shaped orocline pair of continental scale. Recognition of the southern orocline explains the unusual width of the orogen, is consistent with available structural data and the known distribution of shallow water strata of the Gondwanan margin, and also explains the geometry of aeromagnetic anomalies attributable to Variscan rocks.

## STRIATION RECORD OF MULTIPLE GLACIAL FLOW DIRECTIONS IN THE SOUTHERN QUEBEC APPALACHIANS

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Most bedrock lithologies in the southern Appalachian Mountain region of Quebec are ideal for taking and preserving glacial striations. Merging data from over 900 outcrops in this region has led to the development of a regional ice flow history based on multiple striation directions, two or more often preserved on the same outcrop. At each striation site, a chronological identifier was assigned to each direction encountered, whether or not direction and age relationships were unequivocal. The large number of outcrops that bear striations with clear directional indicators and unequivocal age relationships make the relative age determinations very reliable. Given the considerable relief and outcrop-scale roughness of the glacial bed in this area, there was surprisingly little evidence of even minor deflections of flow by either large-scale or small-scale topography. Although instances of as much as 90° of flow deflection were noted on individual outcrops, these were extremely rare, occurring on less than 1 percent of the outcrops examined. In addition to the detailed history of ice flow events revealed, the distribution of different directions in valleys and uplands and on individual outcrops yields insights into the behaviour of the striating ice.

There are seven distinct striation events or phases documented from this area, and they are, from oldest to youngest: 1) southwestward (~220°), 2) southeastward (135±5°), 3) east-southeastward (100±10°), 4) southeastward (135±10°), 5) northward (000±10°), 6) northwestward (340±10°) or northeastward (030±15°), and 7) east-southeastward (090-110°).

Though Wisconsinan-age deposits comprise two packages of glacial and proglacial sediments in this region, the earliest being deposited during the Chaudière Glaciation and the latest during the Lennoxville Glaciation, all but the first southwestward and southeastward striae (phases 1 and 2) are thought to have been formed under Lennoxville ice.

Late in the Lennoxville Glaciation, ice flow from north of the St Lawrence River was deflected down the St Lawrence Valley, cutting off ice supply south of the River and creating a remnant ice mass in which the east-west-trending Quebec Ice Divide developed, north of which flow was northward, toward the St. Lawrence Valley. Glacial striae indicating flow toward 000° (±10°) (phase 5) are ubiquitous north of the divide. The southeastward striae of phase 7 are thought to have formed when Laurentide ice readvanced to the Highland Front Moraine position and up the Chaudière Valley during a late glacial pulse.

## LOOKING FOR LIFE IN LOS ANGELES: ASTROBIOLOGICAL CHARACTERIZATION OF THE LA 002 MARTIAN METEORITE

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Evidence of microbial life in terrestrial basalts and other volcanic rocks has been identified by the presence of various biosignatures. Microbial life on Earth is ubiquitous and biosignatures left behind

(ie: morphological, chemical, mineralogical, etc.) are dependent upon the environmental conditions which persisted while life grew and thrived. Terrestrial basalts are analogous to much of the Martian surface, as evidenced by the composition of known Martian meteorites and surface measurements from recent rover missions. Martian basalts offer a plausible habitat for microbial communities to survive in if Mars hosted life at some point in its history. Previous work on the astrobiological potential of Martian meteorites is highly controversial and generally accepted as inconclusive. Preterrestrial aqueous alteration of Martian meteorites is also a controversial topic, and one that is poorly constrained for many Martian samples. Further understanding of the nature of these processes through detailed study of alteration products will allow us to elucidate more completely the history of water on Mars and the role that the solid subsurface has played in the evolution of Mars through time. The basaltic shergottite sample Los Angeles 002 has been characterized petrologically and mineralogically in order to ascertain its potential of having been a habitable environment for life and hosting biosignatures. A suite of analytical techniques was employed to study distinct mineral phases as well as alteration materials, including electron microscopy, in situ micro-XRD and geochemical analyses. Comparison of preliminary work with published literature suggests that the Los Angeles meteorite differs significantly from modern terrestrial subaqueous basalts, which has implications for both the future astrobiological study of Martian meteorites and in situ studies of ancient Martian environments.

#### **TERRESTRIAL TECHNIQUES FOR PLANETARY APPLICATIONS**

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Prospecting for terrestrial ore deposits relies on numerous methods ranging from large scale geophysical surveys to smaller scale geochemical sample analyses. Exploration entails physical methods, such as remote sensing and seismic or gravitational surveys to evaluate the surface and subsurface of the Earth to detect or infer the presence of valuable deposits. Geoscientists use 3D modeling to determine the geometry and placement of these deposits.

In January 2010, the Northern Centre for Advanced Technology, Inc. (NORCAT) demonstrated the use of a 3D model for use in planetary exploration during an analogue field test at approximately 9000 ft elevation on the slopes of Mauna Kea in Hawaii. This activity was meant to mirror a lunar In Situ Resource Utilization (ISRU) mission where robotic precursors are deployed and must survey the surroundings to allow ground operators to select a suitable location to begin construction of a landing site for future lunar modules. It is necessary to ensure the excavation activity is only attempted in a location where the task is within the operational capability of the mobility platforms. The 3D model was created from surface data acquired by an appropriate vision system for potential use in a permanently shadowed crater on the moon, requiring little to no light (Neptec Design Group's TriDAR) and subsurface data acquired by Ground Penetrating Radar (GPR). The data were processed by a hybrid processing component (Xiphos Technologies, Inc. 3Di Hybrid Processor Card (HPC)) embedded on board the TriDAR, for transmission over a limited bandwidth communications link. A remote operator accessed and fused the datasets to create the 3D model. An explicit set of geotechnical criteria applied to the data enabled the operator to effectively

determine the suitability of the location for continued work, such as construction or excavation.

This presentation will describe NORCAT's 3D model and discuss its potential to enhance overall effectiveness for ISRU prospecting. The focus will be on the addition of space based datasets into the model, specifically a method of implementation and its proposed evolution into an on board, autonomous decision making process. Data implementation into the model is especially important due to the fact that data must be transmitted over limited bandwidth communications links. The end objective is to evolve mission/sortie planning capabilities by a remote operator through the use of the interactive 3D model.

#### **BIOGEOCHEMICAL ORIENTATION SURVEY OVER CARBONATITE-HOSTED Ta-Nb DEPOSIT, BLUE RIVER AREA, BRITISH COLUMBIA**

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This survey shows that coniferous trees are suitable sampling media in the exploration for carbonatites and related rare earth elements (REE), Ta, Nb, phosphate and fluorapatite mineralization.

Twenty four samples of twigs with needles from Subalpine Fir (Fir) and White Spruce (Spruce) were collected over the Upper Fir carbonatite and surrounding amphibolites and paragneisses. Twigs and needles were analyzed separately. Twigs were milled using a Wiley mill and resulting pulps were digested in HNO<sub>3</sub>, then Aqua Regia and then analyzed by ICP-MS/ICP-ES. Twenty four samples of needles were ashed and submitted for ICP-MS/ICP-ES analysis after Aqua Regia digestion.

Light rare earth elements (LREE), Y, Zr and P in both twigs and needles are good exploration vectors for carbonatite-related REE and apatite mineralization. Concentrations of heavy rare earths (HREE) are near or below the detection limit. The highest concentrations of REE are detectable directly over the carbonatite. Chondrite-normalized plots of vegetation samples show negative Eu anomalies.

Ta is found in detectable concentrations only in twigs, in samples spatially related to carbonatite. Detectable Ta concentrations range from 0.001 to 0.003 ppm. Nb concentrations range from 0.02 to 0.24 ppm Nb in Spruce twigs, 0.005 to 0.071 ppm Nb in Spruce needles (dry weights normalized), and 0.012 ppm to 0.030 ppm in Fir needles (dry weight normalized).

Spruce twig data show positive correlations between Fe, REE and Zr; and Nb correlates positively with Fe, Ti, Ce, and Nd. Fir twigs were not analysed.

Spruce needle data show strong positive correlation between P, Mg and Ti; moderate correlation between P and Ca; and strong correlation between Nb and REE, Zr and Fe.

There are not enough Fir needle samples for formal statistical analysis; however, strong correlations between Fe and REE, Fe and Ti and also P and Zr are suspected.

#### **DEFINING THE LIMITS OF THE CONTINENTAL SHELF: INTERPLAY OF SCIENCE AND LAW**

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The result of several years of negotiations, the United Nations Convention on the Law of the Sea of 1982 recognizes certain exclusive rights for coastal States over the continental shelf up to 200 nautical miles (M), and beyond if specific criteria are met. More specifically, article 76 of the Convention provides the rules under which the parties to the Convention are to delineate the outer limits of their continental shelf beyond the 200M exclusive economic zone. The article is the result of international compromise,

part of the “package deal” contained in the Convention’s 320 articles and several annexes, dealing with all aspects of the law of the sea.

Article 76 also involves a unique amalgam of law and science. The rules of article 76 on how to define the outer limits of the continental shelf have been described as “dreadfully complex” ... for the international lawyer. On the other hand, the scientist finds familiar concepts such as the continental shelf being defined in unfamiliar ways. The provisions of article 76 dealing with ridges have been called an “enigma”. The Commission on the Limits of the Continental Shelf, which is a body of scientists, has been given the task to apply these provisions and provide recommendations to coastal States on the outer limits of their shelf.

This paper will trace the historical and legal developments that have led to article 76 and its definition of the continental shelf. It will provide an overview of the legal framework of rights and obligations that pertain to the continental shelf. It will explain the article 76 process, and address some of the difficulties mentioned above. It will also touch on how international law deals with potential disputes over areas of extended continental shelf.

#### **THE SIGNIFICANCE OF A LONG-LIVED CRUSTAL FAULT SYSTEM ON OROGENIC GOLD MINERALIZATION: THE LAPA GOLD DEPOSIT, ABITIBI GREENSTONE BELT**

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The Lapa gold deposit (1.1 Moz of Au @ 8.8 g/t Au) is one of the few deposits located directly within the Cadillac-Larder Lake Fault Zone (CLLFZ), a first order crustal scale fault that separates the Abitibi Greenstone Belt to the north and the Pontiac Subprovince to the south. This fault was active over a long period of time, marked by numerous episodes of deformation, metamorphism and fluid flow. The Lapa deposit is characterized by a number of features that are compatible with orogenic gold deposits including: (1) deformed and metamorphosed host rocks, (2) low sulphide content, (3) abundant quartz veinlets, and (4) spatial association with transpressional or compressional structures (e.g. CLLFZ). However, this deposit differs by being hosted directly within the CLLFZ.

Ore zones are vertically continuous from 400 to 1400 m in depth and occur mainly along the greywacke (e.g. Cadillac Group) and ultramafic schist (e.g. Piché Group) contact. Host rocks comprise strongly altered and foliated units, metamorphosed from upper greenschist to lower amphibolite facies. Near the contact, several mafic, felsic and sedimentary centimetric to decimetric fragments are distributed within the ultramafic schist. These fragments are the result of the strong transposition of host units along the principal foliation Sp, resulting in the development of asymmetric Z-shape decimetric to metric drag folds along the Cadillac-Piché contact. Gold mineralization occurs mostly as disseminated sulphides (arsenopyrite-pyrrhotite ± pyrite) and as native gold in deformed quartz ± carbonate veins and veinlets and their alteration selvages.

Textural and mineralogical relationships in the host rocks of this gold deposit show evidence of several events, including: (i) three deformation increments (D<sub>1</sub>, D<sub>2</sub> and D<sub>3</sub>); (ii) three metamorphic episodes (M<sub>1</sub>, M<sub>2</sub> and M<sub>3</sub>), and (iii) two gold mineralization phases. Furthermore, timing relationships demonstrate that the first gold mineralization stage, corresponding to the disseminated auriferous arsenopyrite, is syn- to post-D<sub>1</sub> and pre-peak of M<sub>2</sub> metamorphism. Whereas the second gold episode, associated with deposition of native gold, is characterized by progressive gold en-

richment initiated during the M<sub>2</sub> metamorphic peak and continued during the M<sub>3</sub> retrograde metamorphic event.

The complex relationships between ore, structural features and metamorphic assemblages indicate that gold mineralization formed during a protracted history of precipitation and remobilization, a feature not typical of classical orogenic gold deposits. However, this can be related to the complex deformation and metamorphism recorded by the CLLFZ, which were induced by the successive variations in tectonic regime, crustal level, heat flow and fluid flow. The Lapa gold deposit was upgraded during its protracted tectonic history, demonstrating that gold concentration within the CLLFZ may have required late gold enrichment to transform an uneconomic deposit into an economic one

#### **RADARSAT 2 POLARIMETRIC SCATTER OF GEOLOGICAL UNITS AT HAUGHTON CRATER**

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The Haughton Crater, as a CSA/NASA Mars analogue site, has been the focus of several geological investigations. Recent geological mapping of the Haughton Crater on Devon Island has shown that the crater is a well-preserved impact structure. A thick sequence of Lower Paleozoic sedimentary rocks of the Arctic Platform, overlies Precambrian metamorphic basement of the Canadian Shield. The sedimentary succession consists of thick units of dolomite and limestone, with subordinate evaporite horizons and minor shales and sandstones. Pale gray-weathered crater-deposits possess a matrix of calcite and silicate-rich glass which covers the central area of the structure. Recent work has shown that the high Si and Al content of calcite and micro-textural evidence indicate that the carbonate silicate matrix was originally a melt.

In this paper we investigate the uses of RADARSAT 2 polarimetric images to discriminate these well preserved mapped units. Our results show that the polarimetric scatter of the crater deposit is considerable different from the surrounding limestone and dolomite units. There is a 5 db difference between the crater-filled deposits and the surrounding units from the RADARSAT VV and HH backscatter. This difference is mainly due to the surface roughness of the respective units. Based on these characteristic roughness differences we used several decomposition and ratio techniques of the RADARSAT 2 HH, HV VV and VH polarimetric images. Our resulting image maps of the impact structure coincide well with the known geological units. These enhancements of RADARSAT 2 polarimetric images may be useful to characterise the melt sheets other well-preserved impact craters.

#### **BOTTOM WATER REDOX CONDITIONS DURING Zn-Pb AND PHOSPHATE MINERALIZATION, HOWARDS PASS DISTRICT, YUKON TERRITORY**

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We report here the first detailed multi-proxy trace-element study of secular variations in the redox state of bottom waters during formation of a sediment-hosted Zn-Pb deposit. Stratabound sulphide deposits of the Howards Pass district in eastern Yukon occur in the Middle Ordovician-Early Silurian Duo Lake Formation (DLF), which tectonically overlies limestone-rich strata of the Ordovician Rabbitkettle Formation and conformably underlies bioturbated dolomitic mudstone of the Silurian Steel Formation. From base to top, the DLF in the district comprises four members: pyritic mudstone, calcareous mudstone, active (Zn-Pb), and upper siliceous mudstone. Sulphide lenses in the active member consist

of layered, laminated, and massive sphalerite  $\pm$  galena, variably deformed by shears and mylonite zones. Pyrite forms thin laminae of fine-grained framboids; apatite is generally minor. The upper siliceous member contains black mudstone with cherty intervals and locally abundant, 0.1–1.5-cm-thick laminae of apatite and/or subordinate limestone.

Whole-rock analyses have been obtained for Zn- and Pb-poor mudstone from two drill cores in relatively undeformed parts of the XYZ ( $n = 28$ ) and HCW ( $n = 15$ ) deposits. Black mudstones of the DLF contain variable silica (to 90 wt %  $\text{SiO}_2$ ) and carbonaceous material (to 16 wt % TOC). Among redox-sensitive trace elements, V concentrations are high in the upper siliceous member (800–3000 ppm). Calculated marine fractions are used to determine Cr/Mo, V/Mo, and Re/Mo ratios, which reflect redox conditions in bottom waters, not pore waters. Similar trends are shown by all three ratios. Re/Mo ratios, considered the best proxy, record sulphidic or anoxic conditions ( $\text{Re/Mo} < 0.001$ ) during deposition of the calcareous mudstone and active members; these conditions existed in the basin prior to and during Zn-Pb mineralization, thus aiding accumulation and preservation of sulphides. Re/Mo ratios are mostly higher (0.004–0.013) in the upper siliceous member and lower Steel Formation, indicating suboxic ( $< 5 \mu\text{M O}_2$ ) bottom waters. Initiation of suboxic conditions in the upper siliceous member promoted deposition of abundant phosphate, based on analogy with modern phosphate precipitation in suboxic bottom waters of the Peruvian and Namibian shelves. In contrast to previous workers, we propose that the phosphate-rich nature of this member reflects upwelling of nutrient-rich waters and not hydrothermal P mineralization. Lithologic similarity to the Monterey Formation (Miocene) of coastal California suggests that the DLF and contained Zn-Pb deposits formed in a restricted basin near a continental margin, accompanied by high productivity required for the accumulation of abundant phosphate, biogenic silica, and organic matter.

#### MAJOR AND TRACE ELEMENT CHEMISTRY OF PERIDOTITIC XENOCRYSTS FROM THE VICTOR KIMBERLITE, SUPERIOR CRATON

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The Victor kimberlite, the first diamond mine on the Archaean Superior craton and in Ontario, provides the unique opportunity to study the association of a diamond deposit with a post-Archaean rift system (the 1.1 Ga Keweenawan Midcontinent Rift). Victor forms part of the Attawapiskat kimberlite cluster, which was emplaced at ca. 170–180 Ma subsequent to the Midcontinent Rift. Details of the history and composition of the lithospheric mantle below the Superior craton are not well constrained, due to a general scarcity of mantle xenoliths. In particular, the impact of the 1.1 Ga Keweenawan Midcontinent Rift on diamond-bearing lithospheric mantle beneath the Superior Craton is poorly understood. Previous work on garnet xenocrysts from the Kyle Lake (~1.1 Ga) and Victor kimberlites indicate that the local lithospheric mantle was modified to lherzolitic compositions after emplacement of the Kyle Lake kimberlites, possibly through melt infiltration associated with the Midcontinent Rift.

Here we present initial major and trace element results from a suite of xenocrysts from the Victor kimberlite, comprising olivine, orthopyroxene, clinopyroxene and garnet. Olivine with two distinct colours and compositions were analysed – green olivine with a more depleted composition ( $\text{Mg\# } 0.90 - 0.94$ ) and brownish-green olivine with less depleted compositions ( $\text{Mg\# } 0.89 - 0.91$ ). Geothermobarometry on Cr-diopsides yielded a local ge-

otherm equivalent to ~38 mW/m<sup>2</sup> surface heat flow at 180 Ma, cooler than the geotherm calculated for Kyle Lake (~44 mW/m<sup>2</sup> at 1.1 Ga).

Garnet xenocrysts have lherzolitic compositions with Cr-in-grt barometry indicating their origin in the shallow lithosphere ( $< 4$  GPa). Garnet REE patterns normalised to a primitive mantle garnet composition (REE J4) as well as Y and Zr contents of garnet record both depleted compositions and metasomatic overprint. Depleted garnets have low Y and Zr contents ( $< 5$  ppm and 25 ppm, respectively) and are HREE depleted with positive Er J4 – Yb J4 slopes. Garnets with metasomatic overprint show increased Y and Zr and are enriched in LREE. Garnets considered to be melt metasomatised have MREE to HREE of primitive mantle garnet abundance. These results indicate that the shallow lithosphere below this portion of the Superior craton has been significantly modified by both pervasive fluid and melt metasomatism. The nature of these metasomatic agents will be further constrained through Hf, Nd and Sr isotope analyses.

#### FLUID INCLUSION COMPOSITIONS IN ARCHEAN FIBROUS DIAMONDS FROM WAWA, ONTARIO

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Fibrous diamond is a distinct variety of diamond that has grown along radiating fibers. It is typically turbid or opaque due to a high content of fluid and/or mineral micro-inclusions. Studies of fluid inclusions in fibrous diamonds from around the world reveal two main compositional trends: a silicic to low-Mg carbonatitic trend and a saline to high-Mg carbonatitic trend. The fluids in most fibrous diamonds are Phanerozoic, having been trapped shortly before eruption of the host kimberlite. Relatively unaggregated nitrogen contents in fibrous diamond support this by indicating short mantle residence times.

We have used electron microprobe and secondary electron microscopy to analyze the composition of inclusions in a suite of fibrous diamonds from a metaconglomerate in the Michipicoten Greenstone Belt near Wawa, Ontario, Canada. The primary source of these diamonds may have been the nearby diamondiferous lamprophyre dikes and volcanic breccias or eroded kimberlites. These samples are the likely the oldest fibrous cuboids and fibrous diamond coats studied so far.

The micro-inclusions in Wawa fibrous cuboid diamonds are distinct from micro-inclusions in fibrous coats on octahedral diamonds. The fibrous diamond coats from Wawa have saline compositions that are similar to those from the Diavik and Koffiefontein Phanerozoic kimberlites. The Archaean mantle was capable of producing saline fibrous diamond-forming fluids with the same composition as those produced in the Phanerozoic. The average molar composition is 39.7% Cl, 29.4% K, 12.4% Na, 4.8% Ca, 4.7% Ba, 4.1% Mg, 3.6% Fe, and 1.3% Si (excluding H, C, and O). Other elements are below the detection limit in most or all fluid inclusions analyzed.

Fibrous cuboid diamonds from Wawa do not exhibit the same saline-rich fluid inclusions. Instead, these samples are dominated by single-phase mineral micro-inclusions of forsteritic olivine, and lesser amounts of garnet and Mg-chromite. The same peridotitic suite dominates larger mineral inclusions in octahedral Wawa diamonds. The cuboids also contain variable contents of volatile-dominated inclusions, which manifest as empty cavities on polished faces. The cavities range in size from sub-micron to tens of microns and are bound by diamond {111} surfaces. The contrasting character of micro-inclusions in coats and cuboids may indicate the involvement of a different kind of diamond-forming fluid. Alternatively, the fibrous cuboids might have grown from

the same fluid if a separate factor affected the way inclusions were incorporated. Perturbing factors could be temperature, pressure, carbon supersaturation, or any factor that could alter growth and fluid–crystal interaction.

#### PALEOCLIMATE OF EARLY EOCENE BRITISH COLUMBIA FROM ANALYSIS OF THE FALKLAND AND QUILCHENA MACROFLORAS

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The Falkland and Quilchena sites in the southern interior of BC are two of several Okanagan Highlands (OH) fossil floras now known to date mostly to the Ypresian (Early Eocene). These fossil sites are rich in both insect and plant remains, offering multiple paleoclimate proxies and information about the character of the forest communities that surrounded these Eocene lakes. Volcanic ashes interbedding the fossiliferous shales at Quilchena and Falkland are dated radiometrically at  $51.5 \pm 0.4$  Ma and  $50.61 \pm 0.16$  Ma, which places these 2 floras at the middle and end of the Early Eocene Climatic Optimum (EECO), a significant hyperthermal episode 2–3 million years in duration associated with atmospheric carbon dioxide levels ( $p_{CO_2}$ )  $> 2 \times$  Holocene values (i.e.  $p_{CO_2} > 800$  ppm). Both leaf-physiognomic analysis of dicot leaves and bioclimatic reconstructions using a nearest living relative (NLR) approach have determined that the paleoclimate of Quilchena was both the warmest and wettest of the OH sites of similar age, with Falkland showing a secular decline in both temperature and  $p_{CO_2}$  up-section, consistent with its stratigraphic position at the waning phase of the EECO. The majority of the OH floras are interpreted as having little temperature seasonality. While other fossil floras from this upland region, including Falkland, are classified as microthermal ( $MAT < 13^\circ C$ ), Quilchena is warmer and falls within the mesothermal category ( $\sim 15^\circ C$ ), consistent with its stratigraphic position at the middle of the EECO. The presence of thermophilic taxa used in the NLR climatic analysis of Quilchena is confirmed by reproductive organs of taxa such as *Glyptostrobus*, *Taxodium*, *Pseudolarix*, *Sequoia*, *Keteleeria*, *Eucommia*, *Dipterocarpus*, and others. Rarefaction analyses of plant diversity at these sites corroborates recent analysis of insect diversity at the McAbee OH site, showing tropical-style diversity for both Falkland and Quilchena. High diversity at these sites is not, however, associated with tropical-character temperature regimes, but rather a novel combination of moderate temperatures and mild winters. As chronologies of other localities become better constrained, it is hoped that a time series of climate and vegetational changes will be developed that will assess the impact of the changes surrounding the warmest interval ('hyperthermal') of the Cenozoic. A comparison of Quilchena and Falkland with other OH floras such as Republic, Princeton, McAbee, Thomas Ranch, and Driftwood Creek constitutes an opportunity to better understand the long-term consequences of climate warming and cooling on ecosystems.

#### DETERMINATION OF CERIUM SPECIATION IN SILICATE MELTS AND ITS APPLICATION TO THE Ce IN ZIRCON OXYBAROMETER

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As with all rare earth elements (REEs), cerium commonly forms stable 3+ ions. What is unique to Ce among the REEs is that it can also form stable 4+ cations. Using the standard state free energies

of the component oxides, speciation calculations for cerium suggest that under the range of conditions common to terrestrial magmas both  $Ce^{3+}$  and  $Ce^{4+}$  are potential melt species. This is supported by the observation of Ce anomalies in some igneous phases including zircon. We have synthesized a series of Ce doped glasses ranging in composition from basaltic to rhyolitic at 1 atm and 1 GPa under  $f_{O_2}$  conditions varying from FMQ -10 to FMQ +9.6 and temperatures between 1100 to 1400°C. Determination of the  $Ce^{4+}/Ce^{3+}$  ratio in the experimental run products was carried out using Ce M4,5-edge X-ray absorption near-edge structure (XANES) spectroscopy in the region of 870 to 920 eV. For a given melt composition the change in  $Ce^{4+}/Ce^{3+}$  ratio with  $f_{O_2}$  follows the trend predicted from the reaction stoichiometry. In addition to  $f_{O_2}$  we have found that melt composition exerts a significant control on Ce speciation, with large increases in the proportion of  $Ce^{4+}$  accompanying increased melt polymerization. The  $Ce^{4+}/Ce^{3+}$  ratio can be expressed through the equation

$$\log\left[\frac{Ce^{4+}}{Ce^{3+}}\right] = 1/4\Delta FMQ - 0.776(\pm 0.025)\log[NBO/T] - 2.78(\pm 0.11).$$

Changes in oxidation state, and subsequently ionic radius, will have significant effects on the partitioning behaviour of Ce between phases and has been suggested as the origin of elevated Ce concentrations, relative to its neighbouring REEs, which are nearly ubiquitous in zircon. If the parent melt composition is known, the  $f_{O_2}$  can be estimated from the magnitude of the Ce anomaly with knowledge of the D-values for  $Ce^{3+}$  and  $Ce^{4+}$ . Application of these results to zircons from the Bishop tuff, California, and Toba tuff, Indonesia, give  $f_{O_2}$  values in broad agreement (though systematically lower) with those determined from Fe-Ti oxides.

#### A CRATON'S EDGE

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Cratons are traditionally defined as the cores of continents characterized primarily as the strongest parts of the lithosphere. Also relatively buoyant, it is their depleted composition and relatively cooler temperatures that provide higher viscosity and mechanical strength. Deep-probing geophysical seismic and magnetotelluric methods typically used for exploration are sensitive to both of these physical properties and both have thus been used to estimate the lateral and depth extents of cratons. Deep seismic reflection profiling sensitive to more localized physical property contrasts, has revealed the geometries and overall architecture of component geological structures of cratons and produced cross sections with interpretations of serrated or inter-wedged cratonic boundaries. Lithoprobe's SNORCLE line 1 is an excellent example and shows the Archean Slave craton wedged into accreted Paleoproterozoic lithosphere at both crustal and uppermost mantle levels. Subsequent teleseismic and magnetotelluric surveys across this same margin reaffirmed these geometries but have also demonstrated similar structure to the southeast across the Great Slave shear zone where near-vertical structures were traditionally assumed. This serrated boundary and wedge structure has important implications in that younger crustal terranes mapped at the surface are underlain, sometimes with several hundred kilometres overlap, by much older cratonic mantle lithosphere. This overlap has also been deduced by geochemical surveys using Nd and other isotope ratios. To date, only a few such deep cross sections across craton margins exist in Canada, but these few suggest that vertical boundaries should be hypothesized only where compelling evidence exist for such structures. In most cases, cratons are similar to the mechanically equivalent icebergs in having much greater lateral extent at depth than at the surface.

## USE OF IMAGING TOF-SIMS FOR THE STUDY OF SMALL FEATURES IN GEOLOGICAL SAMPLES – APPLICATION TO THE STUDY OF EXPOSED MELT INCLUSIONS

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Time-of-Flight Secondary Ion Mass Spectrometry (ToF-SIMS) has emerged as an important, versatile surface analytical technique for study of many different types of materials research. This arises from its excellent spatial resolution (down to 100 nm), high mass resolution and sensitivity resulting in both chemical and distributional (laterally and depth) for a wide variety of materials and applications. Recently, we have applied this technique to the study of melt inclusions, tiny portions of silicate melt and gases trapped inside crystals during their growth in magmatic environments. This provides a valuable geological tool for understanding the evolution of magmas and the source of metals for some ore deposits. While ToF-SIMS yields chemical and molecular information from the surface, it is highly matrix dependent and, furthermore, to achieve either high mass or high spatial resolution is at the expense of the other. Thus understanding the various modes of operation and the information that each provides is crucial to the analyst in order to optimise the type of data that is obtained. In this paper, we will discuss the various aspects and methodologies the geologist needs to address in order to extract the most information from these small features. This will include aspects of sample preparation, choice of ion source or combination thereof for both pre-cleaning and data collection, which mode the primary gun is to be operated in – for high mass resolution, high spatial resolution or a compromise, and finally the choice of appropriate standards to obtain good quantitative results for selected major and trace elements. It will be seen that with the versatility of most modern state-of-the-art ToF-SIMS instruments and the combination of the various modes of operation that a wealth of information can be obtained from such studies.

## THE EXPLORATION OF MERCURY BY THE MESSENGER SPACECRAFT

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NASA's MESSENGER spacecraft flew by Mercury three times in 2008-09 en route to insertion into orbit about the planet in March 2011. The flybys confirmed that the planet's internal magnetic field is dominantly dipolar, with a vector moment closely aligned with the spin axis. MESSENGER detected Mg and Ca<sup>+</sup> in Mercury's exosphere, demonstrated that Mercury's anti-sunward neutral tail contains multiple species, and revealed that exospheric Na, Ca, and Mg vary differently with space and time, signatures of multiple source processes. MESSENGER's laser altimeter showed that the equatorial topographic relief of Mercury exceeds 5 km, revealed an equatorial ellipticity aligned with the ellipticity in Mercury's gravitational potential, and profiled numerous impact craters and fault scarps. MESSENGER images provided evidence for widespread volcanism, and candidate sites for volcanic centers were identified. Newly imaged lobate scarps and other tectonic landforms support the hypothesis that Mercury contracted globally in response to interior cooling. The ~1500-km-diameter Caloris basin was a focus for volcanic centers, some with evidence of pyroclastic deposits, and widespread contractional and extensional deformation; smooth plains interior and ex-

terior to the basin postdate the basin-forming event. The interior plains of the ~290-km-diameter Rachmaninoff basin are among the youngest volcanic material on the planet. Mercury surface units are distinguishable by color and composition; smooth plains occupy ~40% of the surface area, and low-reflectance material occupies ~15% of the surface area and is primarily seen in deposits excavated by impact. Reflectance spectra show no evidence for FeO in surface silicates, and reflectance and color imaging observations support the view that Mercury's surface material consists dominantly of Fe-poor, Ca-Mg silicates with an admixture of spectrally neutral opaque minerals. In support of the hypothesis that those opaque minerals are Fe-Ti oxides, thermal neutron measurements indicate that the surface abundance of Fe plus Ti is comparable to that of some lunar mare regions. MESSENGER's flybys revealed that Mercury's magnetosphere is more dynamic and responsive to imposed solar wind conditions than that of any other solar system body, and they showed that the planet often experiences conditions favorable to direct impact of solar wind plasma onto the dayside surface, an important contributor to Mercury's exosphere and space weathering of surface materials. MESSENGER's continuous operation for one Earth year in a near-polar orbit has enabled global observations of Mercury and its environment at higher spatial and temporal resolution than was possible during the flybys.

## GEOCHEMICAL BEHAVIOUR OF CESIUM RESIDUE LEACHATE IN A GROUNDWATER/TAILINGS SYSTEM

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A Cesium Products Facility (CPF) manufactures a cesium-formate drilling fluid from pollucite ore from the pegmatite at TANCO Mine, Manitoba. Waste slurry from the CPF process is initially discharged to double-lined containment cells before being dewatered, and dry-stacked on old mine tailings. Migration of the residue leachate from the residue appears to be slower than predicted from ground water studies. This research was initiated to investigate the geochemical interactions that may be slowing leachate migration and to predict whether there is a geochemical rather than physical rate-limiting effect on leachate migration from the residue placement area. The mobility of Ba, Ca, Li, Sr, and Cs were examined through mineralogical observations as well as a chemical analysis of water after a series of sequential extractions of the residue and tailings.

Lithium, Cs and Ba are mostly immobile in the mine tailings in spodumene (LiAlSi<sub>2</sub>O<sub>6</sub>), pollucite ((CsNa)<sub>2</sub>[Al<sub>2</sub>Si<sub>4</sub>O<sub>12</sub>]) and barite (BaSO<sub>4</sub>), which remain after ore processing. Most Rb and K were found to be in residual alkali feldspar in both the residue and tailings. Gypsum (CaSO<sub>4</sub>·2H<sub>2</sub>O) precipitated in the residue. Cesium from the residue and Sr in both the residue and tailings were much more mobile.

## DIVERSE MINERALIZATION AND ALTERATION STYLES AT THE PITARRILLA, SILVER-ZINC-LEAD DEPOSIT, SIERRA MADRE OCCIDENTAL, MEXICO: AN EXAMPLE OF A VERTICALLY ZONED MAGMATIC-HYDROTHERMAL ORE SYSTEM

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The Pitarrilla Ag-Zn-Pb deposit is a vertically zoned ore system comprising iron oxide- and sulfide-associated mineralization. The former occurs as a laterally extensive semiconformable cap, whereas the latter occurs as a discordant zone of disseminated and



veinlet, semi-massive replacement, and massive sulfide vein mineralization.

The disseminated and veinlet sulfide mineralization forms an areally restricted, but vertically extensive stockwork zone, which is centered on a felsic dike complex. The replacement mineralization is restricted to limestone clast-bearing conglomerates at the Cretaceous-Eocene unconformity where sulfides preferentially replaced limestone clasts. Sharp-walled and breccia massive sulfide veins immediately overlie the semi-massive replacement mineralization. The sulfide-associated mineralization grades upward into a laterally more extensive zone of semiconformable, disseminated and fracture-controlled silver and base metal mineralization that is hosted by Oligocene felsic sills, dikes, and volcanic strata.  $\delta^{18}\text{O}$  data suggest that low temperature hydrothermal alteration of the base and precious metal sulfide mineralization resulted in the iron oxide-associated mineralization.

Fluid inclusion analysis indicates the presence of L-rich and V-rich aqueous inclusions in vein quartz and sphalerite with L-V-Halite types confined to microcrystic quartz hosted by a felsic dyke from deeper in the system. Thermometric data indicate a continuum in both Th and salinity values from about 300°C and 14 wt percent NaCl equivalent to 150°C and 0 wt percent NaCl equivalent. These data suggest that mixing with meteoric water was the dominant process that resulted in base metal and silver precipitation, with lesser importance attributed to boiling.

The restricted lateral extent and vertical stacking from iron carbonate and chlorite ( $\pm$  sericite) at depth, upward to tourmaline and argillic alteration is interpreted to define a crudely discordant alteration pipe that also contains the bulk of the sulfide- and iron oxide-associated mineralization. This alteration pipe is surrounded by broad, laterally extensive, semiconformable zones of propylitic and weak argillic alteration. Tourmaline alteration is not typical of epithermal deposits, but may represent the high-level product of an earlier and deeper porphyry system that was overprinted by a silver and base metal-rich, magmatic hydrothermal system.

#### **EFFECTS OF RECHARGE UNCERTAINTY ON PREDICTIONS OF WELL RESPONSE TO CHANGES IN LAND USE**

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Groundwater models are widely applied to support source water protection decisions. In these models, recharge is a very important parameter. It plays a critical role in replenishing aquifers and transporting or diluting contaminants. Recharge varies spatially and temporally and it is of relatively difficult characterization in the field, especially in large-scale studies. Because of this difficulty, often practitioners rely on recharge distributions obtained using only scarce or even none-field-based recharge estimates. Usually there is a great deal of uncertainty involved in these recharge estimations. In practice, this means that several alternative recharge distributions for the same site can be defined and it is impossible to identify the "correct" one. To assess the effects of recharge uncertainty in groundwater model results, three models were developed using distinct recharge spatial distributions obtained using alternative approaches and model codes. These models were used to estimate potential changes in nitrate concentration at a water supply well induced by changes in farming practices. The site is located in the Waterloo Moraine, a glacial aquifer system located in Southern Ontario, Canada. These three models were calibrated to an acceptable fit through slight adjustments on hydraulic conductivity values, indicating the non-uniqueness of the model. Although calibrated to the same observation dataset, the models yielded significantly different capture zones and breakthrough

curves at the well. This work indicates that recharge distributions obtained by model calibration should be used with caution, as predictions obtained using these distributions are subject to significant uncertainty. This work also stresses the importance of an adequate recharge characterization, based on field data. The incorporation of more field measurements would constrain the possible alternative scenarios and consequently reduce prediction uncertainty.

#### **3D REGIONAL GEOPHYSICAL MODELING OF THE BAIE VERTE PENINSULA, NEWFOUNDLAND**

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The Baie Verte Peninsula records the closure of the Iapetus Ocean and a period of orogenic activity responsible for the creation of the Appalachian mountain belt. Bisected by the Baie Verte Line, a northeasterly trending composite fault zone, the Baie Verte Peninsula is divided into two major litho-tectonic terranes. West of the Baie Verte Line, are the remnants of the ancient continental margin of Laurentia. To the east are the Ordovician ophiolitic and island arc sequences of the Baie Verte Oceanic Tract (BVOT). These sequences are the vestiges of the narrow Humber Seaway, which were accreted to Laurentia and subsequently intruded by a surge of Silurian magmatism. Past geophysical and geologic studies have interpreted a continental margin below the BVOT as a ramp or wedged structure with a slope dipping to the east. This study presents a series of 2D forward geophysical models of gravity and magnetic data, with intersections throughout, to provide a geophysically supported geologic framework of the Baie Verte Peninsula. 3D magnetic inversions provide additional support for some interpreted structures.

The results of this study indicate that basement morphology mirrors many surficial trends. In some instances, such as at Mings Bight, significant faulting has caused exposure of continental basement at surface. A similar phenomenon may explain near surface exhumation of ophiolite near Betts Cove. Geophysically the Snooks Arm and Pacquet Harbour groups are similar; these lithologies may underlie the Cape Brule Porphyry hosting an antiform within the vicinity of the Baie Verte Flexure. On a regional scale the Cape St. John volcano-sedimentary continental cover sequence comprises a series of overturned anticlines and synclines where late stage faulting may propagate fold limbs into their core. Finally, 3D magnetic inversions depict the Baie Verte Line as a near vertical conjugate fault zone that may have been dissected by late stage extensional faulting supported in many cross cutting west dipping structures.

#### **THE THERMO-TECTONIC EVOLUTION OF HOODOO DOME, ELLEF RINGNES ISLAND: IMPLICATIONS FOR SVERDRUP BASIN SALT TECTONICS**

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Over one hundred evaporite diapirs, cored by Carboniferous Otto Fiord Fm. reside along the Sverdrup Basin's axis in the Canadian High Arctic. However, due to the remoteness of this region their tectonic evolution and hydrocarbon potential remain poorly understood. This study focuses on one of the better known diapirs, Hoodoo Dome, located on Ellef Ringnes Island. We use ground-based geological mapping as well as (U-Th)/He thermochronology to better understand the thermal evolution of the rocks around the dome and tectonic influences on salt migration. Our goal is to im-

prove the understanding of thermal histories and hydrocarbon potential of the salt structures in the Sverdrup Basin.

The Sverdrup Basin is a steep sided pericratonic trough estimated to contain approximately thirteen kilometres of Carboniferous to Tertiary strata. At Hoodoo dome we collected sandstone samples from the Cretaceous Isachsen Fm. for (U-Th)/He thermochronology, a fairly new low temperature thermochronometric technique that yields cooling ages marking a sample's passage through the ~ 70°C isothermal surface. This complements recent studies conducted using legacy 1D seismic and well log back-stripping across Hoodoo Dome which were conducted to qualitatively answer questions regarding the rate, mechanism, and regional influence of diapirism during the Dome's development. Our results add new quantitative data regarding the ascent of the evaporite core as well as thermal histories for the rocks surrounding Hoodoo Dome. We hope that these data will provide insights into the timing and nature of the salt tectonic processes operating within the Sverdrup Basin in general.

#### **THE GEOLOGICAL SETTING AND USE OF GAHNITE AS AN EXPLORATION GUIDE IN THE SEARCH FOR METAMORPHOSED MASSIVE SULFIDE DEPOSITS – AN UPDATE**

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The use of gahnite as an exploration tool in the search for metamorphosed massive sulfide (MMS) deposits was probably first recognized by Frank Stillwell for the Broken Hill area, Australia, in the early 1920s. However, additional studies in the 1960s and 1970s reinforced the idea of its exploration potential by noting the spatial association between MMSs and gahnite. Although theoretical calculations were first made on the stability of gahnite in the late 1960s, it was Steve Scott in the late 1970s who initiated the only experimental study done on phase relationships between sphalerite and gahnite, as part of his studies on the effects of metamorphism on massive sulfide deposits that also involved silicate-sulfide-oxide relationships (e.g. chlorite) in and around such deposits.

Although gahnite is spatially associated with MMS deposits in Mg-Ca-Al alteration zones and in Fe-Al metasedimentary and metavolcanic rocks, it also occurs in marbles, skarns, quartz veins, metabasites, pegmatites, contact metamorphic aureoles, granites, unaltered Fe-Al-rich metasedimentary rocks, Al-rich granulites, and iron formations, and as resistate minerals in unconsolidated sediments (e.g. soils, glacial till). Such diverse geological settings for gahnite mean that its presence in a rock does not necessarily equate to close proximity to sulfides. High T-P reversed experiments showed that the composition of gahnite is dependent on P, T, and sulfur, oxygen, and water fugacities. Recent studies of the composition of gahnite in Mg-rich rocks in Colorado (second largest gahnite district in the world) show that some have a high spinel (*sensu stricto*) content. Utilizing these compositions, along with nearly all of the available major element compositions of gahnite in the literature, suggests that zincian spinel in Mg-poor and Mg-rich MMS deposits/alteration zones have the following compositions: gahnite45-90%hercynite0-45%spinel0-25% and gahnite0-65%hercynite0-50%spinel25-90%, respectively. However, compositional ranges are not a panacea for distinguishing gahnite in sulfide-free rocks from gahnite in or near MMS deposits because the major element composition of gahnite in the supergiant Broken Hill deposit, for example, is essentially the same as that for gahnite in minor BHT deposits (most of which are devoid of sulfides) in the Willyama Complex (largest gahnite district in the world). In an attempt to establish a better compositional fingerprint

for using gahnite as an exploration guide, major element and trace element compositions are being determined, using electron microprobe and laser ablation-inductively couple plasma-mass spectrometric techniques, by research groups at Iowa State, East Carolina, and Queen's Universities, the GSC, and the USGS.

#### **UTILIZING CATHODOLUMINESCENCE AND BACK-SCATTER ELECTRON IMAGING WITH U-Pb ZIRCON LAM-ICP-MS AGE DATA TO CONSTRAIN THE EVOLUTION OF THE KLUANE METAMORPHIC ASSEMBLAGE, SOUTHWEST YUKON**

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The poly-deformed Cretaceous Kluane metamorphic assemblage (KMA) is located at an important tectonic boundary in the northern Canadian Cordillera separating peri-cratonic rocks of Yukon-Tanana terrane to the east from exotic, oceanic rocks of Insular terrane to the west. The KMA is a 160-km-long northwest-striking biotite- to muscovite-quartz-rich schist that contains multiple overprinting tectonic fabrics. Numerous, well-exposed deformed and undeformed granitoid intrusions occur within and adjacent to the KMA. The KMA's location, large size, and relationship with pre-, syn, and post-kinematic intrusions make it critical to understanding how and when this portion of the Cordillera was amalgamated. This study aims to integrate cathodoluminescence (CL) and back-scatter electron (BSE) imaging of zircon, U-Pb zircon geochronology using laser ablation microprobe – inductively coupled plasma – mass spectrometry (LAM-ICP-MS), and micro- and macroscopic structural information of one migmatitic KMA sample and two granitoid samples to better constrain the deformational history of the KMA.

U-Pb zircon age data for an undeformed biotite-hornblende-tonalite dyke indicates that deformation of the KMA ceased by  $55.3 \pm 1.7$  Ma. This age corresponds to metamorphic rims ( $\text{Th/U} < 0.015$ ) surrounding xenocrystic zircon cores ( $\text{Th/U} > 0.133$ ) and, it overlaps with  $55.6 \pm 3.3$  Ma magmatic zircon grains from a larger, magmatically-foliated biotite-hornblende-diorite intrusion. The third sample is a biotite-rich migmatite that outcrops between the KMA to the west and the syn-kinematic, Early Paleogene granitoid Ruby Range Batholith (RRB) to the east. The migmatite has similar compositional (tonalitic leucosomes) and textural (well-developed schistosity) features to that of the RRB and the KMA, respectively. CL and BSE imaging of zircon grains from this migmatite reveal a suite of grains with  $65.6 \pm 2.5$  Ma metamorphic rims ( $\text{Th/U} < 0.006$ ) and populations of xenocrystic cores ( $\text{Th/U} > 0.017$ ) at  $92.2 \pm 4.5$  Ma and  $175.4 \pm 9.6$  Ma. This study reveals that the KMA experienced two distinct metamorphic events. The younger event is related to post-deformational granitoid intrusions while the older one is related to the larger syn-kinematic RRB.

#### **MINERALIZATION AND ALTERATION OF THE LATE TRIASSIC GLACIER CREEK Cu-Zn VMS DEPOSIT, PALMER PROJECT, ALEXANDER TERRANE, SOUTHEAST ALASKA**

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The Late Triassic Palmer VMS property, situated at the northern tip of Southeast Alaska is a significant new discovery within the well established, yet poorly explored Alexander Triassic metallogenic belt. The presently defined 4.75 Mt Glacier Creek deposit, averaging 1.84% Cu and 4.57% Zn, is hosted within four principal

lenses on both limbs of an overturned anticline, cut nearly along its axial plane by a thrust fault. Mafic, and locally felsic volcanic rocks of the Hyd and Tats groups host mineralization at Palmer, and much like the host rocks to other nearby Late Triassic deposits, such as the world class Greens Creek and Windy Craggy deposits, have undergone significant deformation. Intense, widespread alteration of the footwall, combined with multiple episodes of deformation has made stratigraphic correlation and targeting of ore a challenge. Detailed petrographic and geochemical analysis of the ore lenses and altered host rocks at Glacier Creek will help to simplify depositional and structural models, and aid further exploration at Palmer and within the belt. Identified ore zones remain open, and the property holds excellent potential for further VMS-style discovery.

#### **SULFUR BIOGEOCHEMISTRY OF OIL SANDS COMPOSITE TAILINGS**

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The Alberta oil sands companies face the difficult problem of remediating their composite tailings (CT) materials produced from the by-products of bitumen extraction from oil sands processing. In particular, high concentrations of hydrogen sulfide ( $H_2S$ ), a safety and environmental hazard, have been detected in CT, associated with dewatering processes; indicating the need to characterize sulfur biogeochemistry in these materials. In addition, a fen is currently being created over the CT deposit as a pilot reclamation project. Thus, the field and laboratory objectives are to establish the occurrence of S and Fe microbes within the sand cap underlying the developing fen as well as within CT over seasonal and annual timescales. This sand cap is an important interface between the CT brine and the freshwater fen. The first field campaigns were conducted in May and August, 2010, collecting sediment cores and well water samples, which are currently being enriched for S and Fe oxidizing and reducing microbes. Sulfide concentrations from well water were greater than 3 mg/L and  $Fe^{2+}$  concentrations higher than 0.2 mg/L indicating active S and Fe reduction within both the sand cap as well as the underlying CT. Confirming the likely importance of microbes in these processes, positive enrichment growth has been observed for sulfur and iron oxidizing and reducing bacteria (16S DNA characterization currently underway). These field and lab results along with the proposed microbial geochemical experiments will be presented.

#### **SORTING OUT THE DATA: WHAT'S A CONTAMINANT AND WHAT'S NATURAL? WHAT'S DIRTY AND WHAT'S CLEAN?**

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Human health and ecological risk assessments (HHERA) are frequently used to evaluate risks associated with heavy metals and other contaminants present in the environment. Since these risk assessments often precede clean-up activities, it is important to delineate areas where significant contamination is present, and also to distinguish between substances that are of natural origin, and those that are introduced into or concentrated in the environment as a result of human activities. Stantec will demonstrate the use of multivariate statistical techniques including cluster analysis, non-metric multidimensional scaling (NMDS) and principal components analysis (PCA) to group soil samples according to overall similarity of trace element composition and concentrations, delineate areas of "high", "moderate" and "low" (or background) levels of contamination, and identify suites of trace elements having similar distributions (and potentially common sources) in the envi-

ronment. The use of these statistical techniques provides an objective basis for stratifying areas within sites according to overall levels of contamination, leading to better definition of overall risk to human and ecological receptors using the sites. They can also be used to help define what natural backgrounds might be in disturbed environments, and differentiate between suites of elements that are truly contaminants requiring remediation and those that are of natural origin, for which remediation is not a reasonable objective. Achieving these goals leads to reduced liability and more cost-effective remediation when required.

#### **PARTITIONING OF PGE BETWEEN SILICATE MELT AND RESIDUAL MANTLE PERIDOTITES IN THE BAY OF ISLANDS OPHIOLITE, NEWFOUNDLAND**

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Representative harzburgite and dunite samples from the basal part of the North Arm Mountain Massif in the Bay of Islands Ophiolite were examined to determine the behaviour of the platinum group elements (PGE) during partial melting and metasomatism by the melt in the mantle.

The Massif represents an Early Ordovician ophiolite, showing the residual mantle peridotites and overlying ultramafic cumulates. The residual mantle part is predominantly harzburgite containing layers and veins of dunite and pyroxenite, and the cumulate section is dominated by dunite of boninitic magmas.

The harzburgites are composed of Ol ( $Fo=89.3-91.7$ ,  $NiO=0.29-0.40\%$  wt), Opx ( $Mg\#=85.6-92.1$ ) and minor spinel ( $Cr\#=0.3-0.7$ ,  $Mg\#=0.44-0.70$ ,  $Fe\#=0.02-0.06$ ). The abundance of minerals varies slightly within hand specimens and thin sections. Harzburgite contains Ni ( $>1637$  ppm), Cr ( $>2000$  ppm) and MgO ( $>39$  wt%) in bulk rocks. Dunite is composed of Ol ( $Fo=83.9-90.0$ ,  $NiO=0.13-0.38$  wt%) with minor Cr-spinel ( $Cr\#=0.31-0.49$ ,  $Mg\#=0.39-0.67$ ,  $Fe\#=0.02-0.09$ ). Minor Opx ( $Mg\#=85.5-92.6$ ) and/or Cpx ( $Mg\#=85.7-96.7$ ) occurs in several samples. The NiO contents in olivine show a positive correlation with Fo values both in harzburgite and dunite. Bulk rock compositions of dunite show high Ni ( $>2640$  ppm), Cr ( $>2600$  ppm) and MgO ( $>42.4$  wt%). Sulphide contents are low in both types of rocks, showing a broad correlation between Cu and S; 24-133 ppm S and 1.2-15 ppm Cu in harzburgite and 33-894 ppm S and 2-170 ppm Cu in dunite. Pyrrhotite is the major sulphide in dunite samples.

Harzburgite samples contain the total PGE ranging from 20.5 to 40.4 ppb. They have high Ir-type PGEs showing a negatively sloped primitive-mantle normalized pattern ( $[Ir+Os]_N/[Pt+Pd]_N=0.6-2.5$ ). The contents of Ir-type PGEs in dunite are low showing a positively sloped normalized pattern ( $[Ir+Os]_N/[Pt+Pd]_N=0.03-1.4$ ) with the total PGE ranging from 16.8 to 115 ppb.

Our PGE data are consistent with experimental results showing that Ir-type PGEs remain in residues during partial melting whereas the Pd-type PGEs are incompatible (i.e. Brennan et al., 2005). The high contents of Ni in olivine and the lack of correlation between PGE and S contents, suggest that sulphides are not a major carrier for PGEs. Samples with high contents of S show localized occurrences of S, suggesting sulphides of the secondary origin.

Assuming that dunite represents solidified melt, the bulk distribution coefficients for PGEs between residual mantle peridotite and partial melt are  $D_{Os} (32.2) > D_{Ir} (10.3) > D_{Ru} (7.71) > D_{Pt} (0.92) > D_{Rh} (0.38) > D_{Pd} (0.17)$ .

## **RADIOGENIC ISOTOPES AND THE PROVENANCE OF THE PAINTING MATERIALS OF CORNELIUS KRIEGHOFF**

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Cornelius Krieghoff was a 19<sup>th</sup> century Canadian artist (1815-1872) renowned for his winter landscapes, and depictions of aboriginal and rural Quebec life. During the 19<sup>th</sup> century, the artist's palette consisted primarily of ground minerals, synthetic inorganic pigments, organic pigments of plant or insect origin, and carbon-based black pigments. Krieghoff, for example, used mineral pigments such as cinnabar, iron oxides and calcium carbonate (as an extender), and synthetic pigments such as vermilion, Prussian blue, chrome yellow, cadmium yellow and Naples yellow. The most important pigment was lead white, composed of lead carbonate hydroxide (a synthetic analog of hydrocerussite) often with lead carbonate impurities. Krieghoff used lead white in the preparation layer on the canvas and as a white pigment (either alone or in mixtures to lighten other colours). Pb and Sr isotope data were obtained from micro-samples of lead white and calcium carbonate of 15 Krieghoff works painted between 1844 and 1871. Four paint samples with other lead-containing pigments (chrome yellow or Naples yellow) in various mixtures were also analysed. The isotopic data of the lead white and calcium carbonate provide constraints on provenance in order to determine where Canadian artists of the era obtained the tools of their trade (local vs. European vs. American).

The bulk of the lead isotope data yield very restricted isotopic compositions that are consistent with data obtained from lead white in European paintings of the same or earlier periods. This is true for samples taken from white areas of Krieghoff paintings, from the underlying white preparation forming the first layer of the canvas, or from the coloured paint mixtures. Thus, the bulk of the white pigment was derived from European sources. However, a paint sample from an 1844 painting, and paint and ground (first layer) samples from an 1847 painting yielded lead isotope compositions that were more radiogenic than the other samples and lie outside the range of lead isotope compositions of European lead mines. These compositions are suggestive of a North American origin. The Sr isotope ratios of the samples are more variable ranging from values consistent with Palaeozoic carbonates to more radiogenic values in excess of present day seawater. The results suggest that the calcium carbonate was derived from silicate-contaminated carbonates and that the source of the calcium carbonate additive was more variable than that of the lead white.

## **CHALLENGES AND OPPORTUNITIES IN EARTH SCIENCES**

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For the last century during the greatest technical evolution and human population growth in Earth's history, humans have used the natural resources of the earth for societal benefit. At the same time, readily available resources have generally become depleted, polluted or unsustainable, threatening the standard of living for future societies. Additionally anthropogenic influences on Earth from resource use have changed the face of the planet, changed human demographics and have added greenhouse gases to the atmosphere contributing to the rate of climate change. This presents challenges to earth scientists and engineers to find new resources, often in more remote or deeper locations; to develop new tech-

niques to respond to rising sea levels and melting permafrost; to manage water resources in changing climatic regimes; and to assess energy alternatives from shale resources, gas hydrates, geothermal, wind and solar. This also represents an opportunity to demonstrate to government and civil society the critical linkages and integration between natural resource availability, strategic resource management and societal overall benefits and standard of living, and that this linkage still applies even to a sustainable and green society. The Canadian Federation of Earth Science (CFES) exists to provide a unified voice at the national level for Canada's earth sciences and geo-engineering community to reach out and communicate to government, industry and civil society the importance of Canada's natural resources in sustaining the Canadian economy, society and environment. The objective is to achieve sufficient earth literacy that scientific principles and informed debate will effect future societal and political decisions respecting natural resources management, development, and protection.

## **THE NATIONAL MINERAL COLLECTION OF CANADA CELEBRATES ITS GOLDEN ANNIVERSARY**

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In 1961, the mineral collection of the Geological Survey of Canada was formally recognized as the National Mineral Collection of Canada; jointly managed by the GSC, which took the responsibility for reference series, and the Museum of Nature responsible for the display series. The mineral collection had been acquired since the establishment of the GSC in 1842 with the first materials collected during the field season in 1843. The first formal organization of the mineral collection was in 1893, although the collection was on tour as early as 1851 at "The Great Exhibition of the Works of Industry of all Nations," England, whereby the industrial capitals of Europe were made aware of the vast mineral wealth of Canada for the first time. The floor plan of the original museum on Sussex Street had the Section of the Geological Museum (1893) in three main sections: A. Systematic Collection of Minerals, B. Collection of Economic Minerals and Rocks and C. Stratigraphical Collection of Rocks. When the museum and the GSC were separated in the 1920's, the mineral collection continued to be a cornerstone of the holdings of the GSC. The last few years has seen an increase in organizing the database for the reference series and a rebirth of the Collection of Economic Minerals and Rocks.

## **CALDERA SUPERVOLCANOES, RESURGENCE, AND MINERALIZATION**

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Available evidence at Valles and Lake City calderas indicates that major pulses of hydrothermal activity are associated with and linked to caldera formation and resurgence, since resurgence immediately postdates collapse at both calderas. Based on these observations, we propose a mechanism for caldera-related hydrothermal systems and mineralization. Intermediate-composition, sulfur-rich magmas are introduced into the caldera system during collapse and resurgence. These magmas degas catastrophically as they rise and decompress, providing a source of magmatic-hydrothermal fluids which may be ore-bearing or barren. The intermediate magmas also supply a new source of heat with which to drive hydrothermal cells. Furthermore, the rising magmas cause deformation and fracturing to occur during resurgence, notably as inward-dipping reverse faults which are generated along the ring fracture of the caldera. The development of this

fracture permeability is another key component allowing for a large hydrothermal system to develop rapidly. The permeability also provides pathways for meteoric fluids to circulate and interact with magmatic fluids. Notably at both calderas, the locations of the most intense hydrothermal activity (Sulphur Springs at Valles and Red Mountain at Lake City) are found along and around the calderas' ring fracture. As deformation and resurgence proceed, the inward-dipping reverse faults are progressively opened and filled with degassing magma and magmatic-hydrothermal fluids. These structures are akin to cone sheets and serve as repositories for magma, hydrothermal fluids, and potential ore minerals. These structural pathways are supplemented by other structures such as regional faults which cut through the caldera system. In summary, initiation of such hydrothermal systems is the result of heat, magmatic fluids, and fracture development from the intermediate magma which rises into the caldera system, interacts with resident magma, and drives resurgence. Hence the timing of caldera formation, resurgence, and hydrothermal activity is synchronous.

#### **A RECORD OF ENVIRONMENTAL CHANGES AND HUMAN SETTLEMENT DYNAMICS DURING THE FOURTH MILLENNIUM BC FROM LOUGHMEENAGHAN, CO. SLIGO, IRELAND**

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The Neolithic represents an important period of early human development in Ireland that was associated with a transition in economy from hunting and gathering to farming and a rapid increase of the archaeological presence of humans in the landscape. To contribute to a better understanding of the environmental changes and human settlement dynamics during this period, high-resolution palynological and geochemical analyses were performed on a sediment core from a small lake in County Sligo. This region is known for its abundance of megalithic monuments, including those of the passage tomb cemeteries at Carrowmore and Carrowkeel.

The palaeoecological evidence indicates that the primeval woodland, largely consisting of elm, oak, and hazel, experienced first minor clearances at the beginning of the early Neolithic, ca. 100 years prior to the elm decline that occurred between 3825 and 3720 years BC. The decrease in the local elm population during that time was accompanied by a period of relatively high precipitation. At 3780 years BC, wheat cultivation was established in the lake catchment area and performed for at least 120 years until 3660 years BC. Climatic amelioration associated with a rise in summer temperatures and a decline in precipitation commenced ca. 50 years after the onset of arable farming, suggesting that the change in economy was not exclusively controlled by climate. Driest conditions associated with maximum openness of the landscape during the Neolithic were attained between 3650 and 3560 years BC. No evidence for arable farming was recorded for this interval, implying that declined water availability might have affected crop production at Loughmeenaghan. The period of drier and warmer conditions ended abruptly at the beginning of the mid-Neolithic. The subsequent establishment of a wetter and cooler climate led to a transition in agricultural economy towards pastoral activities and the continuous abandonment of the area by the first farmers. By 3000 years BC, the woodland had recovered to pre-elm decline extent.

Palynological and archaeological evidence from other sites in Ireland confirms that cereal cultivation formed an integral part of the farming economy during the early Neolithic between 3800 and 3600 years BC. Increased human activity during this period is reflected in the abundance of archaeological structures and artefacts. Evidence for human activity declined notably thereafter at the transition to the mid-Neolithic period, corroborating the observations from Loughmeenaghan.

#### **DISASTER RESILIENCE BY INTEGRATED DESIGN**

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Land-use planning can be an effective strategy in building community resilience to disaster. Land-use choices change patterns of vulnerability and risk for a community or region. Land-use choices that build resilience rather than increase vulnerability are facilitated by methods and tools that model existing and potential risk, and that support the strategic and operational planning process.

An interdisciplinary team of researchers and practitioners share a mandate to develop an integrated risk-based land-use decision support system. This system provides guidelines to assess the integrated quantitative hazard and risk, and analyse the benefit of various development options. The system tools reflect emerging best practices in the fields of pre-event emergency management and place-based planning. The research and development is founded on geology and is socially integrated through practical application in communities. That work has developed risk assessment decision support schema, engaged municipalities in building a risk-based decision support guide, provided guidance on the extent and standards for hazard assessment, built a network of mitigation and risk-assessment practitioners, tested a risk-based land-use planning evaluation and training exercise, begun adaptation of a rigorous quantitative natural hazard risk assessment tool (HAZUS-MH) for use in Canada, applied components of the system in a moderate-sized urban centre, and initiated support for risk assessment users.

Networks of broadly cross-disciplinary groups focused on disaster reduction have increased awareness of the large extent of available local knowledge. That awareness has led to use of the network as an informal classroom, and for increasing optimism and desire for action triggered by the recognition of widespread concurrent goals, and technological and social initiatives.

#### **COSMIC RAYS AND EARTH'S CLIMATE**

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It has been suggested that cosmic ray variations in the Earth's atmosphere are influencing climate by changing the microphysics of clouds.

Evidence for this link is based 1) Experimental studies of aerosol nucleation in air, containing trace amounts of ozone, sulphur dioxide and water vapour at concentrations relevant for the Earth's atmosphere. The production of new aerosol particles is found to be proportional to the negative ion density, and suggest that ions play an important role in the formation of aerosols in the atmosphere. 2) Observational studies of cloud formation when coronal mass ejections from the sun results decreases in cosmic ray counts at the Earth's surface. It is found that the liquid water in low clouds can diminish by as much as 7% following such events. Parallel observations of aerosol reveal falls in the relative abundance of fine aerosol particles which, in normal circumstances, could have evolved into cloud condensation nuclei. Indicating a link between the sun, cosmic rays, aerosols, and

liquid-water clouds appears to exist on a global scale. 3) Finally the supernova rates (the sources of cosmic rays) are compared with geological data on past climates. It is found that astrophysical processes responsible for star formation in the solar neighbourhood are fundamental for the climatic conditions on Earth.

#### **PORPHYRY Cu-Au AND EPITHERMAL Au DEPOSITS IN HASSAN-ABAD REGION, NE OF IRAN**

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Porphyry Cu-Au and related epithermal Au deposits are intrusion-related and formed by fluids coming from magma intrusions, emplaced at shallow depths. These types of deposits are essentially linked to water-rich, high-K calc-alkaline to shoshonitic/adakitic intrusions from active continental margins/collisional belts.

High-K calc-alkaline to mildly alkaline (shoshonitic) volcano-plutonic rocks are widespread in NE of Iran, resulting from subduction of Neo-Tethyan oceanic lithosphere beneath the Central Iranian/Lut block during Late Cretaceous? to Eocene. This subduction event plays a role on the formation of Eocene calc-alkaline/shoshonitic and younger adakitic volcano-plutonic rocks, associated with porphyry Cu-Au and epithermal Au deposits in NE of Iran.

Here, we try to combine all geological data including type of Cu-Au deposits occurrence, alteration zonation, geochemistry of host plutonic/volcanic rocks, fluid inclusions from the ore-related carbonate/quartz veins, stable isotope geochemistry to unravel the characteristics of Cu-Au porphyry and epithermal Au deposits in Hassan-Abad region, NE of Iran.

#### **LARGE IGNEOUS PROVINCES AND KIMBERLITES? ORIGIN OF THE NEOPROTEROZOIC AMON KIMBERLITE, NORTH-CENTRAL BAFFIN ISLAND**

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Although kimberlite magmatic events produce only insignificant volumes of magma, it has been recently recognized that kimberlite magmatism can be spatially and temporally associated with large outpourings of continental flood basalts. Examples where kimberlites form part of Large Igneous Provinces (LIPs) include the Siberian Trap event in Russia and the Deccan event in India, but the potential genetic relationships between these contrasting types of magmatism remain unclear. Here we report geochronology and geochemistry data from the Amon kimberlite dyke system in northern Baffin Island, for which an apparent spatial and temporal relationship exists with the middle Neoproterozoic Franklin LIP in the Canadian Arctic. Groundmass rutiles from the Amon kimberlite dyke yielded an U-Pb age of  $672.7 \pm 5.3$  Ma (2-sigma, ID-TIMS method), which is only marginally younger than the 723-718 Ma old 'giant' Franklin mafic dyke swarm that runs across northern Baffin Island in northwest-trending direction.

Our new mineralogical, geochemical, and isotopic data for the Amon kimberlite dykes show that they are compositionally akin to South African Group-I kimberlites, for which a mantle plume-induced origin has frequently been advocated. For example, groundmass spinels follow a magmatic Trend-1 of near constant Mg/Fe and groundmass phlogopites exhibit evolutionary trends of Al- and Ba-enrichment. Furthermore, the Amon kimberlites compositionally fall at the CO<sub>2</sub>-rich end in the global kimberlite database and show strong enrichment in incompatible elements, suggestive of very low-degrees of partial melting of carbonated peridotite. Although moderately depleted Sr-Nd-Hf isotope compositions of the Amon kimberlites point to magma

derivation from a convective mantle source, enrichment of the lower cratonic lithosphere by asthenosphere-derived carbonate-rich magmas shortly prior to kimberlite magmatism can equally well explain the observed compositions.

Our geochemical constraints on the origin of the Amon kimberlites, combined with the Neoproterozoic geologic evolution of the northeastern Canadian Arctic, allow us to suggest that an enrichment of the lower cratonic mantle may have occurred near the 'colder', more distal parts of an impinging mantle plume head that gave rise to the Franklin igneous event at ca. 720 Ma. In our model we propose that after the plume-related thermal anomaly vanished, extensive stretching of the metasomatized cratonic mantle lithosphere during the latest Neoproterozoic triggered low-volume kimberlite magma production beneath northern Baffin Island at ca. 673 Ma.

#### **3-D VISUALIZATION OF MULTI-PHASE HYDROTHERMAL FLOW, SILICIFICATION, AND HYDRATION: ARCHITECTURE OF THE HORNE HYDROTHERMAL SYSTEM, ROUYN-NORANDA**

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Interpolated whole-rock oxygen isotope compositions, Si/Al ratios, and H<sub>2</sub>O (wt. %) of outcrop and drill core samples yield 2D and 3D patterns that describe the architecture of the hydrothermal system responsible for the world-class Horne VMS deposit. Estimations respected the Horne Creek and Andesite faults bounding the 'Horne block', and other regional faults in adjacent areas.  $\delta^{18}\text{O}_{\text{WR}}$  values of 132 outcrop samples within ca. 5km of the Horne mine vary systematically 2.8 to 12.4‰ with alteration mineral assemblage; fresh rocks have  $\delta^{18}\text{O}_{\text{WR}} \approx 6.0$  (andesite) to 8.0‰ (rhyolite). 182 samples of drill core in the Horne block and Horne mine yielded  $\delta^{18}\text{O}_{\text{WR}}$  from 3.8 to 11.0‰. Si/Al ratios from 4845 screened samples vary from 1.2 to 19.7 in both mafic and felsic rocks; wt.% H<sub>2</sub>O varies from 0.02 to 4.03 in mafic rocks, and from 0.02 to 2.14 in felsic rocks. Values of  $\delta^{18}\text{O}_{\text{WR}} < 6$  and  $> 9$ ‰ were chosen to denote high- and low-temperature alteration, respectively; values of Si/Al  $< 3.2$  and  $> 4.8$  (mafic rocks), and  $< 4.0$  and  $> 7.0$  (felsic rocks), denote de-silicified and silicified rocks, respectively. Values of wt.% H<sub>2</sub>O were kriged to yield gradient maps.

High- to low-temperature, eastward directed flow paths, including a discordant, low  $\delta^{18}\text{O}$  (high-temperature) zone emanating from the Powell Pluton associated with elevated Cu/(Cu+Zn) ratios, mark several, successive hydrothermal episodes. Where not overprinted by younger alteration, silicified rocks (especially andesites) occur downstream, associated with zones of higher  $\delta^{18}\text{O}_{\text{WR}}$ . Within the Horne block, isotopic data indicate at least two periods of hydrothermal activity. High-temperature upflow in the Horne footwall occurred between the Upper H and Lower H orebodies, and near the termination of the Lower H, possibly along previously identified synvolcanic faults. Silicification of a broad, concordant zone beneath the Upper and Lower H orebodies, down to ca. 4000', is coincident with discordant and concordant zones of high  $\delta^{18}\text{O}$  rocks, and suggests fluid mixing during protracted cooling led to silicification and mineralization. High-temperature alteration in the hanging wall records subsequent hydrothermal activity.

Whereas, zones of silicification may be associated with isotopically mapped thermal gradients and hydrothermal flow paths, maps of hydration are less clear, although, some high-temperature (chloritization) and low-temperature (sericitization) reaction zones do correspond with analogous, oxygen-isotope mapped zones. The nature and architecture of the hydrothermal system may have played a key role in the size of the deposit. Higher resolution structural models may further enhance the potential for depth predictability of new resources.

#### **VARIATIONS AND CONTRASTS IN MAGMATIC-CENTRED HYDROTHERMAL SYSTEMS, BLAKE RIVER GROUP, QUÉBEC AND ONTARIO, AND THEIR RELATIONSHIP TO MINERAL DEPOSITS: REGIONAL OXYGEN ISOTOPE ZONING PATTERNS AND DATABASE**

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The nature and style of magmatic-centered and ore-forming hydrothermal activity varied in the Blake River Group (BRG) over the course of some 22 m.y. of synvolcanic to syntectonic intrusive history. Associated styles of mineralization included Cu-Zn and Zn-Cu VMS deposits, Au-rich VMS deposits and veins, porphyry-style deposits. Oxygen isotope mapping of the 'footprints' of the principal, paleo-magmatic-hydrothermal systems in the BRG (based on several projects spanning a number of years, plus published studies; ca. 2140 whole-rock analyses), reveals a range of system size, style, isotopic systematics, and number of related stages. All studied hydrothermal systems are marine in nature, but differences in system size and heat budget, longevity, tectonic setting, nature and timing of magmatism, depth and temperature between centres across the BRG are reflected by the isotopic characteristics of each system. Intrusive centres and/or mining camps compared here include, from west to east in the BRG: the Clifford Stock, Monsabrais Pluton, Flavrian Pluton (FP), central Noranda camp, Powell Pluton, Horne-Quemont deposits, Cléricy Pluton, Mooshla Pluton, and Doyon-Bousquet-LaRonde (DBL) camp. Not all of these intrusions, or phases of these intrusions (e.g. Late leucotonalite, FP), supported large marine hydrothermal systems. The younger intrusive centres (e.g. Monsabrais and Clifford) exhibit only weak hydrothermal activity and mineralization associated with single-stage systems.

The FP and the central Noranda camp deposit-bearing volcanic wall rocks were tilted eastward during the regional deformation.  $\delta^{18}\text{O}$  mapping in this sector provides an oblique, cross-sectional view of the largest, and little deformed, hydrothermal footprint, which is a composite of the effects of at least four hydrothermal episodes. In contrast, strain has markedly shortened the altered rocks in the DBL camp, and removed evidence for magma chamber(s) related to the wide-spread paleo-hydrothermal alteration and sources of the felsic flows. Synvolcanic faults played key roles in the development, organization, maintenance, and longevity of hydrothermal systems; long-lived hydrothermal

conduits are responsible for several VMS deposits in the central Noranda camp. Systematics evident from this multi-phase system, and evident on reduced scales in other, simpler systems (e.g. Cléricy), provide useful exploration guides. Hydrothermal activity associated with FP was contained within the Noranda cauldron; there is no mappable evidence for synchronous paleo-hydrothermal activity along larger, caldera-like structures. Contrasting tectonic/geographic settings are reflected by differing isotopic systematics: marked  $^{18}\text{O}$  depletion associated with deeper, multiple high-heat flow systems in the central Noranda camp to  $^{18}\text{O}$  enrichment in lower heat-flow, perhaps shallower systems of the DBL camp.

#### **MINERALOGY AND GEOCHEMISTRY OF AN ORBICULAR-TEXTURED ULTRAMAFIC LAMPROPHYRE FROM THE LATCHFORD AREA, NORTHEASTERN ONTARIO.**

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An unusual, orbicular-textured, ultramafic lamprophyre was discovered on the western shoreline of Anima Nipissing Lake, in Northeastern Ontario during a regional diamond exploration program. This sample was thoroughly examined using XRF, microscopy and electron microprobe analysis. The mineral assemblage of the orbicular dyke consists of: phlogopite, diopside, Mg-ilmenite and apatite macro- and/or phenocrysts, in an altered groundmass of Ti-magnetite, carbonate, chlorite and serpentine. Compositionally, the orbicules are similar to the matrix of the dyke, suggesting that they are pelletal lapilli that formed around Mg-ilmenite and diopside macrocrysts. The mineral paragenesis has similarities to both kimberlites and ultramafic lamprophyres. Mg-ilmenite compositions show moderate MgO contents (4-5 wt%) characteristic of ultramafic lamprophyres and at the lower end of kimberlite megacryst compositional range. Phlogopite macrocrysts are Ti-rich (up to 7.7 wt%  $\text{TiO}_2$ ) and follow an evolutionary path similar to that of ultramafic lamprophyres. Ti-magnetite and Cr-free diopside compositions also show characteristics similar to those found in lamprophyres, particularly damtjernites. Abundant apatite is the host of the high P, Sr and LREE concentrations found in the whole rock. In addition to the orbicules, the rock contains glomerophyric, droplet-like textures that are believed to be products of liquid immiscibility. Although the whole rock composition is similar to both kimberlites and ultramafic lamprophyres, the mineral chemistry shows a better correlation with ultramafic lamprophyres, specifically damtjernite. Although intrusive contacts remain covered by overburden, this lamprophyre dyke lies along strike of a Sudbury olivine diabase dyke and occurs approximately 10 km southwest of the KRVY diamond-bearing breccia. The ultramafic KRVY body exhibits similar textures (i.e. heterolithic breccia and pelletal lapilli) and mineralogy (i.e. phlogopite, carbonate, ilmenite, apatite and diopside) as the lamprophyre dyke. However, further study of the latter occurrence is required to determine if a genetic relationship exists between these two unusual occurrences and to determine whether they represent members of a larger intrusive event.



# STRATIGRAPHY, ARCHITECTURE AND SEDIMENTARY MODEL OF DEEP-MARINE BASIN-FLOOR DEPOSITS OF THE NEOPROTEROZOIC UPPER AND MIDDLE KAZA GROUP (WINDERMERE SUPERGROUP), BRITISH COLUMBIA

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Proximal to more distal basin-floor deposits of the Upper and Middle Kaza Group, respectively, provide a unique opportunity to study deep-marine fan deposits of the Windermere turbidite system. In this study six architectural elements were identified, including deep and shallow channels, sandy terminal-splays, debrites, and inter- and intra-splay turbidite sheets. Of particular note is that the outcrop exposures are of sufficient horizontal and vertical scale to be compared with seismically-resolved elements, which typically are described simply as “sheet-like deposits”.

Deep channels that scour up to 15 m are uncommon in the Upper Kaza and absent in the Middle Kaza. Their fill consists of muddy and heterolithic bypass facies. Shallow channels, which at their base scour a few to several meters, are common in the Upper Kaza but rare in the Middle Kaza. In their axis channels are commonly filled with bypass facies (dunes and mudstone breccia) at their base and Ta sandstone that grade laterally over 10s to 100s of meters into progressively higher division turbidites. Sandy terminal-splay deposits, common in both the Upper and Middle Kaza, form laterally extensive amalgamated coarse sandstone sheets with little lateral facies variation over several hundreds of meters. Debrites are 1-20 m-thick, laterally continuous, matrix-rich units with abundant deformed clasts of various sizes and lithologies, and are rare in the Upper Kaza and absent in the Middle Kaza. Inter- and intra-splay turbidite sheets are common in both the Upper and Middle Kaza and consist of laterally extensive sheets of thin- to medium-bedded fine-grained turbidites. Locally these strata contain sand-filled scours several meters deep and occur only in the Upper Kaza.

The large-scale elements observed have an apparent simple “sheet-like” morphology consisting of alternating 5-55 m thick sand “sheet” separated by up to 35 m thick fine-grained units, but upon closer inspection are shown to be internally stratigraphically complex. The smaller scale architectural elements populate the depositional sedimentary body non-randomly and build up the (sub-seismic scale) architecture of the “sheets”. The repetitive and consistent stacking of these stratal units illustrates the dynamic, yet systematic nature of basin-floor deposition. This study identified a hierarchy of architectural elements and composite sedimentary facies for the basin-floor depositional system based on observed similarities and differences between the lithology, stratigraphy and architecture of the Upper and Middle Kaza Group, which then were arranged in an evolutionary model for a deep-marine basin-floor system.

## EARLY NEOPROTEROZOIC ANORTHOSITE AND FERRONORITE IN APPALACHIAN GANDERIA: LOWER COVERDALE PLUTON, BROOKVILLE TERRANE, SOUTHERN NEW BRUNSWICK, CANADA

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The Lower Coverdale pluton underlies an area of 30-40 km<sup>2</sup> south of Moncton, New Brunswick, based on the extent of an associated positive aeromagnetic anomaly. The pluton does not outcrop at surface, but has been intersected in 11 drill holes at depths of 100-200 m below unconformably overlying Carboniferous sedimen-

tary rocks, and extends to a depth of at least 1100 m. The host rock is unknown, but based on regional trends, the pluton is located in the Ganderia Brookville terrane. Based on core and cuttings samples, the pluton consists dominantly of interlayered coarse-grained anorthosite and ferronorite, both intruded by gabbro, quartz monzonite, and felsic dykes. The ferronorite contains varying proportions of interstitial apatite and ilmenite, and layers of apatite-ilmenite rock (nelsonite) up to several metres thick. The core shows effects of low-grade metamorphism and alteration but microprobe analyses of freshest samples revealed that plagioclase in both anorthosite and ferronorite is of andesine composition. In some anorthosite samples, plagioclase contains exsolution lamellae of K-feldspar with up to 1.5% Ba. Orthopyroxene in the ferronorite is magnesian (En<sub>62-70</sub>). Apatite contains 3-4% F. Whole-rock chemical analyses show that the anorthosite contain 50-60% silica, with high alumina, Ca, and Na. The ferronorite has silica between 25-45%, with 25-14% Fe<sub>2</sub>O<sub>3</sub> and 14-3% TiO<sub>2</sub>, and up to 8% P<sub>2</sub>O<sub>5</sub>. The gabbroic rocks differ in mineralogy and chemistry from, and appear unrelated to, the anorthosite and ferronorite. Quartz monzonite intersected at a depth of 1095 -1206 m in one drill hole is yielded a previously reported Middle Devonian U-Pb zircon age of ca. 390 Ma. Eleven zircon fractions, mostly single grain fragments, from a ferrogabbro sample yielded an age of 975.5±7.8/-6.9 Ma (2 sigma error, including uncertainty in the decay constant). This Early Neoproterozoic age is considered to represent the igneous crystallization age of the pluton, and hence it is the oldest dated unit in Ganderia. The Lower Coverdale pluton has petrological similarities to Grenvillian massif-type anorthosite suites, but its age is younger than the Mesoproterozoic ages reported for such suites. It is similar in age to the Jotun massif anorthosite and has petrological similarities to the younger (932 Ma) Rogaland anorthosite complex, both in Norway, but Brookville terrane is typically linked to Gondwana, not Baltica. The distinctive age and petrological features of the Lower Coverdale pluton provide a potential way to positively identify the paleogeographic position of Ganderia, if similar bodies can be found elsewhere.

## TRANSFORM-PARALLEL INTRACRATONIC FAULT SYSTEMS ALONG THE IAPETAN RIFTED MARGIN OF LAURENTIA

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Northeast-trending rift zones and northwest-trending transform faults define the trace and structure of the late Precambrian–Cambrian Iapetan rifted margin of Laurentia. Transform faults offset rift zones and/or partition domains of opposing dips of simple-shear detachment faults. Transform-parallel intracratonic fault systems extend into continental crust in alignment with continental-margin transform faults. Rift-parallel intracratonic graben systems record rift extension of continental crust inboard from the rift.

The Southern Oklahoma intracratonic fault system, containing a bimodal suite of plutonic and volcanic synrift rocks (530–539 Ma), parallels the Alabama-Oklahoma transform in the Ouachita embayment. Localized thermal uplift delayed post-rift passive-margin onlap until middle Late Cambrian; anomalously thick passive-margin carbonates document high-amplitude post-rift thermal subsidence.

The Rough Creek and western Rome intracratonic grabens, an oblique system of transtensional faults linking and dextrally offsetting the rift-parallel Mississippi Valley and eastern Rome graben systems, are aligned with transform faults between the upper-plate Virginia promontory and the lower-plate Tennessee embayment of the Iapetan margin. The Rough Creek graben con-

tains exceptionally thick (Early?–early Late Cambrian) synrift clastic sediment; anomalously thick passive-margin carbonates document high-amplitude post-rift thermal subsidence.

The Ottawa-Bonnechère intracratonic graben is aligned with transform faults that bound the lower-plate New England rift zone. Synrift igneous rocks along the graben have ages of 590–563 Ma.

The Saguenay intracratonic graben is aligned with the Saguenay-Montmorency transform, which separates the upper-plate Quebec rift zone from the lower-plate Gaspé rift zone. Carbonatite complexes along the graben have ages of 564 Ma.

The Sept Îles transform offsets the rift from the lower-plate Gaspé rift zone to an upper-plate segment of the Long Range rift zone. Although not associated with a recognized intracratonic fault system, the Sept Îles layered mafic intrusion (565 Ma) is inboard along trend from the transform fault at the rifted margin, suggesting synrift transform-parallel intracratonic fractures that penetrated the upper mantle.

Mesozoic–Cenozoic analogs around the Atlantic Ocean document concentration of synrift and passive-margin sediment, as well as synrift magmatism, along transform faults and transform-parallel intracratonic fault systems. Seismic anisotropy along modern transform faults documents a transform-parallel fabric (aligned olivine crystals) in the mantle lithosphere, suggesting a distributed ductile-shear fabric caused by differential mantle flow on opposite sides of transform faults. A shear fabric along transform faults and transform-parallel intracratonic fault systems is a possible cause of localized weakness of the lithosphere, focusing enhanced subsidence during rifting, post-rift cooling, and subsequent tectonic loading.

#### **METEORITE NORTHWEST AFRICA (NWA) 869: A STUDY OF DIVERSE CLASTS IN THE L 4-6 BRECCIATED ORDINARY CHONDRITE**

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Meteorite Northwest Africa (NWA) 869 has been classified by others as a brecciated L 4-6 ordinary chondrite (recently reclassified as an L 3-6).<sup>1</sup> There are currently over 300 distinct fragments in the Royal Ontario Museum collection. Each fragment has been weighed, photographed and analyzed for distinct features. The weight of the samples ranges between 10 g and 3.0 kg. Eight fragments were cut, thin-sectioned and a detailed characterization of both the matrix and the clast material was undertaken. The samples host a variety of texturally, mineralogically and chemically distinct clasts distinguishable from the matrix material. A variety of features were observed, including crystalline achondritic textures, rimmed feldspathic clasts, and mega-chondrule type material. These clasts have been described petrologically and analyzed using EMPA and oxygen isotope techniques in order to contrast their composition in relation to the matrix material. The EMPA data suggests several clasts have a chemical signature distinct from the typical range for L chondrites: between 6 and 15% below the Fa content of matrix olivine. Several of the identified clasts have olivine grain chemistries placing well out of the accepted range for L chondritic meteorites. The unique texture and chemistry of these clasts suggests that they may be derived from a heterogeneous L parent body undergoing unrecognized igneous-style processing, or that NWA 869 may include material from several distinct parent bodies. The completion of oxygen isotope analysis on several clasts suggests that they may not have a unique or homogenous origin. The clasts identified as unique were analyzed

through an oxygen isotope study with results ranging from material exhibiting HED-type values to those on the terrestrial fractionation line. These results indicate this rock is undergoing novel amalgamation or processing techniques, incorporating material derived from or representative of a variety of meteorite classes.

<sup>1</sup>Metzler K. et al. (2008) LPSC 39, #1120.

#### **PRELIMINARY SEQUENCE STRATIGRAPHY AND $\delta^{13}\text{C}$ DATA FROM THE MINTO INLET AND WYNNIATT FORMATIONS, SHALER SUPERGROUP, WESTERN MINTO INLIER, VICTORIA ISLAND, NWT**

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The Minto Inlier is exposed on northwestern Victoria Island and hosts Neoproterozoic sedimentary rocks of the Shaler Supergroup. The Shaler Supergroup is > 4-km-thick and is characterized by fluvial/deltaic cross-bedded sandstones, platformal carbonates, basinal black shales, and sabkha evaporites. In ascending order, the Shaler Supergroup consists of the Rae Group, Reynolds Point Group, and the Minto Inlet, Wynniatt, Kilian, and Kuujua formations. These rocks were deposited in the Amundsen Basin, interpreted as a shallow intracontinental basin that records the history of sedimentation within supercontinent Rodinia; from its amalgamation at the end of the Grenvillian Orogeny (ca. 1000 Ma), to its break-up at ~750 Ma. The sedimentary strata are intruded by diabase sills and overlying continental flood basalts of the Natkusiak Formation, part of the widespread ca. 720 Ma Franklin magmatic event.

Proterozoic strata in northwestern Canada are composed of three first-order, unconformity-bound sequences, A, B, and C. The Shaler Supergroup belongs to sequence B, which has been further subdivided into five second-order sequences. Our study is focused on the Minto Inlet and Wynniatt formations of sequence sB4. The Minto Inlet is comprised of sulphate evaporites (restricted marine), and peritidal carbonates (open marine). There are four informal members in the Wynniatt Formation, a lower supra- to intertidal carbonate member, a basinal black shale member, a subtidal stromatolitic carbonate member, and an upper peritidal carbonate member. New insights on the sedimentology and sequence stratigraphy, built upon previous studies, are presented here. These include the recognition and characterization of 3<sup>rd</sup>-order cycles in the Minto Inlet and Wynniatt formations, defined by shoaling upward successions, exposure surfaces, and flooding surfaces.

$\delta^{13}\text{C}$  analyses of carbonates from stratigraphic sections are a useful correlation tool, particularly in Proterozoic sedimentary rocks where the fossil record is greatly limited in comparison to the Phanerozoic record. A negative  $\delta^{13}\text{C}$  excursion in the Wynniatt Formation was recognized in a section from northeastern Minto Inlier and has been correlated with the global Bitter Springs Stage, a ca. 800 Ma negative  $\delta^{13}\text{C}$  excursion first recognized in the Amadeus basin of central Australia. This stratigraphic interval is revisited, from a locality in southwestern Minto Inlier, to investigate the validity of the excursion and to test its intrabasinal correlation. Preliminary  $\delta^{13}\text{C}$  results from the Minto Inlet and Wynniatt formations are presented.

#### **ARCHEAN GREENSTONE EVOLUTION IN THE LIGHT OF NEW RESEARCH ON BIFS**

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Greenstone belts commonly consist of multiple ultramafic/mafic to felsic assemblages capped by sedimentary interface zones consisting of chemical and minor clastic metasediments. Using the

Abitibi greenstone belt as an example, its 7 assemblages developed over 50 My, thus, the average assemblage developed in ~7 My. Greenstones in the northwestern part of the Superior Province have gaps up to 100s of millions of years. Examination of the iron formations at the Deloro-Tisdale contact in the Abitibi reveals the iron formation cherts originated as 1) variably contaminated marine sediments, 2) hydrothermal precipitates, or 3) replacement of pre-existing volcanic units. The disparate origins of the cherts indicate that hydrothermal systems developed and died during the gaps in volcanism, and replacement of precursor units obviously took time. Modeling of the rates of development of magmatic systems, based on modern analogues, shows the sedimentary interface zones represent lengthy periods of accumulation of mainly chemical sediments. Volcanism could represent as little as 10-20% of the time represented by the duration of volcanism of a single assemblage. The best constrained example shows that the iron formation at the Deloro-Tisdale contact required 0.0-6.7 My to accumulate. Archean Algoma type iron formations may represent condensed sections developed during marine transgression.

Therefore, sedimentary interface zones with their iron formations represent potentially significant stratigraphic markers within greenstone belts. These markers exist at the group level throughout most major greenstone belts including the Abitibi. Specifically within the Abitibi, iron formation and/or exhalative cherts also occur at the formation and member levels. In general hydrothermal systems producing syngenetic mineralization (VMS and komatiite-related Cu-Ni-PGE) develop during hiatuses in volcanism. Economic occurrences of Algoma type Iron formation appear to represent quite lengthy volcanic hiatuses of up to 100 My.

#### **THE DISTRIBUTION OF GALLIUM IN THE NECHALACHO REE DEPOSIT, NWT, CANADA**

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The layered Nechalacho Nepheline Syenite at Thor Lake, which is located within the alkaline to peralkaline Blachford Lake Complex near Yellowknife, Northwest Territories, is a potential source of exploitable gallium. It also contains large reserves of Rare Earth Elements (REE), Y, Nb, Ta and Zr, which are most enriched in the Basal Zone, an altered eudialyte cumulate layer. Intense hydrothermal alteration involving replacement of primary magmatic mineral assemblages by a potassic assemblage comprising K-feldspar, biotite and magnetite, was followed by late albitization. Bulk-rock geochemical analyses and analyses of secondary minerals indicate that the Nechalacho Nepheline Syenite has unusually high concentrations of gallium and that this element was both enriched and depleted by hydrothermal processes. Gallium occurs in concentrations more than a magnitude higher than its average concentration in crustal rocks. Similar enrichments are rare in nature, and the Nechalacho deposit therefore provides an excellent opportunity to identify the geochemical and mineralogical factors controlling the distribution of this element. Gallium can substitute for  $Al^{3+}$ ,  $Fe^{3+}$  and other elements with similar valence and ionic radius but is rarely found in a mineral dominated by this element. Aluminium-bearing minerals from samples of the Nechalacho Syenite with bulk rock Ga contents of 150 ppm or higher were analyzed using the electron microprobe, following petrographic analysis. These samples are not unusually enriched in the REE. Albite, orthoclase, biotite, chlorite, and allanite in order of decreasing modal proportion were found to contain appreciable concentrations of gallium. By contrast, the content of Ga in the  $Fe^{3+}$  mineral, aegirine, is below the limit of detection. Median Ga concentrations were ~250 ppm in albite, biotite, and chlorite and ~150 ppm in orthoclase. Variations of 200 ppm Ga or higher were observed in individual albite and orthoclase grains, and are linked to

hydrothermal alteration. Fluid inclusion-rich zones in albite and orthoclase are characterized by significantly lower Ga contents than fluid inclusion-poor zones, in both albitized and non-albitized samples. Chloritization of biotite resulted in a Ga enrichment of ~150 ppm. Based on these observations, albite and biotite are the principal hosts of Ga in the Nechalacho Syenite, Ga enrichment was independent of REE concentration and Ga was both enriched and depleted by hydrothermal processes.

#### **DISTINGUISHING METAMORPHOSED HYDROTHERMALLY ALTERED ROCKS FROM RESTITE USING PHASE EQUILIBRIUM CALCULATIONS, SHERRIDON COMPLEX, MANITOBA**

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Upper amphibolite facies assemblages consisting of garnet + cordierite + biotite + quartz  $\pm$  sillimanite  $\pm$  orthoamphibole  $\pm$  feldspar can develop in metapelitic rocks, restite formed via melt extraction from quartzofeldspathic rocks, and pre-metamorphic hydrothermally altered rocks. Determining which of these rock types is the precursor for rocks with these assemblages is difficult at uppermost amphibolite facies conditions when deformation is intense and partial melting is common. This study reports the results of phase equilibria modelling of bulk-rock compositional changes and mineral assemblage changes associated with partial melting and melt extraction of suitable precursors from the Sherridon Complex, Manitoba, in an effort to identify simple criteria that can successfully distinguish hydrothermally altered rocks from restite. Regionally metamorphosed rocks in the Sherridon Complex of the Trans-Hudson Orogen contain upper amphibolite facies gneiss dominated by quartzofeldspathic rocks (QF) containing garnet + biotite + plagioclase + quartz  $\pm$  K-feldspar assemblages and metapelite-like rocks (GCSB) containing garnet + cordierite + sillimanite + biotite + quartz  $\pm$  plagioclase  $\pm$  orthoamphibole assemblages. Although GCSB rocks have been interpreted as metapelites by some workers, they were recently interpreted as representing metamorphosed hydrothermally altered rocks. However, it is also possible some GCSB rocks represent restite derived from QF via significant amounts of melt extraction.

Phase equilibria modeling of partial melting of QF rocks in the MnNCKFMASHTO system indicates that GCSB assemblages can develop with episodic melt removal over the duration of the melting path. While this suggests it is possible that GCSB rocks might not represent hydrothermally altered rocks, there are three simple observations that indicate the majority of them are. The modes of garnet, cordierite, and orthoamphibole predicted for melt-extracted QF rocks never reach the observed modes in GCSB rocks. The mode of plagioclase predicted for melt-extracted QF rocks is significantly higher than commonly observed in GCSB rocks. Finally, an aluminum saturation index (molar  $Al_2O_3/(CaO+Na_2O+K_2O)$ ) predicted for melt-extracted QF rocks is generally <1.5 to 2, even at significant melt loss where orthoamphibole is predicted as stable, whereas GCSB rocks have indices ranging from 3 to 6. These three criteria can be observed during fieldwork, core logging, or using standard litho-geochemistry data collected during the course of a mineral exploration program, and serve as first-order methods to distinguish hydrothermally altered rocks from non-altered melt-extracted quartzofeldspathic rocks with assemblages containing garnet + cordierite + orthoamphibole  $\pm$  sillimanite. However, it is possible that moderate amounts of pre-metamorphic K-alteration could produce rocks that could subsequently have melt extracted, resulting in increased abundance of garnet, cordierite, and orthoamphibole.

## **A SPATIAL ANALYSIS OF THE GEOMORPHOLOGY AND GEOCHEMICAL ALTERATION OF COLD-BASED ZONES TRANSITIONAL WITH WARM-BASED ZONES, MELVILLE PENINSULA, NUNAVUT**

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The geomorphological characteristics of the cold-based zones and their gradual transition to warm-based zones is spatially analyzed using field observations, remote sensing data, geochemistry and GIS analysis. The cold-based areas of the Melville Peninsula are characterized by boulder fields. Similar features occur elsewhere, including the highlands from Baffin Island, the Torngat Mountains, the Appalachian Mountains and the Scandinavian Peninsula. The genesis of those boulder fields is probably a geologically long process that extends from the end of Tertiary to the Holocene, with enhanced frost shattering and permafrost activity during interglacial times, superimposed on variable, glacial and glaciofluvial processes during glaciations. Other geomorphological features are indicative of the influence of the Quaternary glaciers over the previously developed Tertiary (?) regolith, such as the high density of lakes, deranged river systems, landscape roughness, marks of glacial erosion, glacial macroforms and marginal glaciofluvial landforms. A quantitative to semi-quantitative GIS-based analysis, successfully depicts the effects of glacial erosion on the landscape, and outlines the pre-glacial landscape. To evaluate the impact of the ancient regolith and of the younger glacial activity on the interpretation of the surface sediments geochemistry, the observed and modeled geomorphological features will be compared to the geochemical indicators of alteration in surficial sediments, mainly sulfide minerals and major element geochemistry.

## **GOLD PROSPECTIVITY OF MAJOR FAULT ZONES IN THE ABITIBI SUBPROVINCE, CANADA: A QUANTITATIVE EVALUATION BASED ON LITHOLOGICAL AND REGIONAL ALTERATION INDICATORS**

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Major gold deposits in Archean greenstone belts are recognized to be associated with major fault and deformation zones. In the Abitibi Subprovince, three major gold-bearing fault zones can account for most of the gold production. They are, in order of relative importance, 1) the Cadillac-Larder Lake fault zone, 2) the Porcupine-Destor-Manneville fault zone, and 3) the Casa Berardi fault zone. However, many other fault zones are recognized all across the Abitibi Belt without any significant gold content. This relative fertility can be explained by genetic models that integrate 1) their relative significance in terms of movement, 2) their role as terrane boundaries or simply 3) their rooting in the crust to produce effective channel ways for hydrothermal fluids. On the other hand, empirical associations can also be proposed and some are listed as follows: 1) the spatial association with specific rock types such as ultramafic or Timiskaming type sedimentary units, 2) the presence of alkaline intrusions, 3) specific hydrothermal alterations such as pervasive carbonatization, 4) rheological contrasts between competent and incompetent units. However, no quantitative demonstration of these associations was performed for the Abitibi Subprovince. Recognized fault zones in the Abitibi belt were first divided and classified into 40 to 80-km segments with specific orientation and without any intersection with other fault zones. The abundance of specific rock types within a 2 km buffer zone of each segment was calculated. The chosen rock types were: 1) conglomerates,

2) alkaline intrusions, 3) alkaline volcanic rocks, 4) intermediate to felsic porphyry intrusions, 5) ultramafic intrusions and 6) ultramafic volcanic rocks. A lithogeochemistry database provided by CONSOREM partners was used to characterize alteration signatures around the different segments. Each segment was also classified according to its stratigraphic setting and structural characteristics. The number of gold showings and the past production and reserves of non-volcanogenic gold deposits were also compiled. Statistical analysis indicates that ultramafic volcanic rocks are the rock type that is best correlated with gold content in a fault zone segment. Conglomerates and intermediate to felsic porphyry intrusions are also significantly correlated. Correlations between rock types and gold content are noticeably higher when only segments that contain current or past gold producers are considered. Significant correlations are noted between gold content and some alteration indexes such as the 95<sup>th</sup> percentile of NORMAT IAB (albite), IPAF (carbonate) and IOR (orthose) alteration indexes.

## **3D GEOPHYSICAL INVERSIONS OF THE NORTHEAST AMER BELT AND THEIR RELATIONSHIP TO GEOLOGIC STRUCTURE**

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This study of a well exposed highly deformed supracrustal belt uses high resolution aeromagnetic and gravity data to develop geophysical models that can be applied where this belt unconformably underlies the northeast Thelon Basin. The Thelon is similar to the Athabasca Basin and has potential to host unconformity-associated uranium deposits where underlain by the supracrustal belt. The Amer Lake area is located approximately 160km northwest of Baker Lake, Nunavut. Located within the Churchill Structural Province in the District of Keewatin, the Amer Lake area comprises two distinct geological entities: Archean basement and the unconformably overlying Paleoproterozoic Amer Group metasedimentary belt. The basement comprises granitic to granodioritic gneiss with subordinate metabasalt and diorite intrusions. The Amer Group forms a major fold and thrust belt that stretches from east of Amer Lake toward the southwest below the NE Thelon Basin. At the NE end of this structurally complex belt, a selected study area has an oval shape interpreted overall as a broad southwest trending canoe-shaped D<sub>2</sub> synclinorium. Outcrop within the interior NE Amer Belt is sparse, making all geologic interpretations based on limited structural measurements speculative. Other structural geometries are possible. One hypothesis being tested geophysically is that the canoe-shaped structure may include a central dome generated by an interference fold-north-south trending fold axes of shorter wavelength interfering with longer wavelength east-west trending fold axes. Depending on the structural model, different estimates of depth to the unconformity surface will be invoked. Developing a better understanding of geological structures present in the Amer Belt is a useful precursor prior to attempting to determine the form of the unconformity surface between the Amer Belt and the overlying Thelon cover.

Extensive high-resolution aeromagnetic data is available over the synform. As well, intersecting gravity transects were completed during the summer 2010 during which a suite of samples were collected to petrophysically characterize the key lithologic units comprising the synform. A series of constrained and unconstrained inversions are performed on the aeromagnetic data to determine the validity of each structural model and generate an approximate depth to basement. To further test each hypothesis, synthetic models are generated for the two structural models and the calculated signal is compared to the observed signal in the ex-

isting aeromagnetic data. Finally the validity of the inversion models is checked by using the geometry from the inversions as input to forward modeling of the gravity data.

#### **ASSESSING LONG-TERM RATES OF SEDIMENT TRANSFER FROM GEOCHEMICAL AND LITHOLOGICAL INDICATORS, CHILLIWACK VALLEY, B.C.**

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Detailed sampling of fine (<63 µm) fluvial sediment geochemistry and coarse sediment lithology (up to boulder range) is used to provide an estimate of long-term sediment transfer in Chilliwack Valley, a large (1230 km<sup>2</sup>) Cordilleran valley in southwestern British Columbia. The geochemical and lithological composition of major source areas was compared with material sample from active river bars, in order to assess the relative contributions of each to the annual sediment budget.

Factor analysis helps to distinguish amongst freshly eroded granitic headwater source material, metamorphic rocks in the lower valley, and abundant till and floodplain sources throughout the catchment. A quantitative mixing model is proposed, based on the estimated volume of material stored in river floodplains and source area contributions. In the upper mainstem, the mineral concentrations show a distinctive pattern of recharge at each tributary junction, followed by downstream dilution. In the lower mainstem, the dilution effect is much stronger owing to the relatively larger mass of active floodplain sediments and lateral source material.

Yield of freshly weathered material from tributaries is low in comparison to transfers along the mainstem. Thus geochemical and lithological composition of the river load is strongly affected by the mean residence time and the volume of accessible floodplain material over the long term. In the case of Chilliwack River, long-term sediment transfer appears to be dominated by reworking of abundant stores of weathered till and alluvium.

#### **BLACK SHALE, METAL CONTENT AND OCEAN VENTILATION – RESULTS AND CAVEATS FROM THE ca. 1.1 Ga ARCTIC BAY FORMATION, BORDEN BASIN, NU**

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Redox-sensitive metal chemistry of black shale of the Mesoproterozoic Arctic Bay Formation (Bylot Supergroup, Borden Basin) permits examination of two important aspects of Proterozoic black shale accumulation. (1) Redox-sensitive elements can be used to make a first-order assessment of the shale basin's base-metal prospectivity, because basin euxinia is a precondition for precipitating economic metals from solution. (2) Redox-sensitive element systematics permit assessment of whether black shale geochemistry is a reliable proxy for global ocean ventilation in the Proterozoic. The redox-sensitive metal chemistry (Fe, Mo, U, Re) of black shales is increasingly being used to reconstruct important aspects of global atmospheric and oceanographic evolution. Molybdenum concentration is particularly useful in this regard.

Three stratigraphic sections, each several hundreds of metres thick, were measured, described and analyzed in the field for a suite of metals using a hand-held XRF device. The field data reveal many features of syn-sedimentary rifting, such as slope failure and missing parts of sections. A 24-sample stratigraphic traverse was subjected to detailed laboratory analyses (major elements, 4-step loss on ignition, ultra-trace elements and Pb-isotopes).

Arctic Bay Formation black shales show systematic stratigraphic variation in redox-sensitive metal content, in particular in

Mo, U, and V, but also Ni and Cd. The variable extent of U-enrichment led to development of reasonably radiogenic Pb, yielding an imprecise whole-rock isochron age of 1137±98 Ma. Interestingly, enrichment in redox-sensitive elements does not correlate with content of pyrite, Fe, Mn or reduced C, but is clearly associated with variations in dolomite concentration in the shale. This finding strongly suggests that secondary processes affected metal distribution in these unmetamorphosed shales. This would also explain enrichment in certain metals (e.g. Ni) for which oceanic redox models offer no convincing explanation.

Sedimentological and stratigraphic characteristics indicate that the Arctic Bay Formation was deposited in a rift graben during extension. Although no venting can be geochemically demonstrated for the vicinity of the section studied, the euxinic bottom-water chemistry would have been appropriate for the development of exhalative or polymetallic deposits if base metals were supplied in solution. Metal distribution in the black shales is complex, suggesting that the shales may have been affected by diagenetic metal redistribution. If undetected, such characteristics could easily lead to erroneous conclusions regarding global atmosphere-ocean evolution.

#### **BASAL MACKENZIE MOUNTAINS SUPERGROUP, YT AND NWT**

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The origin of the Mackenzie Mountains supergroup (MMSG) basin is unknown because exposures in NWT do not reach the base of the succession. Indirect evidence suggests that kilometres of strata may underlie the lowest known unit, the informal "H1 unit". Mapping in the Wernecke Mountains (YT) suggested that strata formerly assigned to the upper Pinguicula Group belong instead to the MMSG. The "H1 unit" and former Pinguicula Group units D-F are here documented in order to correlate from NWT into YT, to determine the nature of the extension that initiated the MMSG basin, and to trace the regional paleoenvironmental evolution of the lower MMSG.

The exposed part of the "H1 unit" (NWT; ~480 m) records pronounced but subtle shallowing from below storm wave-base (large, cusped stromatolites), through biohermal stromatolite and cortoid-intraclast grainstone intervals to an upper dolomitic quartzose wacke with symmetrical and asymmetrical ripples, tepees, and isopachous sea-floor cements. The sharp contact between upper "H1" shallow-water carbonate rocks and Tsezotene Fm. outer shelf siltstone indicates rapid rise in relative sea level that was probably caused by enhanced subsidence.

The lower MMSG in YT contains three new formation-scale units that are assigned to the revised and formalised Hematite Creek Group, which forms the base of the MMSG in YT and unconformably overlies unit C of the Pinguicula Group. The Dolores Creek Formation (black mudrocks and orange microbial dolostone; ~260 m) is overlain by the Black Canyon Creek Formation (cyclic peritidal dolostone; ~285 m) and Tarn Lake Formation (desiccation-cracked shallow-marine siltstone and sandstone; ~300 m). The Black Canyon Creek and Tarn Lake formations are probably stratigraphically equivalent to the 'H1 unit' and Tsezotene Formation in the NWT, respectively, but are strikingly different in composition and thickness, and have a subtly gradational contact; regional thickness and lithofacies variations suggest considerable paleobathymetric variation that is not consistent with patterns established in the NWT. Deposition of MMSG basal strata (Dolores Creek Fm.) took place in sulphidic but comparatively shallow water, which is compatible with early development of restricted rift basins.

The Hematite Creek Group is overlain by the Katherine Group (quartz arenite). The highest MMSG strata documented to date in YT belong to the lower Basinal assemblage (Little Dal Group). It is unknown how much of the upper part of the MMSG may be present in the Wernecke Mountains. The economic potential of the MMSG in YT is unknown and requires further investigation.

### THE BATHURST MINING CAMP IN 3D: RESOLVING THE HIDDEN STRUCTURE OF A POLY-DEFORMED REGION

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The Bathurst Mining Camp (BMC), NB, is host to numerous base metal deposits and occurrences, but the great majority of these were discovered over fifty years ago and almost all were identified because they directly outcrop at the surface or beneath a thin discontinuous glacial veneer. As with many mature mining camps, the likelihood is that if there are significant deposits awaiting discovery, then they will be hidden or deeply buried. Despite the poor outcrop control across the BMC and its structural complexity, the spatial distribution of units at the surface is reasonably well established. However, prior to this study, the trace of these units to depth has, for the most part, been only very poorly constrained. In part this is due to the prevalence of steeply dipping fabrics over much of the BMC that do not necessarily reflect the overall enveloping surface of the mineralised horizons. Detailed investigation and integration of geophysical and geologic data provides an improved understanding of the 3D geological structure, which in turn will enhance the ability to vector in on mineralised horizons, even into areas that have hitherto been considered to be largely unprospective.

The data used for the modelling are the 1994 EXTECH II airborne geophysical survey for total field magnetic field, resistivity and gamma spectrometry, TGI 3 2006/2008 ground gravity surveys and the Government of New Brunswick's digital elevation model that gives a 70 m topography grid for the region. These data are reprocessed and combined to produce a series of transects across major structural and/or economically significant parts of the BMC.

The thickness of units is derived primarily by Bouguer gravity, and this shows that the Flat Landing Brook Formation extends to below 10 km in the central portion of the BMC, and the Nine Mile Synform amplitude in excess of 5 km. A large wavelength gravity anomaly to the southeast of the BMC is interpreted as a hidden ophiolite, for which the Tomogonops Formation is in part its cover, as opposed to it overlying the Little River Formation. Models also indicate that the Miramichi Group is tectonically emplaced as thin sheet over the younger Sheephouse Brook felsic volcanic rocks and the associated Chester ore horizon, effectively increasing the area of high mineral prospectivity by approximately 35%.

### GROUND PENETRATING RADAR FIELD CAMPAIGNS AT CANADIAN IMPACT CRATERS IN SUPPORT OF PLANETARY SCIENCE

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Ground Penetrating Radar (GPR), a widely used technique in near-surface terrestrial geophysics, is commonly cited as an important future technique for examining other rocky bodies in the solar sys-

tem. Field campaigns in 2010 were carried out at Houghton impact structure, Devon Island, Nunavut and Mistastin Lake impact structure, Labrador over impact-related breccias. These campaigns were carried out for the purpose of field testing GPR in the context of lunar and planetary exploration. At Houghton, 200, 100 and 50 MHz 3D GPR surveys comprising 562 lines on a 30 × 30 m grid were carried out over frozen calcite-dominated impact melt rocks in an attempt to simulate the radar propagation conditions expected in a lunar environment. At Mistastin, 250 MHz 6 parallel lines (2.5D) were collected over anorthosite-rich polymict brecciated units chosen to match the principal mineralogical component of the Moon (anorthosite). After processing and plotting in 2D and 3D, we tested depth of penetration. Initial results suggest that the depth of signal penetration is less on brecciated material due to complex signal scattering. The scattering may reduce the usefulness of GPR when operated at frequencies normally considered useful in other typical terrestrial settings. 3D processing of the results allows for visual identification of features to approximately 20% greater depth than 2D. Additional lab testing of samples and modelling of the Houghton site is expected to confirm these results.

### ALTERATION SYSTEMS IN THE SHEA CREEK DEPOSIT (ATHABASCA, CANADA): VERTICAL VARIABILITY OF CLAY ALTERATION

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Shea Creek is the most advanced uranium exploration project in the western Athabasca basin (Saskatchewan, Canada). It is an unconformity related deposit and the major discoveries were made at depths ranging from 700 m to 900 m below surface.

In this project the three types of mineralization reported in different unconformity deposits of the Athabasca basin are found together with 1) perched mineralization in sandstone, 2) mineralization at the contact between sandstone and basement, and 3) mineralization located within the basement up to 200 m below the unconformity. Shea Creek can be considered as a reference for the exploration of deep seated uranium deposits in the Athabasca basin.

These various types of unconformity mineralization are surrounded by large alteration haloes used as pathfinders in exploration. The ongoing work's objective is to improve the knowledge of the spatial and temporal relationships between mineralization and host rocks alteration. The study of a reference drillhole intersecting mineralization and alteration at different levels in the Kianna prospect (central part of the Shea Creek project) reflects mineralogical heterogeneity in alteration of both basin sandstone and basement rocks.

In the sandstone, a broad vertical heterogeneity is noted in the compaction rate and pressure solution associated with sediment diagenesis, in particular at the basin basis where an under compacted zone is developed. Kaolinite (not dickite) is the diagenetic mineral marker of the under-compaction zone while illite is the marker of later hydrothermal alteration. Hydrothermal alteration in sandstone is observed up to the present erosion surface.

In the basement rocks, the alteration is guided by intense fracturing and faulting (brecciation) and is characterized by the development of clay gouges. Such structures can be traced to the deepest drilled level (934 m). Illite, sudoite and trioctahedral chlorite are the main markers of alteration. Illite and sudoite were formed prior to trioctahedral chlorite.

Smectite and aluminium phosphate- sulfate minerals (APS) are present on both sides of the unconformity.

The average concentration of light rare earth elements increases strongly close to the mineralized bodies. In the sandstone, this chemical signature can be detected up to 200 m above the perched mineralization.

The model of clay mineral distribution and associated mineral phases (APS) will be used as a reference for ongoing alteration study (~50 drillholes) at the Shea Creek project.

#### **RECHARGE OF PERENNIAL GROUNDWATER DISCHARGING IN THE CONTINUOUS PERMAFROST WATERSHED OF THE FISHING BRANCH RIVER, NORTHERN YUKON**

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Groundwater discharge along a 15 km perennially ice-free section of the Fishing Branch River sustains an important chum salmon population near Bear Cave Mountain, situated on the Arctic Circle in the northern Yukon. A significant hydrological feature in regions of continuous permafrost, the site was the focus of this geochemical and isotopic investigation of springs and discharge to elucidate the origin and mechanisms of groundwater recharge. Groundwater flow occurs in karsted marine carbonate rocks as well as alluvial river talik. Precipitation at Old Crow shows a bimodal isotope distribution ( $\delta^{18}\text{O} = -28$  to  $-33\text{‰}$  Oct to March and  $-13$  to  $-17\text{‰}$  April to August) while groundwaters and river water are remarkably invariant with values near  $-21\text{‰} \pm 1\text{‰}$ . This suggests considerable groundwater storage within the catchment with no seasonal bias in recharge. This is supported by  $^3\text{H}$ - $^3\text{He}$  ages which provide mean circulation times up to 17 years. Measured DIC, pH,  $\delta^{13}\text{C}_{\text{DIC}}$  and calculated  $\text{P}_{\text{CO}_2}$  indicate groundwater dissolves  $\text{CO}_2$  during recharge through organic soils and weathers limestone in the aquifer, with geochemical facies corresponding to variations in bedrock geology. Recharge temperatures between 0 and  $5^\circ\text{C}$  from Kr and Xe concentrations suggest thermal equilibration with ground temperatures and no significant influx of enthalpy by recharge during warm summer months. Recharge and flow in permafrosted karstic terrain is shown to be very similar to that in temperate climates.

#### **BC YEAR OF SCIENCE: PARTNERSHIPS TO PROMOTE YOUTH ENGAGEMENT WITH SCIENCE, THROUGH WEB-BASED ACTIVITIES, SCIENTIST PROFILES, AND CLASSROOM AND COMMUNITY PRESENTATIONS**

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British Columbia has designated the 2010/2011 school year as the 'BC Year of Science' (YoS). The slogan "Choose Science. Go Far", reflects the goal of YoS to raise awareness among young people in BC of the value of a science education, and the range of jobs and careers available, through such an education, in science, technology, engineering and math-related fields. BC's YoS is also "a unique opportunity to discover the fun and excitement of science" and engage our youth and communities in science activities and events.

The University of Victoria has developed partnerships with two BC Ministries (BC Ministry of Advanced Education and Labour Market Development, and BC Ministry of Forestry, Mining and Lands), as well as with the community (including school districts across BC, teachers, and community education groups) to promote

science awareness through two projects: Earth Science and Society, and Science in Our Lives. Earth Science and Society trains and mentors university students (the next generation of science educators and outreachers) to deliver Earth science classroom presentations to schools and communities across BC, on societally relevant topics ranging from Water, Earth Resources and Sustainability, Oceans and Climate Change, Reading the Rocks to Understand Earth's Dynamic Past, Plate Tectonics, and Earth Science and Society. A teacher professional development program is also part of this initiative. The Science in Our Lives project is a collaboration between the University of Victoria's Faculty of Science and Pacific CRYSTAL to develop a series of web-based Science Activities of the Month, featuring science that impacts society (e.g. December-Science to Understand Our Forests: What conifers live near you, and how healthy are they? Or January – Mathematics and Society: Exploring how voting systems can impact election results). Accompanying each hands-on activity is a scientist profile or "5 Minutes with a Scientist" designed to dispel the myths and misconceptions around the real people that scientists are. These personal glimpses into scientists' lives are designed to assist young people as they consider potential careers in science.

#### **ALTERATION OF THE LUNDBERG AND ENGINE HOUSE ZONE POLYMETALLIC STOCKWORK**

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The Lundberg and Engine House Zones form a peripheral polymetallic stockwork to the ~5.5 Mt Lucky Strike volcanogenic massive sulfide deposit, Buchans, Newfoundland. The stockwork is characterized by veins of massive pyrite, massive quartz-carbonate, disseminated or blebby sphalerite-galena-chalcocopyrite, bladed barite and carbonate, massive polymetallic sulfide veins, and small quartz-carbonate veins with little or no sulfide. Where present, the bladed minerals occur at the top of the mineralized zone suggesting infiltration of seawater during the precipitation of barite and possibly boiling of the hydrothermal fluid and the precipitation of bladed calcite. Five largely concordant alteration facies were identified: a siliceous core zone, quartz-chlorite, quartz-sericite, weak sericite  $\pm$  carbonate, and phengite-quartz-carbonate-chlorite. The siliceous core zone is a proximal alteration facies within and surrounding the stockwork mineralization and locally cutting the entire succession in the center of the Lundberg Zone. The quartz-chlorite facies is proximal to stockwork mineralization within basaltic andesite. It is characterized by CCPI (chlorite-carbonate-pyrite) and AI (Ishikawa) indices larger than 90 characteristic of intense silicification, chloritization, and lesser sericitization. The quartz-sericite zone is more distal to stockwork mineralization above the quartz-chlorite zone within andesite. It is characterized by lower CCPI and AI indices, and larger gains in  $\text{K}_2\text{O}$  than the quartz-chlorite zone. The sericite  $\pm$  carbonate zone occurs above the quartz-sericite zone. CCPI and AI indices are typical of weakly sericitized rocks with weak carbonate alteration. Mass gains within the Buchans River Formation, which hosts the nearby Lucky Strike deposit, are heterogeneous and much lower gains than within the underlying basaltic andesite, which hosts the Lundberg Zone. The structurally emplaced hanging-wall rhyolite is altered to phengite-quartz-carbonate-chlorite facies and is characterized by both CCPI and AI indices typical of diagenesis and only weak hydrothermal alteration.

Shortwave infrared spectroscopy (SWIR) was used to characterize the alteration mineralogy in these assemblages. Relative proportions of chlorite and illite were calculated from the depths of chlorite and illite absorption features and gave results similar



to least-squares calculations of normative mineralogy based on whole-rock geochemistry. Chlorite and white mica were readily identified with strong, contrasting absorption features; quartz addition dramatically decreased the slope of the spectra. Within the sericite-quartz-carbonate-chlorite alteration facies, shortwave infrared spectroscopy clearly identified phengite as the dominant muscovite, distinguishing proximal versus distal alteration in the thrust emplaced hanging-wall succession. Short wave infrared spectroscopy therefore provides a useful exploration tool, supplementing chemostratigraphy for defining favourable horizons within the Buchans mining camp.

#### **ADSORPTION, TRANSFORMATION, AND BIOACCESSIBILITY OF NICKEL SPECIES IN SOIL**

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To understand risks and develop effective remediation strategies for nickel in soil, it is necessary to correctly identify the nickel species present within the soil. Artificial (OECD) soils were spiked with various nickel compounds ( $\text{NiSO}_4$ ,  $\text{NiO}$ ,  $\text{NiS}$ , and  $\text{Ni}_3\text{S}_2$ ) and then subjected to a series of wet-dry cycles to rapidly age the soils, simulating the natural oxidation of nickel which would occur in the environment. The nickel species present in the soils were identified using X-ray Absorption Near-Edge Structure (XANES) Spectroscopy. Microprobe experiments using synchrotron radiation were undertaken to determine with which soil components the nickel is associated. Mineral Liberation Analysis (MLA) was performed to identify the nickel mineralogy in the soil samples, and bioaccessibility and sequential extraction were used to assess the bioavailability. The MLA and SR-microprobe experimental results are compared to better understand the usefulness of these techniques in identifying metal species present in environmental samples. In conjunction, these tools (speciation and bioaccessibility) are instrumental for the management of soil Ni contamination.

#### **GEOLOGY OF THE SOUTH-CENTRAL SEAL LAKE GROUP, LABRADOR: GRENVILLIAN DEFORMATION OF A MESOPROTEROZOIC COPPER-BEARING SUPRACRUSTAL SEQUENCE**

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The Mesoproterozoic (ca. 1250 Ma) Seal Lake Group is the youngest supracrustal sequence of the Central Mineral Belt in Labrador and consists of predominantly clastic sedimentary rocks and amygdaloidal basalt flows which are intruded by gabbro sills. The rocks are disposed in a regional-scale, doubly-plunging syncline of which the southern limb has been variably deformed and overturned to the north along several southward-dipping Grenvillian thrust faults and ductile shear zones.

Strata within the core of the syncline near the southeast-plunging western closure of the fold structure are partially overthrust and tectonically overridden by greenschist facies rocks on the overturned limb. The southwestern extent of the Seal Lake Group is marked by a complexly reactivated unconformity with older felsic volcanic and associated rocks of the Mesoproterozoic Letitia Lake Group.

In the southern area, recumbent and north-verging folds, south-dipping mylonitic fabrics and other kinematic indicators affect both basement and multiphase-deformed cover rocks near the inverted sub-Seal Lake Group unconformity. These structures indicate a predominant northwestward movement along several dip-slip thrust faults. The southern margin of the group is also in fault

contact with Paleoproterozoic granitoid rocks of the North Pole Brook intrusive Suite.

Two of the upper stratigraphic formations of the Seal Lake Group are host to several historical copper prospects and showings associated with localized shearing of the contacts of clastic sedimentary rocks, basalt flows and gabbro sills. In contrast, elevated radioactivity is recorded from supracrustal rocks in the stratigraphically lower formations of the group and is a possible indication of uranium mineralization.

#### **Ar/Ar THERMOCHRONOLOGY IN THE THOR-ODIN DOME, BRITISH COLUMBIA: TECTONIC IMPLICATIONS FOR CRETACEOUS TO EOCENE TIME-TEMPERATURE COOLING PATHS**

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In the Thor-Odin dome, high-grade metamorphic rocks that were polydeformed in the Late Cretaceous to Eocene are exposed in the footwall of extensional fault systems. The transition between regional shortening and extension occurred in the Eocene and was concomitant with denudation, the cause of which (extension, extrusion and/or diapirism) is controversial. Lithotectonic domains, with different tectonothermal histories, within an ~12 km thick south-southwest dipping panel of rocks include the Thor-Odin dome, overlying margin at Cariboo Alp, and structurally overlying panel of rocks on the dome's southern flank. Cooling paths were constructed for different structural levels within the section using U-Pb zircon, monazite and titanite geochronology data in conjunction with new hornblende, biotite and muscovite  $^{40}\text{Ar}/^{39}\text{Ar}$  data. The timing of deformation at peak temperatures and U-Pb zircon crystallization ages in leucosomes youngs downward through the section, and is ca. 80-60 Ma at the highest structural level on the southern flank of the dome, ca. 62-58 Ma at Cariboo Alp, and ca. 56-52 Ma in the dome. No geologically reasonable hornblende cooling dates were obtained from the dome due to excess argon. However, hornblende cooling dates are ca. 60-55 Ma at the highest structural level and ca. 55-53 Ma at Cariboo Alp. Biotite cooling dates are all ~52-51 Ma; they are identical throughout the dome, margin and overlying panel. Thus, the cooling paths for the three domains show that they cooled at different rates from ~700°C to ~300°C; however, they all reached the biotite closure temperature at ca. 52 Ma, indicating that the panel was tilted and cooled to ~300°C prior to ca. 52 Ma. Muscovite from Cariboo Alp and the dome have  $^{40}\text{Ar}/^{39}\text{Ar}$  ages of  $51-50.5 \pm 0.2$  Ma. The muscovite is intergrown with chlorite, indicating low-grade conditions and muscovite growth below its closure temperature of ~400°C. Therefore the ca. 51 Ma date is a crystallization age. Because the muscovite is restricted to extensional structures, muscovite ages date extension in the dome at ca. 51 Ma. Geology and geochronology document a downward younging progression of thermal-peak metamorphism and leucosome crystallization, which is consistent with internal deformation within a strained crystalline thrust sheet overriding a basement ramp, creating a tilted section. Exhumation in the upper part of the section was ongoing during the last stages of transposition and folding in the dome during northeast-directed transport over a basement ramp in the Eocene at ca. 56-54 Ma. By ca. 51 Ma, extensional structures were active at all structural levels reflecting crustal scale extension.

# DOES THE MONASHEE COMPLEX (FRENCHMAN CAP DOME AND THOR-ODIN DOME) REPRESENT A SINGLE BASEMENT DOMAIN? IMPLICATIONS OF NEW LA-ICP-MS DETRITAL ZIRCON DATA FROM THREE QUARTZITES IN THOR-ODIN DOME, BRITISH COLUMBIA

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The structural culminations of the Thor-Odin and Frenchman Cap domes in the Monashee complex of south-eastern British Columbia comprise Paleoproterozoic Laurentian “basement” orthogneiss and paragneiss, and Proterozoic to Paleozoic predominantly supracrustal metasedimentary “cover” rocks. In both domes, a quartzite marker at the base of the cover rocks has been interpreted as: i) unconformable on basement, and, ii) the same unit in both domes. This formed a basis for correlating the two domes; it has been accepted that the two domes are part of the same basement domain and have a shared history. However, we question this because of differences in basement lithology and age, timing of deformation and tectonothermal history. Detrital zircon U-Pb age data from three Thor-Odin dome quartzites (i.e. Mount Thor and Icebound Lake in the dome interior and Cariboo Alp on the southwestern flank) form a basis for comparisons with the basal quartzite in the Frenchman Cap dome. The Mount Thor and Icebound Lake quartzites have: major detrital zircon age populations from ca. 1.9–1.65 Ga; minor populations spanning ca. 2.2–2.8 Ga; and minor populations >3.0 Ga. The youngest zircons indicate that the quartzites are younger than ca. 1.65 Ga. In comparison, the basal quartzite in Frenchman Cap is older than ~1.85 Ga, based on the presence of crosscutting igneous rocks, and should be interpreted as part of the basement with respect to the Cordilleran orogen rather than as part of its cover. The Cariboo Alp quartzite has major detrital zircon age populations from ca. 1.9–1.65 Ga and ca. 1.1 Ga, and minor populations between ca. 1.2–1.4 Ga and >3 Ga. The youngest zircons indicate that the quartzite is younger than ca. 1.1 Ga. This quartzite is younger than the so-called basal quartzites in both the Thor-Odin and Frenchman Cap domes, and has a different provenance. Results of this study and comparisons with published data show that there are at least three quartzites of different ages in the unit previously thought to represent the basal quartzite marker horizon of the cover sequence overlying basement. Taken together with different ages of basement rocks, differences in peak metamorphism and style of deformation in the two domes, the LA-ICP-MS detrital zircon quartzite data support the conclusion that the Monashee complex is made up of two different basement domains that have different basement geology, cover sedimentation and tectonothermal histories as far back in time as the Paleoproterozoic and as recently as the Eocene.

## BIRTH, LIFE AND DESTRUCTION OF THE CELTIC MICROPLATE AND ITS CAUSAL RELATIONSHIP TO SILURIAN THROUGH DEVONIAN OROGENESIS IN THE APPALACHIAN-CALEDONIAN MOUNTAIN BELT

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The number, size and extent of the peri-Gondwanan microcontinents in the Appalachian-Caledonian orogen and when and how they accreted to Laurentia have been a matter of ongoing debate. Three microcontinents have been recognised in the Canadian Ap-

palachians: Ganderia, Avalonia and Megumia, which are generally held responsible for the Silurian through Devonian orogenesis. This contrasts with the one microcontinent (Avalonia) view generally held in the British Caledonides. Existing stratigraphic, geochemical, paleontologic and paleomagnetic data combined with several other independent recently published lines of evidence, suggest connections among these three terranes and a formation close to one another. All three areas show evidence for having been being situated along Gondwana's Amazonian margin (Ganderia) and/or near the junction of Amazonia and West Africa (Avalonia and Megumia). Rifting in Avalonia and Megumia started at ca. 550 Ma and culminated with the departure of Avalonia by ca. 475 Ma. We propose that Megumia was still attached to Avalonia at this stage, albeit separated by an unfinished rift. Ganderia rifted-off slightly earlier at ca. 505 Ma, while its leading edge was an arc. Diachronous departure of these three terranes opened the Rheic Ocean from west to east and isolated them on the Celtic microplate, with a seaway of pre-Rheic oceanic lithosphere separating Avalonia and Ganderia. This microplate must have had a plate boundary to the east with elements of the Armorican terranes; its boundary to the west is unknown. Tectonic and paleomagnetic constraints suggest that the leading edge of the Celtic microplate (Popelogan-Victoria arc), had a latitudinal drift of ca 9 cm/a until it collided with Laurentia (situated at 20°S) at ca. 455 Ma, whereas the rest of the microplate had a similar drift rate between 490 and 470 Ma, but slowed down to ca 5 cm/a thereafter. The discrepancy of 4 cm/a between these two drift rates was compensated by seafloor spreading in the Tetagouche-Exploits backarc basin after 470 Ma, which split the Ganderian part of the Celtic microplate into two parts. The Gander margin and Avalonia accreted to composite Laurentia at ca 440 Ma (start of Salinic orogeny) and 421 Ma (start of Acadian orogeny), respectively. Continuous Ordovician rifting between Avalonia and Megumia may have culminated in opening of a narrow oceanic seaway at ca. 440 Ma, but accretion of Megumia to Laurentia at ca. 395 Ma (start of Neocadian orogeny), suggests that spreading, if it indeed happened, cannot have amounted to much.

## MULTIPLE MAGMATIC EVENTS THROUGH THE TERTIARY AND QUATERNARY IN THE FISH CREEK MOUNTAINS, GREAT BASIN, NORTH-CENTRAL NEVADA

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The Great Basin of the western United States is a region of Cenozoic lithospheric extension and volcanism that includes the state of Nevada and parts of southeastern California and western Utah. Beginning approximately 50 Ma, a magmatic front began migrating southwestward across southern Idaho, central Oregon and into northern Nevada and Utah. Intermediate, “arc-like” andesite and dacite dominated volcanic activity in northeastern Nevada between about 45 and 36 Ma. By 34 Ma, a northwest-trending belt of rhyolitic ash-flow calderas began to develop through central Nevada, the “ignimbrite flare-up”. Volcanism then migrated westwards towards the Sierra Nevada. The Fish Creek Mountains, located in north-central Nevada, is a site of multiple igneous events ranging from ca. 35 Ma to 1 Ma, covering most of the igneous history of the Great Basin. The oldest lavas are basaltic andesites through dacites that are exposed in the western Shoshone Range, the eastern Tobin Range, and the northern and eastern Fish Creek Mountains. Plagioclase-rich andesites, dacite intrusions, and volcanic breccias occur in a belt along the western side of the Fish Creek Mountains. The bulk of the Fish Creek Mountains is com-

posed of the 24.7 Ma Fish Creek Mountains rhyolitic tuff that is largely confined to an undeformed caldera structure. The caldera and tuff are anomalously young compared to nearby felsic centers such as the Caetano caldera (33.8 Ma) and Shoshone Range (39–35 Ma) and relative to the southwest to west magmatic migration. The basal tuff is unwelded, with abundant pumice and lithic (primarily volcanic) fragments but only rare crystals. Sanidine and smoky quartz phenocrysts become more abundant upsection and glassy fiamme (hydrated to devitrified) are common, but the abundance of lithic fragments diminishes. Along the northwestern margin of the Fish Creek Mountains and in the center of the caldera complex are exposed late Pliocene to Quaternary lava flows and cinder cones of the Buffalo Valley volcanic field. The Buffalo Valley volcanic rocks are alkalic basalts that are locally vesicular, with rare plagioclase and olivine phenocrysts as well as plagioclase megacrysts up to several centimeters in size. Trace element and isotopic characteristics are similar to those of the Pliocene-Pleistocene Lunar Craters volcanic field in central Nevada. Ongoing geochemical analyses will outline variations in mantle sources and post-melting processes in the multiple volcanic systems of north-central Nevada.

### THE ROLE OF SUN AND WATER IN THE FATE OF CARBON DIOXIDE AND CLIMATE

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Terrestrial water and carbon fluxes represent one of the largest movements of mass and energy in the Earth's outer spheres. The studies of large watersheds in North America, South America, Africa, Australia, and New Guinea show that approximately two thirds of the annual water flux from ecosystems typical of higher-latitude regions can be attributed to plant transpiration. Transpiration in high-rainfall, densely vegetated regions of the tropics represents a smaller proportion of precipitation and is relatively constant, defining a plateau in response to incident solar radiation, while at high latitude the transpiration is water limited.

The patterns of water transpiration and net primary productivity mirror each other, confirming that the terrestrial water and carbon cycles are inherently coupled via the biosphere. This offers a conceptual perspective on the dynamics of energy exchange between terrestrial systems and the atmosphere, where the carbon cycle is essentially driven by solar energy via the water cycle intermediary; a scenario consistent with the review of climate proxy data on geological as well as anthropogenic time scales.

### CRYSTAL STRUCTURE, MOSAICITY AND STRAIN ANALYSIS OF HAWAIIAN OLIVINES USING IN SITU X-RAY DIFFRACTION

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Deformation of olivine in a volcanic context is poorly constrained, although deformed olivine is abundant in some volcanic rocks, and its presence is important for the definition of the magmatic history of volcanic edifices such as Kilauea Volcano, Hawaii. Deformed olivines at Kilauea originate in the lower crust; therefore, the classic approaches and interpretations applied to mantle-derived olivine are not applicable here. Deformed olivine crystals from Kilauea lava samples were examined using an in situ XRD technique. Our results validate and refine optical observations of olivine deformation. We also confirm the presence of deformation for olivine crystals of any size, and quantify it. There are significant correlations between deformation intensity (strain-related mosaicity) and olivine composition and crystal size. Although this

technique does not allow the simple estimation of the P-T conditions of deformation and crystal formation or magmatic history, some constraints have been provided here, in particular the threshold degree of mosaicity, above which we consider that a crystal underwent deformation. In situ XRD is shown here to be an easy-to-use, fast, low-cost, non-destructive technique, which is less-ambiguous than optical microscopy, to determine the presence of strain in the crystal structure of magmatic olivines, and quantify it, especially for very small crystals. For crystals optically exhibiting subgrain formation, analysis of asterism by in situ XRD has been used to reconstruct the mosaic spread of the original grain, and thus its original strain condition prior to subgrain formation.

### PROCESS OPTIMIZATION AT THE SAINTE-SOPHIE ANAEROBIC BIOREACTOR LANDFILL, QUEBEC, CANADA

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Bioreactor landfills promote treatment of waste through enhanced biodegradation, thereby reducing the long-term environmental and health risks associated with unstabilized waste in conventional landfills. Rapid waste biodegradation and stabilization, in turn, provide additional advantages of increased landfill gas production (which can be recovered and transformed to energy) and enhanced waste settlement (which maximizes air space and limits the creation of additional landfill footprint). Despite the proposed advantages and the ongoing research regarding bioreactor landfills in the past several decades, the knowledge behind optimal process control of a full-scale bioreactor landfill is still limited as environmental conditions and operating practices vary in the field.

Field research is being conducted at an operational full-scale bioreactor landfill in Sainte-Sophie, Quebec, to develop a better understanding of how operating practices and environmental conditions at a bioreactor landfill operating in a northern climate impact waste stabilization. Starting in November 2009, instrument bundles were installed in the bioreactor landfill cell, as it was progressively filled with waste. To date, three pairs of instrument bundles have been installed within the waste at heights of 0 m, 3 m, and 5.5 m from the cell floor. This presentation will focus on the design and installation of the instrument bundles and the corresponding data collected from each sensor. The instrument bundles include sensors which measure in situ temperature, oxygen content of the air space, moisture content, electrical conductivity, settlement, mounding of leachate, and total load. Data accumulated to date indicate that waste is an excellent insulator against extreme ambient temperatures. Waste placed during winter remained below freezing for the entire subsequent summer, thus significantly delaying the onset of biodegradation and inhibiting settlement. Data from the oxygen sensors show that pore space of the waste gets depleted of oxygen more rapidly than expected. These data and the results anticipated over the next two years will provide valuable insight to assist bioreactor landfill managers to optimize the operations at their facilities.

# MICROSTRUCTURAL CONTROL ON PENTLANDITE EXSOLUTIONS FROM MONOSULFIDE SOLID SOLUTION IN KOMATIITE HOSTED NI SULFIDES FROM THE YILGARN CRATON, WESTERN AUSTRALIA

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Initial crystallization of monosulfide solid solution (MSS) from magmatic sulfide liquid occurs at about 1150°C. For typical Ni-rich sulfides as found in komatiites, pentlandite ((Fe, Ni)<sub>9</sub>S<sub>8</sub>) first starts to exsolve from MSS at around 600°C, and continues to exsolve down to below 250°C, changing in morphology from intergranular blebs to fine lamellae with falling temperature.

Sulfide assemblage in komatiite-hosted deposits consist of intergrowths of pyrrhotite (Fe<sub>1-x</sub>S), pentlandite, pyrite (FeS<sub>2</sub>) and chalcopyrite (FeCuS). To understand the relationship between these phases we used optical microscopy, electron backscatter diffraction (EBSD) and microprobe analyses on samples from high and low grade metamorphic terranes in Western Australia. The sulfide assemblages at low metamorphic grade preserve pockets of annealed “foam” textures inherited from original post-magmatic cooling, whereas sulfides that have been exposed to higher metamorphic grade and high strain retain high-temperature deformation textures. Pyrrhotite from both types shows deformation features (kink bands, subgrains and new grains) closely related to the presence of pyrite and/or pentlandite.

EBSD is used as a tool to understand crystal-plastic deformation in both isotropic (pyrite and pentlandite) and anisotropic (pyrrhotite) minerals. We succeeded in producing for the first time EBSD maps on pentlandite grains. EBSD maps showed that the majority of the deformation is accommodated by pyrrhotite, followed by pentlandite and pyrite respectively. EBSD maps of pentlandite grain show the presence of internal subgrains and enable determination of active slip systems in all the sulfide phases.

Combined EBSD analysis and microprobe elemental mapping shows that some of the pentlandite exsolutions from pyrrhotite are closely related to low angle subgrain boundaries in pyrrhotite. Ongoing research is addressing the question of whether exsolution is governed by the deformation microstructures and if so, at what stage in the cooling and deformation history does exsolution takes place. Results are significant for the interpretation of tenor variations within nickel sulfide ores.

## MORPHOLOGY AND EVOLUTION OF A CHAMPLAIN SEA ICE-CONTACT DELTA COMPLEX, UPPER OTTAWA VALLEY

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Remnants of an ice contact delta were studied in the upper reaches of the Ottawa Valley near Beachburg, Ontario. The delta was formed by glacial meltwater flowing off an ice lobe of the Laurentide ice sheet, as it retreated north-northeast across the present-day Ottawa Valley. Ice flow direction was controlled in part by pre-existing bedrock topography with the irregular surface of the bedrock affecting the latter stages of ice retreat and post glacial drainage. The thinning ice sheet was drained by three distributaries which deposited sands and gravels creating three deltas which partially coalesced into one large delta complex. The delta began to obscure evidence of the moraine and the ice began another phase of retreat. With the retreat of the ice several stagnant blocks formed kettles and controlled drainage across the delta. Rising waters of the Champlain Sea eventually crested the abandoned delta,

reworking the sediments by wave action. Gradual emergence of the complex exposed the remnants of the three discrete deltas. Further lowering of sea level exposed the merged delta complex, with the delta fronts reworked by shoreface processes. Shoreface processes continued to modify the remnants of the delta and receding waters left a series of raised beaches. The waning Champlain Sea was gradually replaced by the broad reaches of the proto-Ottawa River. Modification of the delta complex continued through wave action and increasing fluvial processes, forming spits and beach ridges. The Champlain Sea was a body of water of variable salinities; initially the waters in the area of the delta were cold and with their greatest salinity concentration suggested by *Hiattella arctica*. Salinity decreased and the cold waters warmed as evidenced by the presence of *Macoma balthica* preserved within beach ridge sediments.

## CARIBBEAN IN IAPETUS?

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The history of the modern Atlantic shows that the transition from an opening to a closing ocean is not initiated by subduction of the oldest, coldest ocean floor. The central Atlantic margins are 200 Ma old but are still passive. In contrast, the Caribbean and Scotia arcs represent eastward translation of Pacific ocean floor into the Atlantic realm, and have led to the subduction of Atlantic oceanic crust as young as Neogene.

The margins of the Iapetus Ocean appear to have originated by Atlantic-style rifting in the latest Neoproterozoic, but in contrast to the Atlantic Ocean, Iapetus appears to have entered a closing phase within 60 Myr, when collisional deformation and ophiolite emplacement affected both the Laurentian and Gondwanan margins, marking the earliest phases of Taconian and Penobscot/Monian deformation. The earliest convergent orogens to form on the margin of Iapetus were highly non-cylindrical, as is apparent in the contrasting histories of the peri-Laurentian Dashwoods and Precordilleran fragments. The non-cylindrical character of the Laurentian margin persisted through Ordovician and Silurian time, producing contrasts in the style of accretion tectonics in Newfoundland and the UK. The distribution of peri-Gondwanan fragments in the orogen shows that the SE margin of Iapetus was also characterized by major along-strike variations.

The early evidence of subduction, and the premature closing of the Iapetus Ocean, can be explained if an arc, comparable to the modern Caribbean, was translated westward between Gondwana and Baltica into Iapetus early in its opening history, eventually colliding with the Laurentian margin in the Ordovician Taconian orogeny. A complex realm of arcs, inter-arc basins, and microcontinents, analogous to the modern Caribbean, contained components of the Exploits back-arc basin, Ganderia and Avalonia. The Tornquist collision zone may have evolved from the northern strike-slip margin of this region. Deformation, probably including oblique subduction, along the southern margin of this realm may account for Early Ordovician Penobscot/Monian events in peri-Gondwanan terranes. Tectonic reconstructions of the resulting orogen need to take into account the likelihood of major rotations and along-strike variations in convergence history, and the possibility that coherent Proterozoic terranes may have been fragmented during their Paleozoic history.

## CRYSTAL SIZE DISTRIBUTION ACROSS THE MERENSKY REEF PACKAGE OF THE BUSHVELD COMPLEX

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The Merensky Reef, host to a world-class deposit of platinum group elements, is a texturally distinctive layer that occurs at the top of the Upper Critical Zone in the Bushveld Complex of South Africa. A "normal" reef package (~1 m thick) consists of sulphide-bearing (2-4 vol%) coarse-grained or pegmatitic feldspathic orthopyroxenite to melanorite bounded by thin chromitite stringers with a footwall of much finer grained anorthosite to norite and a hanging wall of melanorite. In this reconnaissance study of the Merensky Reef package from the western limb of the Rustenburg Layered Suite, we use crystal size distribution (CSD) to help identify the processes (e.g. crystal settling, compaction, textural coarsening) that produced this remarkable textural variability. CSD patterns (grain size vs.  $\ln$  [population density]) were determined for plagioclase and orthopyroxene in samples from below and above the pegmatitic feldspathic orthopyroxenite; given the coarse grain-size of the pegmatite (orthopyroxene up to 3 cm across), multiple thin sections will need to be digitized to produce statistically valid results. Plagioclase CSD patterns from the anorthosite and norite lack small crystals (<0.25 mm; all crystals could be measured), are slightly concave-up at coarser grain sizes, and sweep out in a fan such that there is a linear relationship between the slope and population density intercept. In contrast, orthopyroxene CSD patterns from the overlying melanorite are concave-down and also lack small crystals, but at a significantly larger cut-off (<1 mm). These CSD patterns are inconsistent with those produced by the effects of crystal settling and their dispersion is best explained using a communicating neighbours model of textural coarsening (Ostwald ripening) where the smaller crystals were dissolved in the interstitial melt as the coarser crystals grew. The extent of textural coarsening in plagioclase increases systematically up-section (e.g. CSD slope decreases) at the cm-scale towards the basal chromitite of the reef from norite to anorthosite and the coarsest plagioclase grains (3-5 mm) occur just below the chromitite. The contact between the reef and the footwall anorthosite was likely a boundary layer that facilitated transfer of interstitial melt and heat thus allowing for textural coarsening. The overlying melanorite is coarser than the footwall anorthosite and may have been situated closer to the mush-melt interface during consolidation of the intrusion floor allowing for efficient vertical exchange with the magma reservoir, recharge of unfractionated melt, removal of latent heat of crystallization, and enhanced textural coarsening.

## COLLOID FACILITATED TRANSPORT OF THE BACTERIOPHAGE MS2 IN GRAVEL AQUIFER MEDIA

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Recent research has shown that the transport velocity of adsorbing contaminants could be significantly increased when they are attached to mobile colloids. We have aimed to demonstrate that this phenomenon is also true for viruses and that by hitching a ride on mobile colloids, some viruses can move through vulnerable groundwater systems much more readily than would normally be expected, resulting in a risk to drinking water wells.

To understand the role of colloids in the transport of viruses in groundwater and colloid-virus interactions, we carried out column and batch studies using kaolinite clay (model colloid) and

MS2 phage (model virus) under different experimental conditions. The batch studies indicated that bacteriophage adsorption onto clay decreased with higher pH and DOM levels, but increased with a higher ionic strength and clay concentrations.

Poorly sorted heterogeneous aquifer gravels were packed into a 2 m-long column. Without clay, MS2 travelled slightly faster than a conservative tracer, bromide. In the presence of the clay, the transport velocity of MS2 was enhanced and concurrent with the clay particles, and there was a greater difference between the total and filtered (free) concentrations and a lower mass recovery. Increasing the flow rate increased the MS2 transport velocity and mass recovery. At greater ionic strength, more MS2 phage attached to the aquifer media and clay, and the velocity became retarded. With an increase in DOM, less MS2 attached to the gravels and clay. Decreasing the pH increased the attachment of phages onto gravels and clay and lowered the mass recovery.

Our study suggests that favorable conditions for colloid-facilitated virus transport are high pH and DOM levels, high concentrations of colloids, high flow rates, and low ionic strengths. Colloid-facilitated virus transport could be a problem when domestic effluent and sludge is disposed of onto land.

## MAPPING THE PHYSICO-CHEMICAL GRADIENTS CONTROLLING Au DEPOSITION: VICTORY-DEFIANCE COMPLEX, ST IVES GOLD CAMP, YILGARN CRATON, WESTERN AUSTRALIA

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Metal transport and deposition are closely linked to propagation of redox and related physico-chemical gradients (pH, aH<sub>2</sub>, aHCl, aH<sub>2</sub>S, aSO<sub>2</sub>, aCO<sub>2</sub>, aCH<sub>4</sub>, aH<sub>2</sub>O, etc) in mineral systems. Measuring these gradients in the field offers perhaps the best opportunity for defining critical elements of a system such as fluid pathways or fluid aquitards, and identifying potentially productive parts of systems.

Mineralogical mapping (visual logging and reflectance spectroscopy) in combination with isotopic studies of late Archean, greenstone hosted Au mineralization, Victory-Defiance Complex, St Ives Gold Camp, has identified redox, pH and activity H<sub>2</sub>O gradients spatially associated with mineralization. The Victory-Defiance Complex is hosted by a thrust-repeated sequence of mafic and ultramafic rocks, with minor interflow sediments, within the central corridor of the St Ives Camp. Porphyry dykes intrude the core of the complex and gravity and seismic studies have shown that a major intrusive centre lies beneath the complex. Oxidized alteration assemblages (magnetite ± quartz ± pyrite ± albite, epidote ± magnetite ± pyrite, anhydrite ± phlogopite) occur in the core of the complex, zoning laterally and vertically to transitional (amphibole ± feldspar and biotite ± amphibole ± albite ± pyrite) and reduced (clinozoisite ± chlorite ± pyrite ± pyrrhotite) assemblages. The major gold lodes of the complex (Conqueror, East Repulse, Victory-Defiance, Britannia, Sirius) occur on the transitions between reduced and oxidized assemblages. The redox & pH gradients appear coupled. Reduced assemblages formed in acidic environments (clinozoisite ± Fe-chlorite stable) and oxidized assemblages formed in neutral to alkaline environments (feldspars ± epidote ± biotite stable).

Stable isotopes support the mineralogical evidence for redox gradients in the system.  $\delta^{13}\text{C}$  carbonate and  $\delta^{34}\text{S}$  sulphide values are > -5 and 0‰ respectively in reduced assemblages and < -5 and 0‰ in oxidized assemblage. Co-variation of  $\delta^{13}\text{C}$  carbonate and  $\delta^{34}\text{S}$  sulphide values allow definition of contrasting physico-chemical domains (activity SO<sub>2</sub> > activity CH<sub>4</sub>; activity CH<sub>4</sub> > activity SO<sub>2</sub>; activity H<sub>2</sub> > activity SO<sub>2</sub> & CH<sub>4</sub>). Elevated  $\delta^{18}\text{O}$

carbonate values ( $> \sim 15\%$ ) define domains of low activity of  $\text{H}_2\text{O}$  with respect to  $\text{CO}_2$  and  $\text{SO}_2$ . Partitioning of  $^{34}\text{S}$  between pyrite and anhydrite imply temperatures of  $\geq 400^\circ\text{C}$ . The mapped physico-chemical gradients can be related to the interplay of oxidized and reduced anhydrous fluids sourced from the mantle or lower crust, with aqueous fluids of crustal origin. Chemically contrasting fluids, particular fluids of contrasting redox state appear intrinsic to productive mineral systems.

## COMPARISON OF MIS 4 AND 6 GLACIATIONS, YUKON TERRITORY, CANADA

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Yukon Territory has been repeatedly affected by the northern Cordilleran Ice Sheet. This ice complex produced irregular, digitate, horseshoe-shaped glacial limits on the plateau area of central Yukon. Many of these ice flows had separate source areas and dynamics but three broad mappable chrono-geomorphic regions have been defined that were thought to represent regionally coherent advances of the Cordilleran Ice Sheet. However, mapped limits for the penultimate "Reid" glaciation actually represents two separate glaciations.

In central Yukon, the assumed Marine Oxygen Isotope Stage (MIS) 6 age for the penultimate Reid Glaciation is confirmed by the presence of Old Crow tephra (124 ka) above deglacial Reid outwash along the Pelly River. There is no evidence for a MIS 4 glaciation that is more extensive than MIS 2 in central Yukon. In contrast, Cosmogenic  $^{10}\text{Be}$  ages on boulders of 54-51 ka ( $n=4$ ) on penultimate drift in western Yukon Territory confirm that MIS 4 glaciation was extensive in parts of Yukon Territory. We name this glaciation the Gladstone, the first confirmed MIS 4 glaciation in the Canadian Cordillera. The situation is more complex to the west as sections exposed at the penultimate limit along White River in SW Yukon indicate that the MIS 4 Gladstone has an almost identical extent to an older, likely MIS 6 glaciation.

Thus, there is a dichotomy between MIS 4 and 6 glacial extents for at least two of the source areas for the northern portion of the Cordilleran Ice Sheet, indicating different glaciological responses to climatic forcing during glaciations.

The northern CIS was a precipitation-limited system and we propose that variation in regional precipitation, specifically how moisture penetrates the St. Elias and Coast mountains, is a possible cause of the differences between glacial advances. Causes for this regional variation in precipitation remain unclear.

## DRIFT PROSPECTING WITHIN THE QUEST PROJECT AREA, CENTRAL BRITISH COLUMBIA (NTS 093J): POTENTIAL FOR PORPHYRY Cu-Au, VMS MINERALIZATION AND Au-Cu VEINS

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The Interior Plateau region of central British Columbia has experienced a major outbreak of mountain pine beetle, which has decimated pine forests in the region causing a significant economic downturn in forestry-dependent communities. Geoscience BC's Quesnellia Exploration Strategy (QUEST) Project is designed to stimulate mining exploration and provide employment opportunities to those adversely affected by this decline in forestry jobs. The

QUEST project area has good potential for Cu-Au porphyry and volcanogenic massive sulphide (VMS) mineralization, but mineral exploration activity has been hindered in some areas due to the thick cover of surficial deposits.

In part of Geoscience BC's QUEST Project area, central BC, 712 till samples have been collected. The study area is dominated by middle to upper Triassic mafic volcanic rocks and volcanoclastic sedimentary rocks of the Nicola Group. Till geochemical data and heavy mineral grain count data highlight four areas that warrant further work:

- 1) In the northwestern part of the study area, there is a large number of till samples with significantly anomalous Cu and Au contents (and coincident but less significant As and Ag anomalies). The underlying rocks are correlative with those that host the Mount Milligan Cu-Au porphyry deposit. This area also has elevated Hf, REE, Th, Ti, Fe and V, reflecting Fe-rich alkalic igneous rocks in the underlying and up-ice bedrock.
- 2) In the northeastern part of the study area, there are Au, Cu, As, Ag, Sb and Cd anomalies in an area with several epigenetic-type Cu-Au vein showings and two small-scale past-producing Au (and Pt) placer mines.
- 3) In the east-central portion of the study area, till samples have elevated Zn, Cd, and Bi and contents, as well as high pyrite grain counts (up to 10 000 grains in a 10 kg sample). There are no known showings or mineralization in this part of the study area; the till geochemical results suggests the possibility of concealed VMS-type mineralization.
- 4) In the west-central portion and into the central portion of the study area, Hg values and elevated cinnabar grain counts suggest there is fault-associated Hg mineralization up-ice, perhaps similar to the Pinchi Lake mercury mine located to the west of the study area.

In these four areas, increased till sample density combined with geophysics could provide some insight into the locations of potentially mineralized bedrock.

## THE BIOGEOCHEMICAL ARCHITECTURE OF MICROBIAL GEOCHEMICAL INTERACTIONS

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Our work from mine systems, combining field and laboratory integrated microbial geochemical investigation with high-resolution techniques enabling characterization and visualization at the bacterium scale (i.e. STXM), has indicated a repeated motif of socially organized microbial cooperation occurring within microbial consortial macrostructures (pods), that directly enables the specific geochemistry linked to the metabolic needs of the consortial members. These microbially linked geochemical processes have important ramifications for bulk system geochemistry that were previously unknown. Results will be presented that illustrate how the ecology of the pod microbial communities underlies the organized architecture of the pods, enabling coupled metabolism for (1) microbial metal interactions within AMD biofilms and (2) sulfur redox cycling within mine waters. In both instances the pod microbial control over the reactions involved was not predicted by classic geochemical understanding of these systems.

(1) Investigation of AMD biofilm biogeochemical architecture capturing the micro-scale linkages amongst geochemical gradients, metal dynamics and depth resolved micro-organism community structure, illustrates a novel biomineralization process driven by biofilm associated pods controlling biofilm metal capture. Similarly, (2), our recent discovery of an environmental sulphur redox cycling pod forming consortium reveals ecologically driven sulphur cycling with acid generation implications for both

AMD mitigation and AMD carbon flux modeling. These results will be presented, highlighting how microbes cooperatively orchestrate their geochemical environment, underscoring the need to consider community activity in environmental processes and the requirement for integrated, high-resolution techniques spanning geochemistry, molecular microbiology and imaging to reveal the biogeochemistry involved.

#### **THE ORIGIN AND DISTRIBUTION OF PLATINUM GROUP METALS IN THE MT. MILLIGAN ALKALIC Cu-Au PORPHYRY DEPOSIT, B.C., CANADA**

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Porphyry Cu-Au deposits associated with alkaline rocks represent possibly significant secondary resources of the platinum group elements (PGE). The present study investigated the occurrence of PGE in a silica-saturated, alkalic porphyry system at Mt. Milligan, British Columbia, in order to better understand the PGE enrichment that occurs there.

Bulk rock analyses show that highly elevated concentrations of PGE occur at Mt. Milligan (up to 44000 ppb Pd). The PGE occur as platinum-group minerals (PGM). Merenskyite  $[(\text{Pd,Pt})(\text{Te,Bi})_2]$  is the dominant phase, with lesser amounts of mertieite-II  $[\text{Pd}_8(\text{Sb,As})_4]$  and temagamite  $(\text{Pd}_3\text{HgTe}_3)$  present. The highest spot grades of PGE are associated with late stage pyrite veins previously classified as porphyry-epithermal 'transitional' veins. This is in contrast to other PGE-enriched porphyry deposits in which the PGE are typically associated with porphyry-stage Cu minerals. Bulk rock correlations show strong positive correlations between Cu-Au, Cu-Pd, and Au-Pd. Textural evidence suggests that these correlations may simply be spatial coincidence related to the overprinting of porphyry stage and late stage veins. Mineralogical indicators in the highest grade sample, such as phyllic alteration, hematite, and barite, indicate that the hydrothermal fluids at Mt. Milligan were acidic and oxidized during these late stage events, ideal for Pd and Pt transport as chloride complexes. On the other hand, the coprecipitation of the PGE with pyrite argues for bisulfide complexing. Values of  $\delta^{34}\text{S}$  range from  $0.0 \pm 0.5\%$  ( $\sigma$ ,  $n = 19$ ) for porphyry stage pyrite,  $-1.2 \pm 1.0\%$  ( $\sigma$ ,  $n = 21$ ) for porphyry stage chalcopyrite, and  $2.0 \pm 0.7\%$  ( $\sigma$ ,  $n = 9$ , pyrite S only) for pyrite in the porphyry-epithermal 'transitional' veins. Porphyry-stage veins show near-zero  $\delta^{34}\text{S}$  values, indicating that S (and coprecipitated PGE) were sourced from the mantle. Increasing values of  $\delta^{34}\text{S}$  are characteristic of a cooling hydrothermal system, suggesting that the precipitation of PGE was, in part, controlled by cooling. Contour diagrams were produced to predict the spatial distribution of PGE, using Leapfrog<sup>®</sup> software. The diagrams show that a PGE target in the central region of the Southern Star ore zone represents the best potential for finding high concentrations of PGE. Future work should focus on more representative sampling of both pyrite- and chalcopyrite-rich drill core and should utilize the observed mineralogical associations between Au, Te, Sb, Hg, As, pyrite, and the PGE during exploration and mine planning.

#### **PRELIMINARY VOLCANOLOGICAL STUDY OF THE RAINY RIVER GOLD DEPOSIT, NORTHWEST ONTARIO**

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The Rainy River Gold Deposit (RRGD) is located 50 km northwest of Fort Frances, Ontario, within the Rainy River greenstone belt. As of December 2009, the deposit has an NI43-101 compliant gold resource of 2.37 Moz indicated and 2.66 Moz inferred. Gold mineralization at Rainy River is disseminated throughout 2.7 Ga felsic metavolcanic and metasedimentary units focused in five gold zones found as low grade ( $<2$  g/t), low-moderate grade (2-10 g/t), and high grade ( $>10$  g/t). Paucity of outcrop adjacent to the mineralization makes field mapping difficult and heterogeneous appearance of the drill core makes unit identification and correlation complicated. The core is highly altered and deformed which results in many of the units having a false pyroclastic appearance. While previous studies have examined structural regimes and timing of gold mineralization, this research focuses on the physical volcanology and hydrothermal alteration associated with the deposit. Petrography, field mapping, and core logging indicate that the volcanic facies in the deposit are coherent dacitic flows with breccias, sediments, hyaloclastites, and peperites. The coherent dacitic flows can be massive and range in size up to 150 m. These flows grade into a heterogeneous facies characterized by pods and lobes of coherent dacite enveloped by autoclastic breccias and hyaloclastite. The dacitic flows are inter-layered with strongly altered sediments which are punctuated by peperites. Alteration is widespread throughout the deposit and is marked by silicification, chloritization, sericitization, and carbonitization, as well as minor epidote and local biotite. Alteration intensity is commonly related to lithology with sediments and breccias being most strongly altered. Reconstructing the facies architecture of the deposit suggests the presence of a lobe-hyaloclastite dome/flow complex. The feeding fissure is centered to the southwest of the mineralization and the flows show a change from the fissure to the flow fronts. The gold was a result of post-depositional alteration, possibly related to a low sulfidation epithermal system, which was remobilized during subsequent deformation.

#### **THE CHEMICAL AND BIOLOGICAL EVOLUTION OF MATURE FINE TAILINGS IN OIL SANDS END-PIT LAKES**

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The recovery of bitumen from Alberta Oil sands generates enormous volumes of oil sands process material (OSPM). After bitumen extraction, tailings are pumped into retention ponds, where the sand fraction settles, and most of the aqueous slurry (i.e. fines consisting of silts, clays and residual hydrocarbons) slowly densifies which is termed mature fine tailings (MFT). Long term Reclamation management strategies focus on the deposition of this material within large end pit lakes using a CT process. The chemistry and the microbial community structure drivers in oil sands tailings is complex and there is a need for a detailed systematic study bridging the governing physical (mineralogy) and chemical (redox chemistry abiotic vs biotic; cycling of Fe and S) components with the microbial ecology for accurate long term predictive models on how these settling basins will work. In this study laboratory microcosms containing fresh MFT are used to investi-



gate the chemical and biological controls affecting the REDOX chemistry of the MFT and establish the role of developing microbial communities within new MFT sediment upon aging. Changes in the principal chemical, physical and microbiology of the material is assessed under aerobic and anaerobic conditions using a combination of microelectrode arrays, high resolution microscopy and DNA profiling. Laboratory microcosm experiments are used to investigate the REDOX chemistry associated with the MFT/water interface and will document changes in the physico-chemical properties and microbiology of the MFT in aerobic and anaerobic environments. In this study we apply novel microelectrodes stable isotopes and molecular tools (i.e. T-RFLP with qPCR) to assess the chemical and biological evolution of this material over time. The information collected from these experiments will contribute to the development of future prediction models being developed for large end pit lake systems.

#### **THE HYDROSTRATIGRAPHY OF THE NEPEAN, MARCH, AND OXFORD FORMATIONS (POTSDAM-BECKMANTOWN GROUP)**

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In the Ottawa area, Nepean Aquifer is a well known sandstone aquifer, overlain by dolostone of the March and Oxford formations. Nepean Formation is part of the Potsdam Group, of Cambrian age, while the March and Oxford Formations form the Beekmantown Group, of Lower Ordovician age. The Nepean Formation is equivalent to the Cairnside Formation in southwestern Quebec, the hydrostratigraphy of which has been extensively studied as part of the Geological Survey of Canada Groundwater Mapping Program (Châteauguay River Watershed). The hydrostratigraphic sequence is also equivalent to the Cambrian-Ordovician Aquifer System in the Northern Midwest, which is the major drinking water supply for the Chicago-Milwaukee and Minneapolis-St. Paul metro areas (although direct correlation of the stratigraphy is complicated). In the Ottawa area, the Nepean Formation provides the highest quantity and quality water supply from bedrock. This article describes the hydrostratigraphy of this bedrock sequence, based on information available from a variety of local sources. The available physical hydrogeological information includes observations made during water well drilling and bedrock coring, packer testing, groundwater level measurement in multi-level monitoring wells, and anecdotal information on flowing artesian wells. Chemical hydrogeological information includes observations of plume migration from a variety of industrial contaminant sources. Other information includes hydraulic parameter estimates available from model calibration. The hydrostratigraphy is defined as including a semi-confined upper bedrock aquifer, a very competent confining layer within the March Formation, and a highly transmissive lower aquifer, at the interface of the March and Nepean Formations. The source and discharge areas for the deep bedrock aquifer, as well its flow direction, are highlighted as being uncertain, and the need for a comprehensive regional hydrogeological investigation is pointed out.

#### **GRANITOID ROCKS ON THE CUMBERLAND PENINSULA, BAFFIN ISLAND: GEOCHEMICAL CHARACTERISTICS AND TECTONOMAGMATIC IMPLICATIONS**

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Recent mapping of Cumberland Peninsula (CP), part of NRCan's Geo-mapping for Energy and Minerals (GEM) initiative, has high-

lighted the presence of an Archean orthogneiss basement complex and a ca. 200 km long belt of ca. 1.9 Ga plutonic rocks that intrude it. The basement complex yields U-Pb zircon crystallization ages between ca. 3.0 and ca. 2.7 Ga and Nd model ages of 2.99 to 3.15 Ga. It includes a diversity of lithologies, ranging from gabbro through to monzogranite, but consists mainly of interlayered tonalite and granodiorite with the geochemical characteristics of a tonalite-trondhjemite-granodiorite (TTG) suite. TTG suites are the oldest recognized plutonic rocks within most Archean cratons and, as such, often reflect primitive crust formation processes. Comparison of CP orthogneiss data with a limited dataset from central-west Baffin Island Rae craton suggests that, although their U-Pb crystallization and Nd model ages overlap, the latter are quite geochemically evolved rather than being mainly 'TTG-like'.

On large-scale bedrock compilations, western CP has been interpreted to expose the voluminous (~221,000 km<sup>2</sup>), ca. 1.865-1.845 Ga Cumberland batholith. So far, however, CP Proterozoic plutonic rocks have yielded U-Pb crystallization ages of ca. 1.9-1.89 Ga thereby defining a distinctive belt informally designated the Qikiqtarjuaq plutonic suite (QPS). The QPS includes volumetrically significant quartz diorite and granodiorite in addition to monzogranite (charnockite) and, in general, is calc-alkalic, metaluminous and medium-K to shoshonitic. QPS Nd model ages of 2.42 and 2.46 Ga overlap published data from central to northern Cumberland Batholith which is dominated by high-K to shoshonitic metaluminous to slightly peraluminous monzogranite.

Regardless of age, CP granitoid rocks can be spatially subdivided based on variations in Sr contents and Sr/Y ratios. A high Sr and Sr/Y group, that can be interpreted as reflecting formation by medium to high P-T partial melting of mafic protoliths, includes both Archean and Paleoproterozoic plutonic rocks across southeastern CP. In contrast, a low Sr and Sr/Y group that reflects lower P-T petrogenesis is represented by equivalent plutonic units across northwestern CP. These spatially discrete geochemical variations may reflect a transition from a thinner (northwest) to a thicker (southeast) crustal section. This transition may have been present in the Archean, the geochemical signature of which was 'recycled' when 2.7 to 3.0 Ga basement was partially melted in the Proterozoic to produce the QPS. Alternatively, this may reflect a long-lived transition, recorded in both Archean and Proterozoic rocks.

#### **REVISED STRATIGRAPHY AND TECTONIC EVOLUTION OF THE MEGUMA TERRANE OF SOUTHERN NOVA SCOTIA**

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The most outboard tectonic element of the northern Appalachian orogen, the Meguma terrane, includes the Neoproterozoic(?) to Ordovician Goldenville and Halifax groups and the younger Silurian to early Devonian Rockville Notch group, intruded by mainly Devonian plutons and overlain by Carboniferous and younger rocks. The redefined Goldenville Group is divided into several formations and members that consist of varying amounts of massive feldspathic wacke to arenite with minor interbeds of siltstone and slate. It grades upwards into thinly bedded feldspathic wacke, siltstone, and slate and is capped by a Mn-rich siltstone unit. The lower part of the Goldenville Group contains a siltstone unit (High Head member) with abundant trace fossils, including the early Cambrian deep-water ichnofossil *Oldhamia*. The upper part of the Goldenville Group has yielded early Middle Cambrian Acado-Baltic trilobites and acritarchs. The overlying Halifax

Group is divided into several slate-bearing formations and based on trace fossil morphology and graptolite and acritarch species, ranges in age from late Cambrian at the base to Early Ordovician at the top. Chemical signatures of the Goldenville and Halifax groups combined with the presence of numerous syn-depositional mafic sills of within-plate chemical character suggest that the Goldenville and Halifax groups were deposited in a rift setting, perhaps formed as Avalonia rifted from Gondwana.

Younger Silurian to Devonian units of the Rockville Notch group includes bimodal within-plate volcanic and sedimentary rocks of the lower White Rock Formation and overlying siltstone and slate of the Kentville Formation. The uppermost units (New Canaan and Torbrook formations) consist of marine sedimentary and volcanic rocks. The gap in age between the Halifax Group and the overlying Rockville Notch group indicates that a major unconformity spanning approximately 25 Ma exists between the two groups.

Folding, cleavage development, and low-grade metamorphism of these units at ca. 395 Ma (Neoacadian orogeny) is interpreted to have been related to dextral oblique collision of Meguma with Avalonia. These events were followed by emplacement of voluminous granitoid plutons at ca. 380-357 Ma, probably related to on-going subduction associated with closure of the Rheic Ocean. The unique stratigraphy and orogenic history of Meguma indicates that it was a separate microcontinent in the Rheic Ocean throughout Early to mid-Paleozoic.

#### **APPALACHIAN FORELAND BASINS BENEATH THE GULF OF ST. LAWRENCE**

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The Appalachian foreland basin contains strata ranging from Middle Ordovician to Early Devonian and extends over 50,000 km<sup>2</sup>. The basin largely underlies the Gulf of St. Lawrence, precluding direct mapping. Seismic reflection data, gathered off the west coast of Newfoundland, give subsurface information required for interpretation of structures. Ties to onshore stratigraphy and wells are scarce, and corresponding on-land successions are highly deformed in the Humber Zone of Newfoundland. Reflections can be tied to prominent bathymetric features and magnetic anomalies within the Long Point Group. This allows identification of several significant geologic boundaries with reasonable confidence.

Strata of the foreland basin were deposited during time intervals correlative with events in Appalachian history. The St. George Unconformity marks the base of the foreland basin and onset of Taconian deformation. In seismic data this boundary is interpreted as a high amplitude peak that demonstrates clear angular discordance with underlying reflectors. These overlying deep-water siliciclastics of the Middle Ordovician Goose Tickle Group are associated with tectonic loading during Taconian orogenesis and, offshore of Port au Port, are relatively thin (~200 m).

The Late Ordovician Lourdes Limestone, a prominent reflector, locally truncates this basin fill and regionally marks the base of the Long Point Group. The varying position of this reflector, relative to the Tea Cove Thrust, may be due to ramping of the fault through Long Point stratigraphy from south to north, or due to stratigraphic onlap of the Long Point Group onto underlying units. A relatively thicker clastic succession (Winterhouse and Misty Point Formations) overlies the Lourdes Limestone, and standard tectonic scenarios for the evolution of the Newfoundland Appalachians do not offer a straightforward explanation for this second phase of Ordovician subsidence. This package shows pronounced southward thickening, suggesting that subsidence

may be a result of tectonic loading in the Quebec segment of the Orogen. Future provenance work may shed light on the origin of these sediments.

A Salinian unconformity is recognized due to the gap in the sedimentary record on land. Younger strata rest with only subtle discordance on the underlying Long Point Group suggesting Salinian deformation of the former Laurentian margin was not intense. The youngest major structures of the Appalachian thrust front are of post-Emsian, Acadian age.

#### **FIELD REFLECTANCE SPECTROSCOPY GROUND-TRUTHING METHODOLOGY FOR THE CALIBRATION OF MULTI AND HYPERSPECTRAL DATA IN MINERAL EXPLORATION**

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Hyperspectral data is becoming increasingly available and used in mineral exploration. Hyperspectral data may be collected from airborne sensors (Probe, HyMap, ProSpecTIR), and in the future will also be acquired from spaceborne remote sensing satellites with launches planned from 2012 onwards. Multispectral data has also been used extensively in mining, largely sourced from the Advanced Spaceborne Thermal Emission Radiometer (ASTER) sensor, with its improved spectral bandwidth over the short wave infrared (SWIR) region. Prior studies have documented the ability of these remotely sensed imagery sources to differentiate spectral variations which may be tied to lithology or localised enhanced mineral concentrations; often related to zonal patterns of alteration which could vector towards hitherto undiscovered ore bodies. Understanding what these variations represent compositionally at the surface, particularly in a new study area, requires ground-truthing. Successful utilization of results from these multi and hyperspectral sources in an active mineral exploration project is often very dependent on the rigor and effectiveness of the field spectroscopy-based ground-truthing program.

This presentation will outline a field reflectance spectroscopy ground-truthing methodology for use in remote-sensing mineral exploration projects. The aim of this methodology is to have a rigorous procedure to collect, process, analyze, validate and calibrate mineral alteration and lithological variations which may be observed within hyperspectral and multispectral data in a repeatable and statistically meaningful way. This methodology comprises field planning, data and sample selection, spectral measurement protocols and methods, spectral data analysis and processing, and where required sample analysis and characterization. Adopting a rigorous repeatable procedure ensures that accurate and appropriate information and samples are collected when ground-truthing, as going back to the field is often unfeasible or extremely costly. Further, it ensures that the sample and spectral data collected and analyzed are representative and retain spectral accuracy, both of which are important to ensure the integrity of field ground-truthing results. All field data can then be used for future reference as a project sample and spectral database or library. Spectral integrity will also provide the capability for calibration of field data to the remotely sensed datasets. Various calibration options (such as vicarious calibration) are possible, and can improve the quality of the remotely sensed dataset, such that further spectral unmixing and processing operations to identify potential zones of mineralization-associated alteration in the exploration program are improved. A variety of examples from different case studies and projects will be presented.

## **PRELIMINARY AIRBORNE HYPERSPECTRAL MINERAL MAPPING RESULTS FOR THE HOPE BAY GREENSTONE BELT, NUNAVUT, CANADA**

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Innovation funding from SINED (Strategic Investment in Northern Economic Development) supported a hyperspectral mapping survey of much of the Hope Bay Greenstone Belt (HBGB), Nunavut in 2009 that involved personnel from the Geological Survey of Canada, Canada-Nunavut Geoscience Centre and Canada Centre for Remote Sensing, the contractor SpecTIR LLC, and industrial partners Newmont USA Limited, and Sabina Gold & Silver Corporation. The objective of the project was to investigate and demonstrate the potential of hyperspectral airborne imagery as an exploration tool for Canadian mineral deposits and climates. Herein we present preliminary hyperspectral mapping results.

The HBGB is 90 km long by 15-20 km wide and has a northerly trend. It is dominated by mafic pillowed tholeiitic basalt, basaltic andesite and iron-rich tholeiite, with intercalated intermediate to felsic volcanic and meta-sedimentary rocks. The HBGB hosts several orogenic Au (structurally controlled mesothermal quartz vein) deposits, including, from north to south: Doris and Doris N, Madrid, and Boston. The area also has a high volcanogenic massive sulfide potential.

Hyperspectral data were collected using the high spectral resolution ProSpecTIR-VS sensor over the visible to short wave infrared (400 to 2500 nm) at 3 m spatial resolution over most of the HBGB. Raw sensor data were collected along with detailed GPS and locational data, corrected to radiance, and ultimately to reflectance data using ATCOR4 software with a MOTRAN4 atmospheric correction model by SpecTIR. Initial hyperspectral processing and mineral spectral unmixing was carried out by D. Coulter using in-house techniques and algorithms.

Preliminary hyperspectral imaging results generated for the Hope Bay belt highlighted a select number of prospective minerals, which were spatially compared with published geological information, known Au occurrences, and associated publicly available geological and outcrop maps. There is a strong correlation between hyperspectrally mapped minerals (high Al illites and chlorite) and largely mafic volcanic units (often variolitic basalts) that have been reported to host alteration. Associations are repetitive, although alteration host lithologies are variable for each deposit area. These results provide the impetus for future investigation of the technology by conducting more detailed processing as well as detailed ground truth studies. Results of this survey support the technology as a viable mapping tool for highlighting hydrothermal alteration that may be spatially and temporally associated with buried mineral deposits in appropriate regions of Canada. The hyperspectral data obtained during this study will be publicly released by the Geological Survey of Canada.

## **HIGH-RESOLUTION CARBON ISOTOPE STRATIGRAPHY OF THE ORDOVICIAN-SILURIAN BOUNDARY ON ANTICOSTI ISLAND, QUEBEC: REGIONAL AND GLOBAL IMPLICATIONS**

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The end-Ordovician was a critical time in Earth history marked by the occurrence of a mass extinction and a period of continental glaciation. The Ellis Bay Formation on Anticosti Island in Quebec represents up to 100 meters of relatively undisturbed, continuous,

low latitude, shallow water carbonate ramp deposits that span the Hirnantian Stage and terminate close to the Ordovician-Silurian (O-S) boundary. In our study, approximately 400 samples of micritic limestones were collected from six Ellis Bay sections along a shelf to basin gradient.  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  isotopic ratios were measured from these samples and integrated within a framework of sequence stratigraphy and chitinozoan biostratigraphy for the Ellis Bay Formation. The measured  $\delta^{13}\text{C}$  values in most sections show a positive excursion (~2‰) in the lower Ellis Bay Formation followed by a larger excursion (~4‰) in the upper Ellis Bay Formation. The  $\delta^{13}\text{C}$  profile of the Ellis Bay Formation on Anticosti Island is similar to other profiles in graptolite-rich Hirnantian basinal successions in other parts of the world. The  $\delta^{13}\text{C}$  record on Anticosti Island is not consistent with predictions and observations based on current models that describe the state and evolution of the global carbon cycle during the Late Ordovician. Other chemostratigraphic work has largely confined the Hirnantian stage to the uppermost member of the Ellis Bay Formation. We believe this conclusion is also inconsistent with our recent biostratigraphic and sequence stratigraphic framework.

## **EARTH SCIENCE IN THE K-12 CURRICULUM – A PAN-CANADIAN PERSPECTIVE**

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As a result of an initiative of the Canadian Geoscience Education Network (CGEN) I created a compilation by grade level of where different Earth Science topics were located within the various provincial K-12 science curricula. In view of the current predictions, and within the limitations of those predictions, we will see a rapidly declining workforce, aging populations, increasing effects of climate change, and in some cases less availability of resources. Rather than just looking at if specific Geoscience topics are in the different curricula it is also important to identify the larger context in terms of efficacy of learning if our goal is to try and improve the Earth Systems literacy of the population to be able to meet the potential challenges of these social and environmental changes. Although there were a few trends it became obvious that there are significant variations across the country in terms of topics taught and at what grade level. Considering what we know about contextual learning, and concrete versus abstract learning in terms of student age, very rarely was there any attempt to develop significant long-term learning. This presentation will review the curricula data to present a grade by grade comparison of Earth Science education across the country in terms of content, contextual framework and potential for long term learning.

## **INTEGRATING EDUCATION AND OUTREACH THROUGH GEOLOGY, INDUSTRY, AND PEOPLE**

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Early learning is developed through an informal but highly contextualized multi-layered approach that helps us begin to understand the world around us. The broader our experiences, the more contextualized and embedded our learning becomes. Frequently school learning is one of decontextualized abstract concepts through various prescribed curricula. In most of Canada, mining is part of the elementary science curriculum. However, what does the average Grade 5 student holding a lump of coal and then being told that this is used to make electricity and steel really learn?

Coal mining has always been an important industry in Western Canada but there is little remaining evidence of that mining. What does exist is mostly in the form of photographs tucked away in museums with little or no context. Most of the historic industry of southern British Columbia and Alberta is invisible except for

the Bellevue Mine in the Crowsnest Pass and the Atlas Mine at Drumheller in Alberta. What remains of the coal industry in BC today is remote for most residents – up north or in the Rockies somewhere. The majority of school-age children and their parents have never even seen, let alone held, a lump of coal.

In contrast, the underground coal mining of South Wales was at the centre of their industrial development for over a hundred years. Even though the deep pits have all been closed, coal is still being mined through open pit operations. In both Western Canada and South Wales the heritage focus seems to be on the industrial technology. In most cases there is little or no mention of the geology of coal, the how, why and where of its formation, or of the people and communities whose lives revolved around that mining. Those facilities in both Western Canada and South Wales that have the greatest impact are those that try to link the industry, the people and the geology.

This session will focus on the representation of historic coal mining of both countries through a multidimensional model integrating the industry, the people and the geology. As a geoscience educator I believe that such a model can lead to a more powerful learning experience and understanding of our resources in both formal education and outreach.

#### **GEOLOGICAL SURVEY OF CANADA COLLABORATIVE PROJECTS IN THE FIELDS OF LUNAR GEOLOGY AND PLANETARY ANALOGUE RESEARCH**

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Exploration activities in Earth and planetary sciences are connected through the use of common tools and methodologies, from remote predictive mapping (RPM) techniques to field operations, in situ scientific measurements, sample collection strategies, and the development of state-of-the-art laboratory protocols for the analysis of rocks and minerals. The increasing importance of field geology and science instrumentation in the operational requirements of future planetary exploration missions has resulted in research projects that combine expertise from government departments and agencies, universities, and industry. In this paper, we describe the application of geomatics, RPM, digital field methods, and advanced geochemical analysis of minerals by LA-ICP-MS at terrestrial analogues for the Moon in two collaborative projects involving the Geological Survey of Canada.

Trace element compositions of lunar ilmenite by LA-ICP-MS: Oxygen is a key lunar resource for use as a propellant and in life support systems. Ilmenite is present in lunar bedrock and regolith, and is recognized as the best mineral for oxygen extraction from the regolith. The project objectives are: (1) determine the concentrations of harmful elements in lunar ilmenite to be monitored during oxygen production; (2) provide a new set of geochemical data complementary to the existing lunar datasets on ilmenite; and (3) compare the new data to the Earth's ilmenite compositions. A suite of 12 samples from the 6 landed Apollo missions have been requested to NASA for the study. The research will advance our current understanding of the science and engineering requirements

attached to In Situ Resource Utilization (ISRU), and ultimately refine our knowledge of the geological evolution of the Moon.

Planetary analogue research at Askja Volcano, Iceland: The geology of Askja volcano is of interest to planetary scientists because of similarities with lunar volcanic landforms and lithologies. Widespread semi-consolidated volcanic deposits can be investigated as proxies for lunar regolith and dark mantle deposits (pyroclastics). Ice sublayers allow in situ testing of survey instruments for the presence and extent of water and ice in regolith. The interaction of lava flows with the semi-consolidated deposits will provide insight into eruptive processes in regolith-like terrains. The I-ASKJA project objectives include: (1) produce a predictive geological map based on a set of Worldview-2 stereo pair images and DEM of the volcano; (2) carry out RPM groundtruthing and detailed mapping of deposits that constitute the best proxies for lunar regolith; (3) determine the maximum spatial and temporal coverage of lithological units from trenching and ground-based remote sensing experiments; and (4) resolve the stratigraphy of poorly-consolidated volcanic deposits based on the data from 1, 2, and 3, in anticipation of ISRU engineering field tests. Our results will be applied to case studies of similar geologic sites on the Moon using high resolution imagery and data sets from recent exploration missions.

#### **REMOTE PREDICTIVE MAPPING OF INTRUSIVE IGNEOUS ROCKS ON VICTORIA ISLAND, N.W.T.**

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We report the results of remote predictive mapping (RPM) of intrusive igneous rocks carried out under the GEM-Minerals program for an area of approximately 3000 km<sup>2</sup> located on the north shore of Minto Inlet, Victoria Island, Northwest Territories. The map was produced from a careful analysis and classification of Landsat images available for the study area (6 bands). The objective of the 2010 pilot study was to investigate a low-cost approach to RPM focused on a single lithological unit that could be applied to other GEM mapping projects in the North. Predictive geological maps generated for the Victoria Island field team are important tools for targeted mapping in complex terrain, efficient traverse planning, and the economic assessment of mafic-ultramafic Franklin sills exposed in the Minto Inlier.

The Minto North predictive map for igneous rocks is spatially more accurate than the 1:500,000 scale map published by the Geological Survey of Canada. A grid consisting of 20 units of 163 km<sup>2</sup> each was applied to allow the rapid identification of areas of minimum and maximum igneous bedrock exposure (up to 15% along the northern shore of Minto Inlet). From an operational perspective, the pilot project was of limited use during the 2010 field season due to protracted timelines for map production. In anticipation of the 2011 field season, a detailed analysis of the gridded map in the context of (1) published mineral assessment reports, (2) structural data, (3) the 2010 field traverse database, and (4) SPOT 5 imagery is underway to target areas of well-exposed bedrock and gossan zones. We present a set of observations that are specific to the localization of gossan zones associated with three types of host rocks: (1) disseminated pyrite and pyrrhotite near the top of gabbro sills; 2) finely disseminated pyrite associated with vertical fracture systems in shales; and 3) massive pyrite mounds in porous carbonates.

# PHYSICAL VOLCANOLOGY OF THE NEOPROTEROZOIC NATKUSIAK FORMATION FLOOD BASALTS OF THE FRANKLIN MAGMATIC EVENT, VICTORIA ISLAND, NWT, CANADA

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The Natkusiak Formation flood basalts are located in the Minto Inlier on western Victoria Island, Northwest Territories. The basalt flows are the erosional remnant of the extrusive portion of the Neoproterozoic ca. 720 Ma Franklin magmatic event and are exposed as two NE-trending cores of a regional syncline. The Minto Inlier mainly consists of a well exposed, weakly deformed, succession of deep to shallow marine carbonate rocks, evaporites, and fluvial sandstones known as the Shaler Supergroup. The sedimentary succession is intruded by diabase sills and dykes, capped by the Natkusiak flood basalts, and overlies granitic rocks of the Archean Slave Province in the northeast part of the inlier. The Franklin magmatic event is interpreted to be the result of a mantle plume generated hotspot and related to rifting and eventual breakup of the supercontinent Rodinia. Previous work on the Natkusiak flows focused on the northern lobe and includes major element geochemistry, stratigraphy and physical volcanology of a limited sample set. The Natkusiak flows are typical continental tholeiitic basalts with a significant crustal contamination as determined by earlier isotopic and trace-element analysis.

Here, preliminary results from the first summer of field work will be presented and discussed. Systematic sampling and mapping of the volcanic facies, as well as the description of two detailed stratigraphic sections, was undertaken to identify important structures and textures that may better constrain the environment of emplacement and eruption characteristics of the basalts, as well as resolve their geochemical evolution. Native copper was observed within the more massive flows, and the intrusive sills and dykes are thought to host potential Ni and PGE mineralization, previously suggested to be comparable to the Noril'sk-Talnakh Ni-Cu-PGE deposits in Russia. The examination of the basalts has the potential to resolve the physical and chemical evolution of the magmatic centre in much greater detail than working on the sills alone because the temporal relationship between flows can be more easily established. The model of the volcanic evolution thus supplements and calibrates the subvolcanic intrusive complex hosting the mineralization potential.

This project is supported by the Geological Survey of Canada's Research Affiliate Program (RAP) as well as their Geo-mapping for Energy and Minerals (GEM) minerals initiative.

## COLLISION-RELATED MEDIUM-PRESSURE/LOW TEMPERATURE METAMORPHISM OF MAFIC AND FELSIC VOLCANIC ROCKS IN THE ANNIEOPSQUOTCH ACCRETIONARY TRACT (NEWFOUNDLAND) AND SE CAPE BRETON ISLAND (NOVA SCOTIA)

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The pressures to which rocks were subjected in collisional settings characterized by very-low- to low-grade metamorphism are generally poorly known, although such knowledge is essential for tectonic analysis. We studied white-mica bearing mafic and felsic metavolcanic rocks in two regions: the Annieopsquotch Accretionary Tract in central Newfoundland (AAT; 12 samples) and the Mira Terrane of Cape Breton Island (MT; 15 samples). PT-pseu-

dosections for the range 200–450°C, 1–10 kbar were calculated for all 27 samples with the PERPLE\_X software using the thermodynamic data set and solid solution models of Holland and Powell with supplements by Massonne and Willner. The observed peak metamorphic assemblages occupy PT-fields consistent with the position of isolines for maximum Si-contents in white mica.

The foliated felsic metavolcanic rocks contain the assemblage epidote-chlorite-phengite-albite-quartz-titanite with relicts of K-feldspar. Mafic metavolcanic rocks commonly preserved porphyritic and amygdaloidal textures and are commonly weakly deformed. They contain the assemblage epidote-chlorite-phengite-albite-quartz-titanite  $\pm$  actinolite  $\pm$  pumpellyite  $\pm$  calcite. Occasional inhomogeneous equilibration is indicated by local relicts of magmatic clinopyroxene and plagioclase as well as local occurrences of low-pressure metamorphic phases like K-feldspar and prehnite (in the MT) formed during the pro- or retrograde PT-path. The relicts are due to lack of recrystallization and compositional homogenization at thin-section scale at very-low grade. Potassic white-mica in both rock types and regions is phengite with a wide compositional range (3.10–3.50 Si pfu). Maximum Si-contents are typically at 3.30–3.40 apfu, but locally up to 3.50 apfu.

The AAT is a peri-Laurentian collision zone formed between 468 and 450 Ma. PT-conditions appear to be heterogeneous and at least three different imprints were detected: 5.5 $\pm$ 1 kbar, 320 $\pm$ 30°C, 7 $\pm$ 1 kbar, 330 $\pm$ 30°C and finally in mafic rocks containing additional biotite 4.2 $\pm$ 0.5 kbar, 360 $\pm$ 40°C. In the Avalonian MT average peak PT-conditions of 4.0  $\pm$  0.5 kbar, 290  $\pm$  30°C appear to be more homogeneously distributed, but higher pressure conditions may have existed in rocks containing phengite with Si-contents of 3.50 apfu. The medium pressure metamorphism in the MT is compatible with crustal thickening related to collision. Metamorphism predated deposition of overlying Cambrian sedimentary sequences and was probably related to assembly of Avalonia in the Late Neoproterozoic.

Crustal thickening in both collision zones resulted in burial to depths of 15–25 km in the AAT and 12–16 km in the MT and in variable, but low metamorphic geotherms (12–15°C/km up to 21–27°C/km in the AAT and 16–23°C/km in the MT).

## CURRENT AND FUTURE TRENDS IN USGS MICROANALYTICAL REFERENCE MATERIALS DEVELOPMENT

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As the use of LA-ICP-MS expands into new areas of environmental and geochemical assessments concerns mount as to the reliability of analytical results. This concern is especially significant when there is a lack of established microanalytical reference materials (MRMs) for calibration or quality control check. While this reliability issue appears to diminish as labs move towards shorter wavelength and femtosecond lasers there still exists the need to demonstrate data robustness through the analysis of homogeneous well characterized reference materials. To this end the USGS has expanded its supply of MRMs beyond the early basaltic glasses (e.g. BCR-2G, BHVO-2G, BIR-1G, GS-series) to include new synthetic materials. These new materials are seen as invaluable in producing reliable analytical results by matrix matching natural materials for both major and trace element composition. Examples of these new materials include sulfides (MASS-1, MASS-3), Carbonates (MACS-3), Ca-phosphates (MAPS-4, MAPS-5), gypsum (MAGS-1) and organic (MAOS-?). Discussions will focus on homogeneity of USGS MRMs, the effect of using non-matrix matched calibration materials on analytical results, issues surrounding the certification of MRMs and the use of MRMs in international proficiency testing programs (IAG, G-probe).

Information will be presented on future USGS MRM development, some of the notable attempts and failures (zircon, pyrite), and the development of new synthetic minerals MRMs.

### **THIRD GENERATION EXPLORATION IN THE ATHABASCA BASIN-THE CHALLENGE OF GOING DEEP AND GOING STRAIGHT**

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The Athabasca Basin is host to some of the world's highest grade uranium deposits. The dominant style of deposit has been the unconformity model of occurrence where the deposits are created at the contact between the overlying Athabasca Sandstone and underlying Archean rocks, generally near major pelitic-graphitic units in the basement. A primary exploration approach developed in the 1970s was to use airborne EM to define the conductive trends which were then drilled tested in a systematic fashion. A number of deposits were located with this approach.

Exploration that started back in the 1960-early 1970s near the edges of the Basin but now explorers are ranging over the extent of entire Basin where a large part of the Basin is covered with over 0.5 km of sandstone and in the center, thicknesses exceeding 1 km are not uncommon. While the sandstone is a relatively easy rock to penetrate with EM methods, the shear depth to the uniformity is presenting challenges to the effective use of EM techniques alone. As well, there has been an evolution of the deposit models within the Basin and a pure-EM focused approach has been seen to possibly missing deposit styles that have emerged as important target models.

While explorers have increasingly called upon a suite of techniques to help define what is seen as a range of target styles, the cost of exploration data and target testing has increased substantially. This has resulted in a reduction of the amount of target testing and a decrease in the number of smaller players who can engage in what has become a high risk-high cost exploration environment.

A number of exploration plays will be examined so as to help better understand the current capabilities of geophysical technology as applied to discovery in the Athabasca Basin. The limits of current technology will also be assessed and some suggestions as to how to enhance performance and reduce the overall discovery risk will be examined.

### **AN ASSESSMENT OF EM AND POTENTIAL FIELD DATA AT PASFIELD LAKE, SASKATCHEWAN - A SUSPECT ASTROBLEME**

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The Athabasca Basin area of northern Saskatchewan produces approximately 1/3<sup>rd</sup> of the world's uranium production; the majority of this coming from what is termed unconformity style deposits located at the base of the overlying Athabasca sandstone and underlying Archean rocks. Triex Minerals Corporation (now Canterra Minerals) has been conducting exploration in the Pasfield Lake area in the central-eastern part of the Athabasca Basin since 2005. In the course of this program, a series of aerial and ground geophysical surveys as well as some drilling was undertaken. To date, this work has failed to have revealed the presence of any significant unconformity style uranium mineralization but has shown that there is a major uplift of the basement under Pasfield Lake. The magnetics and gravity results have been modeled using 3D inversion codes and show concentrically zoned features within the lake. The magnetics results show what appears to be an area of uplift under the lake as well as number of zones of reversed mag-

netization. The gravity results show there is a concentric zone of low density centered on the lake. Based on the geophysical character of other known astroblemes, there appears to be a reasonable case that Pasfield Lake is located over top of a meteor impact site.

### **DEVELOPING AND TESTING SURFICIAL MATERIALS CLASSIFICATION USING REMOTE PREDICTIVE MAPPING METHODS: PRELIMINARY RESULTS NEAR REPULSE BAY, NUNAVUT**

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Geological mapping of Northern regions in Canada represents an essential step in providing key knowledge for resource development and economic prosperity of northerners. The Repulse Bay study area lies within one of the most active diamond exploration areas of the Western Churchill Geological Province. However, its surficial geology has never been mapped at an effective scale. Currently, surficial geology maps available for this region are at the coarse scale of 1:1,000,000, therefore hindering the potential for exploration programs by the diamond industry.

To direct and focus field mapping activities, and help in the surficial materials and glacial landform interpretation, first order predictive surficial materials maps are being created at a 1:100 000 scale for NTS 46M west and 46L of the Repulse Bay area using Remote Predictive Mapping (RPM) techniques. RPM is a process by which various geoscience data are compiled and interpreted to develop the best representation of what is truly on the surface. Preliminary fieldwork was conducted in the summer of 2010 to gather field observations and determine general classification of surficial materials. This fieldwork formed the basis of training area selection applied to the predictive mapping process, producing categories of: thick till, thin till, bedrock, boulderfield, marine silty sands, marine silts and clays, coarse sands and gravels, morainic material and organic deposits.

Using various software and methods to create predictive maps (i.e. ICM (now referred to as Iterative Classification Method) interface in ENVI), a multi-data approach is being taken, utilizing several types of imagery. The different imagery types are used both individually and in combination to determine the most optimal data (or data combination) to refine the materials classification and produce the best possible accuracy for the study area. LANDSAT 7 TM and finer resolution SPOT 4 and SPOT 5 data are used, along with MERIS, and a Digital Elevation Model (DEM). The imagery and data interpretation help explore the advantages of using different spatial and spectral resolutions, as the resolution across the data types are not uniform across the study area. Together with different types of imagery and a robust collection of field data, separate types of classification, including supervised and unsupervised, are applied and compared. This methodology will help improve the RPM process and results, and further predictive mapping successes in arctic terrain. Along with advancements in the RPM process and methodology, final maps will help guide future fieldwork and diamond exploration efforts in the north.

## **NEW U-Pb GEOCHRONOLOGICAL RESULTS FROM MELVILLE PENINSULA: UNRAVELLING THE ARCHEAN AND EARLY PALEOPROTEROZOIC MAGMATIC HISTORY OF THE NORTH-CENTRAL RAE CRATON**

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New U-Pb geochronological data from Melville Peninsula, obtained as part of the Geomapping for Energy and Mineral (GEM) Program, provide insights into the magmatic and tectonic evolution of the north-central Rae craton, western Churchill Province, hence bridging an important knowledge gap between the geology of the mainland to that of Baffin Island to the northeast. The central part of Melville Peninsula comprises several narrow strands of northeast-trending, komatiite-bearing Archean greenstone belts historically referred to as the Prince Albert Group. U-Pb TIMS and SHRIMP dating of magmatic rocks from two greenstone belts so far reveals at least two distinct ages of volcanism, forcing a revision of the term Prince Albert Group. The Prince Albert greenstone belt, exposed in the type locality of the Prince Albert Group (Prince Albert Hills), includes felsic to intermediate volcanic rocks dated between  $2970 \pm 5$  Ma and  $2968 \pm 3/-2$  Ma. These new age constraints make the Prince Albert greenstone belt the oldest known Archean greenstone belt in the Rae craton, raising questions about the historical correlations with the ca. 2.74–2.71 Ga Woodburn Lake group and the 2.73–2.69 Ga Committee Bay belt to the southwest. In contrast to the Prince Albert greenstone belt, ca. 2765–2760 Ma and 2750 Ma subvolcanic magmatic rocks from the Roche Bay greenstone belt, located in the Roche Bay area in the eastern part of the peninsula, suggest that volcanism within this belt may have occurred considerably later. Based on Nd isotopic and U-Pb data, the Meso- and Neoproterozoic greenstone belts display little or no evidence of crustal contamination. Widespread intermediate to felsic magmatism occurred during multiple pulses at about 2.77 Ga, 2.72–2.68 Ga, and 2.60 Ga, and the middle pulse also included the production of mafic magmas (e.g. 2713 $\pm$ 2/-1 Ma Ni-Cu sulphide bearing ‘BIL’ gabbro). The Neoproterozoic magmatic activity on Melville Peninsula is similar to that documented in other portions of the Rae craton.

In the southern part of Melville Peninsula, dioritic and monzogranitic rocks within the basement to the Paleoproterozoic Penrhyn Group yield distinctly younger ages of ca. 2145 Ma and 2018 Ma, respectively. Based on field relationships, age data, and the local spatial association with gabbro-anorthositic rocks, we suggest that these Paleoproterozoic rocks formed as a result of crustal extension along the southern edge of the Rae craton. Accordingly, these magmatic pulses may provide a record of magmatism associated with the formation and development of the Penrhyn Group.

## **STRUCTURAL ANALYSES AND GEOCHRONOLOGICAL RESULTS: BLACK LAKE SHEAR ZONE, ADIRONDACK LOWLANDS, GRENVILLE PROVINCE, NEW YORK**

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The Grenville Province of northeastern North America is interpreted to consist of crustal blocks that were assembled from 1.4–0.9 Ga. However, granulite facies metamorphism and polyphase deformation has frequently obscured the boundaries between these zones, thus hindering our ability to reconstruct the tectonic evolution of the region.

The Black Lake shear zone has been proposed as a potentially important tectonic boundary in the Adirondack Lowlands based

on geologic and isotopic evidence. New structural, geochronologic and anisotropy of magnetic susceptibility (AMS) results from the Black Lake area constrain the location, kinematics and timing of deformation in the region. Structural data and anisotropy of magnetic susceptibility (AMS) results document a northeast trending zone of high strain between Black Lake and the Saint Lawrence River in northwestern New York State. Within this zone, strain is heterogeneous and includes a strongly developed sub-vertical northeast trending foliation. Less commonly, rocks in this zone are lineated. Regionally, two lineation sets are present, one that is sub-horizontal and another that is down dip. The foliation and granitic dikes are locally folded, forming tight to isoclinal northeast trending folds. Kinematic indicators indicate thrust deformation in areas of down-dip lineation but are mixed in areas of sub-horizontal lineation with a slight majority suggesting left-lateral shear.

These results suggest major northwest directed shortening accommodated by flattening and ductile thrust faults, possibly with a component of sub-horizontal shearing. The two lineations may have formed during discrete episodes or synchronously during transpression. U-Pb SHRIMP geochronology on igneous titanite from deformed dikes, in combination with previous geochronology, show that significant deformation occurred from ca. 1170–1100 Ma. This deformation occurred during the late stages of the Shawinigan orogeny and likely records accretion of the Adirondacks to the margin of Laurentia during terrane assembly.

## **DEFORMATION CHARACTER AND TECTONIC MECHANISM OF MIDDLE-TO-LOWER CRUSTAL FLOW DURING EXTENSION IN NORTH DABIE DOME IN THE DABIE OROGENIC BELT, CHINA**

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The North Dabie Dome (NDD) is located in the northern NW-trending Dabie orogenic belt. Recent studies unravel two stages of deformation for the NDD: the earlier sub-horizontal flow in mid- to lower crust and the later doming. Based on detailed geological mapping, we propose that the sub-horizontal flow in mid- to lower crust was dominated by Poiseuille flow in a channel in the first stage of deformation. The channel flow occurred during lithosphere extension. We also present U-Pb zircon data to suggest the timing for the two stages of deformation.

The NDD is flanked by the Xiaotian-Mozitan fault zone (XMF) to the northwest and the Wuhe-shuihou fault zone (WSF) to the southeast. Structural analysis of the two fault zones suggests that they were two segments of a single shallowly dipping fault zone. In the first stage of deformation, the XMF and the WSF were connected as a single fault zone. We measured quartz lattice preferred orientations (LPO) and investigated shear sense across the XMF and the WSF. Based on the data from quartz LPO and shear sense, we suggest that the ductile fabrics in the shear zones developed in the mid- to lower crust in a channel in the form of Poiseuille flow due to gravitational collapse. In the second stage of deformation, the NDD is uplifted, tilting the XMF to dip toward NW and the WSF to dip toward SE. In this stage of deformation, normal faults developed locally in the XMF and WSF.

We did LA-ICP-MS zircon U-Pb dating to constrain the timing of the two stages of deformation. Transposed migmatitic gneisses and undeformed plutons are selected to date the first stage of deformation. Zircon data from these samples show that the mid- to lower crustal flow started at ca. 144 Ma and ceased at 132 Ma. Brittle-ductile deformed granitic plutons from normal faults are selected to date the second stage of deformation. Data from the



rim of zircons from these samples yield age of 128 Ma which is interpreted as the timing for the second deformation stage.

#### USING TRACER EXPERIMENTS AND NITROGEN ISOTOPE FRACTIONATION TO ASSESS ANAMMOX AND DENITRIFICATION PROCESSES IN CONTAMINATED GROUNDWATERS

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Anaerobic ammonium oxidation (anammox) has been recognized as a critical process for removing nitrogen contamination in marine and surface aquatic systems. However, the relative importance of anammox and denitrification in groundwater environments is still unknown and the rates of the two major N-elimination processes have never been directly quantified. In this study, microcosm tracer incubation experiments with  $^{15}\text{N-NH}_4^+$ ,  $^{15}\text{N-NO}_3^-$  and  $^{15}\text{N-NO}_2^-$  were performed with sediment and groundwater samples from a contaminated aquifer near Elmira, Ontario in order to measure the potential reaction rates and assess the contribution of anammox and denitrification. The isotopic composition of  $\text{NH}_4^+$  and  $\text{NO}_3^-$  was measured to elucidate the kinetic isotopic effects of the two major N-elimination pathways. The tracer experiments showed that anammox accounted for 44.79% of  $\text{N}_2$  production at the Elmira site and the potential reaction rate was  $0.0314 \pm 0.006 \mu\text{mol L}^{-1} \text{ h}^{-1}$ . Denitrification contributed to 55.21% of the produced  $\text{N}_2$  and the reaction rate was  $0.0270 \pm 0.004 \mu\text{mol L}^{-1} \text{ h}^{-1}$ . Elevated  $\delta^{15}\text{N-NH}_4^+$  and  $\delta^{15}\text{N-NO}_3^-$  associated with decreasing  $\text{NH}_4^+$  and  $\text{NO}_3^-$  concentrations were indicative of reactive loss of both  $\text{NH}_4^+$  and  $\text{NO}_3^-$ . Since the incubations were performed under strict anoxic conditions, the significant  $^{15}\text{N}$  enrichment for  $\text{NH}_4^+$  is likely attributable to anammox activity. The preliminary results show that microbial anammox reaction is in agreement with the Rayleigh process with a calculated enrichment factor of -10.05‰, however the nitrate N isotope effect was low, i.e., -2.28‰. Future work will give more insight on the mixed N isotopic effects of anammox and denitrification processes.

#### HSE BEHAVIOR IN MAGMATIC SYSTEMS: INSIGHTS FROM LA-ICP-MS ELEMENT MAPS OF SULFIDES IN CHROMITITES FROM THE UG-2 REEF, BUSHVELD, SOUTH AFRICA

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We investigated the distribution of highly siderophile elements (HSE) in sulfide assemblages and chromite from the UG2 chromitite (Bushveld, South Africa). Two types of sulfides assemblages were analyzed: (1) interstitial to chromite grains and (2) included in chromite grains. Interstitial assemblages lacked pyrrhotite (po) and consisted of chalcopyrite (ccp), pentlandite (pn), and some pyrite (py). Rare sulfide assemblages, ranging in section from a few micrometers to up to 80 micrometer diameter, were found included in chromite and were interpreted to have formed from cooling of immiscible sulfide liquids trapped by the chromite host. These inclusions provide unique information about the behavior of HSE in magmatic systems because they are shielded from secondary processes (e.g. alteration and remobilization by hydrothermal fluids) after entrapment. The largest sulfide inclusion was of particular interest because the section exposed in the polished sample contained pyrrhotite, pentlandite, chalcopyrite and pyrite. We produced traced element distribution maps of sulfide assemblages (and adjacent chromite) using an ArF excimer laser with a wavelength of 193 nm coupled with a quadrupole ICP-MS. Areas of interest were scanned using a laser beam of 5  $\mu\text{m}$  diameter moving across the sample at 2.5  $\mu\text{m/s}$  (with a repetition rate of 5 Hz and a fluence of about 10 J/cm<sup>2</sup>). Time-resolved spectra of sequences

of parallel and closely spaced line scans were combined using the freeware 'Iolite' to produce element distribution maps. Our results show that: (I) chromite contained no detectable HSE in solid solution; (II) HSE distribution in sulfide assemblages interstitial to chromite was variable but, in general, pn dominated the Pd, Rh, Ru and Ir content, whereas Os, Pt, and Au were detected only outside sulfide grains and clearly associated with Bi and Te; (III) in the sulfide inclusion: (a) pyrrhotite did not contain any significant amount of HSE, (b) chalcopyrite contained only some Rh compared to the other sulfides, (c) pentlandite was the main host for Pd, (d) pyrite contained most of the Ru, Os, Ir and Re, (e) Pt and Rh were closely associated with Bi forming a continuous rim between pyrite and pentlandite, (f) no Au was detected. These results show that the use of ArF excimer laser to produce high-resolution trace element maps provide information that cannot be obtained by conventional (spot) LA-ICP-MS analysis or trace element maps that use relatively large beam diameters.

#### PHYSICOCHEMICAL CONDITION OF THE SE- AND TE-TYPES EPITHERMAL Au-Ag DEPOSITS OF WESTERN JAVA, INDONESIA

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Western Java has several gold-silver deposits and all of the mineralization follows the Sunda-Banda magmatic arc, which is the longest magmatic arc in Indonesia. The gold-silver ores of western Java reflect a major metallogenic event during the Miocene-Pliocene ages. Mineralogically, the deposits can be divided into two types i.e., Se- and Te-types deposit with some different characteristics features. The Se-type are mostly lie within and on the flanks of the Bayah Dome and represented by Pongkor, Cikidang, Cisungsang, Cirotan, and Cibaliung deposits, while Te-type are located eastern part and represented by Arinem and Cineam deposits. The principle objective of the study is to summarize the mineralogic and geochemical characteristics and constrain the physicochemical environment conditions of the Se- and Te-types epithermal mineralization within the western Java.

Geological studies indicate that volcanic rocks host the Te-type, while both volcanic and sedimentary rocks host the Se-type. In general,  $\delta^{34}\text{S}$  of sulfide from Se-type deposit of Pongkor is in the range of 0.0 to 3.2‰ and Cirotan is 0.4 to 2.9‰. Te-type of Arinem has a  $\delta^{34}\text{S}$  in the range of -5.5 to (-1.8‰). The  $\delta^{34}\text{S}$  value from both types of deposits indicating an igneous sources of sulfide sulfur.

The dominant ore mineral from Se-type are Se-bearing Ag minerals (argentite, aguilarite, polybasite, naumannite, and pyrrargyrite), electrum and tetrahedrite with various amounts of sulfide minerals of sphalerite, galena, chalcopyrite, arsenopyrite and pyrite. Some rare mineral of Bi- and Sn-bearing minerals such as lilianite and canfieldite occurred in the Cirotan deposit. The Te-type is characterized by the occurrence of hessite, petzite, stutzite, tetradymite, altaite, tennantite-tetrahedrite and with high amount sulfide minerals of sphalerite, galena, chalcopyrite, pyrite, and arsenopyrite. Mineralogical differences between the Pongkor, Cikidang, Cisungsang, Cirotan, and Cibaliung (e.g. naumannite and aguilarite), with Arinem and Cineam (e.g. hessite, petzite, stutzite, tetradymite, altaite) appear to reflect their intrinsic geochemical characteristics.

Mineralogical and geochemical differences can be explained by variation of the physicochemical conditions that existed during gold-silver deposition among those deposits. There are implies that the physicochemical conditions of the Arinem and Cineam exhibit mineral assemblages deposited closer to the heat source

and shallower than those of the Pongkor, Cikidang, Cisungsang, Cirotan and Cibaliung.

The variations of the physicochemical condition of the Se- and Te-mineral formation within the ore deposit may be explained by the phase relation between sulfides, tellurides, and selenides. The presence of selenide or telluride minerals in the deposits is dependent on the relative values of the  $f_{\text{Se}_2(\text{g})}$ ,  $f_{\text{Te}}$  and  $f_{\text{S}_2}$ , and related to their concentration in the hydrothermal fluid. Geochemical analysis results show the concentration of selenium in Te-type deposit is similar or even higher than some other Se-type deposit, but the early substitution of selenium in sulfide minerals of Te-type deposit prevented its concentration in the hydrothermal fluid to the level necessary to precipitate selenide minerals other than selenium-bearing sulfide mineral such as galena. In this condition, the early deposition of sulfide (Se-bearing sulfide) minerals from reducing ore fluids will not increase the  $f_{\text{Se}_2(\text{g})}/f_{\text{S}_2(\text{g})}$  ratio to values high enough to form selenide minerals.

#### **THE GROWTH OF MOUNTAINS IN AXEL HEIBERG ISLAND, NUNAVUT: THERMOCHRONOLOGY, TECTONICS AND CLIMATE**

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The Princess Margaret Range (2,110 m), Axel Heiberg Island, Nunavut, is partially covered by the Muller Ice Cap, analogous to those in the mountains of eastern Ellesmere Island (2,616 m). These mountains rose during the Eurekan Orogeny that resulted from interaction between Greenland and Arctic Canada from late Paleocene to Eocene. Apatite fission track (AFT) thermochronology has been used to constrain the timing of major faulting and exhumation in the region. The Princess Margaret Range lies in the hanging wall of the Stolz Thrust, a >150 km long, NNW structure that puts Triassic-Jurassic rocks over Eocene sediments. Sediments shed into a foreland basin resulting from the advance of the Stolz Thrust host the famous Tertiary Fossil Forest of the Geodetic Hills (79.91°N; 89.03°W), with well-preserved remnants of Metasequoia. The middle Eocene forest grew at a paleolatitude of ca. 80.2°N during an exceptionally warm and humid period.

Apatite samples from Cretaceous sills in the hanging wall of the Stolz Thrust yield (cooling) AFT ages of 60 to 48 Ma similar to those from the hanging wall of thrust faults in Ellesmere Island. Time-temperature modelling of track-length data suggests that the rocks cooled rapidly between 50 and 30 Ma, coinciding with exhumation and the rise of the developing Princess Margaret Range. Apatite within sandstones hosting the Fossil Forest yield ages of 49 Ma, the AFT age of the source; the sandstones remained near the surface since the Eocene.

Thrusts started advancing at ca. 60 Ma, earlier than the peak of northward movement of Greenland (55-34 Ma), and coinciding with hot-spot volcanism in the region, which probably affected the climate. AFT dates recording the rise of the Princess Margaret Range overlap with the Azolla event (ca. 49-48 Ma) when the Arctic Ocean had temperatures 20 degrees warmer than today. We propose that the same warm and humid climate that led to the development of the Fossil Forest accelerated denudation of the rising mountains thus focusing exhumation in narrow belts adjacent to active thrusts. The cooling of the climate that followed reduced erosion rates while the collision with Greenland was still active, leading to higher mountains, and to the development of alpine glaciers responsible for ice-rafted sediments encountered in Middle Eocene deep sea sediments in the Lomonosov Ridge. Our AFT data suggest that exhumation rates decreased greatly since ca. 30

Ma, explaining why imposing mountains are still preserved, despite tectonic quiescence.

#### **NEW U-Pb ZIRCON AND MONAZITE AGES FROM THE YOUNG-DAVIDSON SYENITE-HOSTED GOLD DEPOSITS: A MESOPROTEROZOIC THERMAL REACTIVATION ON THE NEOARCHEAN GOLD MINERALIZATION?**

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The Neoproterozoic Cadillac-Larder Lake deformation zone (CLLDZ) in the southern Abitibi greenstone belt is well known for spatial association with different classes of orogenic gold deposits. However, the timing of gold mineralization and late thermal reactivation still remains poorly constrained. Structural and geochronological studies on the Young-Davidson syenite-hosted gold deposit provide new constraints on this issue.

The Young-Davidson gold deposit is characterized by polyphase deformation and multiple stages of auriferous veins associated with the CLLDZ. Three stages of veining ( $V_1$  to  $V_3$ ) occur after the emplacement of the ca. 2679 Ma syenite. The earliest  $V_1$  is characterized by boudinaged quartz-ankerite veins, dipping steeply to the south.  $V_2$  is represented by folded quartz-pyrite veinlets and disseminated sulfides, dipping moderately to the NNE.  $V_3$  is of similar orientations with  $V_2$  and is comprised of en echelon or planar quartz-carbonate veins, dipping to the NE. The majority of gold mineralization is associated with  $V_2$ , but  $V_1$  and  $V_3$  are also mineralized. Structural overprinting relationships indicate that  $V_2$  and  $V_3$  postdate  $D_1$  and formed during  $D_2$ . A late  $D_2$  E-W-trending shear zone (ca. 2665 Ma) truncates all of the  $V_1$  to  $V_3$  auriferous veins and marks the end of the major phase of the Neoproterozoic gold mineralization.

A distinct group of hematite-quartz-carbonate veins shows similar orientations with  $V_3$  planar veins, but contain specular hematite, more than 50% carbonates and are distinguished from early  $V_1$  to  $V_3$  veins by their low sulphide contents. Zircons from two such veins give a U-Pb age of  $2680 \pm 10$  Ma and are interpreted as the xenocrysts from the wall rock ( $2679 \pm 2$  Ma). By contrast, hydrothermal monazites from the same veins give a Pb-Pb age of  $1737 \pm 12$  Ma that dates the emplacement of the veins. This represents the first a Mesoproterozoic age is reported from the Neoproterozoic gold deposits within the CLLDZ. The hematite-quartz-carbonate veins may have recorded a thermal reactivation of the Neoproterozoic CLLDZ at the Mesoproterozoic time, and could be economically important if they were responsible for gold mineralization or remobilization.

#### **BIOSTRATIGRAPHIC STUDY IN AREAS LACKING OUTCROPS: AN EXAMPLE FROM THE UPPER ORDOVICIAN ON MELVILLE PENINSULA**

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Biostratigraphy focuses on correlating and assigning relative ages of strata by using fossil assemblages contained within them. The aim of biostratigraphy is correlation, demonstrating that a particular horizon in one geologic section represents the same period of time as another horizon at some other section. The key in biostratigraphic study is fossils and well-exposed sections or continuous drill cores. However, how can we do biostratigraphy in areas lacking stratigraphic sections? This study deals with Upper Ordovician biostratigraphy on the tundra of northeastern Melville Peninsula.

Melville Peninsula is located in the Canadian Arctic. During Early Paleozoic time it was part of the southeastern Arctic platform, and today it preserves the Lower Paleozoic sedimentary

record of the Foxe Basin. Due to heavy erosion and a lack of outcrops, a 1:250,000 geologic map (1975) only recognized two stratigraphic units – dolomitic limestone (Ols) and calcareous dolostone (Orf) for the Upper Ordovician in a huge area of 67°45'-69°30'N, 81°15'-83°15'W on northeastern Melville Peninsula, which is mostly covered by carbonate rubble. The age of the units is unclear.

Field studies on northeastern Melville Peninsula, especially in the areas covered by unit Ols, not only included sampling from outcrops, but also from rubble, with focus on the latter. Two rubble-sampling lines (each about 20 km long), roughly perpendicular to the regional strike of strata, were chosen based on satellite images, in areas which appear to have been relatively less affected by glaciers. The interval between rubble samples is about 1 km, a total of 373 kg rubble samples were collected for microfossil conodonts.

The conodont data from the rubble samples support a division of unit Ols into two different units based on two conodont faunas dominated by the Edenian–Maysvillian species *Belodina confluens* and the early Richmondian species *Amorphognathus ordovicicus*, respectively. Conodonts from outcrops of unit Orf are dominated by the late Richmondian species *Rhipidognathus symmetricus*.

The conodonts from rubble samples plus those from outcrops on northeastern Melville Peninsula prove that in the areas lacking outcrops, studying microfossils from relatively undisturbed rubble can be a useful tool for biostratigraphic division and correlation. Late Ordovician conodonts from both rubble and outcrops on northeastern Melville Peninsula, for the first time in the history of Melville geologic study, provide reliable fossil information indicating that the Upper Ordovician on Melville Peninsula can be correlated to that in the Hudson Bay Basin, formed by deposits during Edenian, Maysvillian and Richmondian time.

#### **LATTICE BOLTZMANN MODELLING OF STELLATE PLAGIOCLASE FORMATION FROM ISLE OF RUM, SCOTLAND**

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We propose a model for the formation of branching plagioclase textures visible at both macroscopic (~cm to m) and microscopic scale in Isle of Rum, Scotland. The linking of plagioclase crystals within melagabbro via mechanisms such as twinning forms a large mesh of planar stellate structures (m-scale) with a large range in geometrical organization transitioning from patchy to radiating. Evidence of macroscopic crystal aggregation and alignment may possibly be attributed to interfacial free energy minimization at the microscopic scale. Accordingly a Lattice Boltzmann model was developed to simulate diffusion of plagioclase analogue in the melt phase. Quantitative testing of the Lattice Boltzmann model was done to verify accuracy of the melt model. Isothermal phase transitions modelled via first order chemical reactions are subsequently coupled with stochastic dynamics at the crystal growth front to simulate energy minimization processes including twinning during crystallization in an igneous environment. Aspects of the model and current results will be presented.

#### **PETROGENETIC ANALYSIS OF FELSIC INTRUSIVE ROCKS AT THE SISSON BROOK W-Mo-Cu DEPOSIT, WEST-CENTRAL NEW BRUNSWICK: STABLE ISOTOPE CONSIDERATIONS**

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The Sisson Brook W-Mo-Cu deposit, situated in west-central New Brunswick, is hosted by Cambro-Ordovician volcanic and sedimentary rocks of the Miramichi and Tetagouche groups. These have been intruded by the Early Devonian Howard Peak diorite-gabbro, Nashwaak Granite, a phaneritic felsic dyke swarm, and a distinctively younger Late Devonian porphyritic felsic dyke. This study focuses on petrogenetically characterizing these felsic units and deducing their magma source, based on their petrology and major- and trace-element, and isotope geochemistry.

Three groups of slightly oxidized volcanic arc granites (low P, low T, evolved I-type) have been identified in the vicinity of the deposit: (1) the Nashwaak granite that consists of biotite (20%) with accessory zircon, apatite, monazite, magnetite, and ilmenite; (2) the dyke swarm, which contains biotite (5%) intergrown with apatite, pyrrhotite, and titanite; and (3) the porphyry dyke whose phenocrysts consist of approximately 23% plagioclase, 10% quartz, 8% biotite, and 7% K-feldspar. In these groups, chloritization occurs along the rim and cleavage of the biotite, whereas patchy sericitic replacement is found in the K-feldspar. In the dyke swarm, sericitization drives the molar  $K_2O/Al_2O_3$  of the whole rock close to that of muscovite. Other groups have no obvious trend. The samples for the isotope analysis have the molar  $K_2O/Al_2O_3$  and molar  $Na_2O/Al_2O_3$  of 0.36 to 0.45 and 0.26 to 0.31 for the Nashwaak granites, 0.06 to 0.49 and 0.13 to 0.57 for the dyke swarm group, 0.25 and 0.38 for the porphyry dyke. These values distribute along the plagioclase–K-feldspar (or biotite) association ratio and may indicate their relative fresh features.

The whole-rock hydrogen and oxygen isotope composition for these granites are:  $-79\text{‰} > \delta D > -76\text{‰}$  and  $7.9\text{‰} > \delta^{18}O > 9.5\text{‰}$  for the Nashwaak group;  $-77\text{‰} > \delta D > -62\text{‰}$  and  $9.7\text{‰} > \delta^{18}O > 12.3\text{‰}$  for the dyke swarm group, and  $\delta D = -67\text{‰}$ ,  $\delta^{18}O = 10.1\text{‰}$  for the porphyry dyke. These data exhibit a narrow distribution and the  $\delta D$  values are positively correlated with the water content of these granites, whereas the variation in oxygen isotope values is indistinguishable. The minimal difference of hydrogen and oxygen behavior indicates a high T, low water/rock ratio during alteration of these least-altered dykes. Thus these  $\delta^{18}O$  values represent the primary values and are consistent with the isotope data for each of the coeval granitoids intruding the Gander Zone (New Brunswick); they could be derived from melting of lower-middle crustal source (infracrustal), consistent with earlier interpretations of this magmatic suite.

#### **EXTENSIONAL STRUCTURES IN PASTO VENTURA REGION OF THE PUNA PLATEAU, NW ARGENTINA: DISTRIBUTION, SLIP RATE AND GEODYNAMIC IMPLICATIONS**

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Lithospheric foundering processes can be traced by studying the structural evolution at the surface of the Earth. On the southern Puna plateau, in the Pasto Ventura basin, NW Argentina, a number of faults offset geomorphic features. We mapped them and meas-

ured the displacements across two major faults (PVW-01 and PVW-02) that cut through basaltic lava flows and associated cinder cones using a kinematic GPS mapping system. The lava flows are 0.3 Ma and  $1.46 \pm 0.15$  Ma ( $^{40}\text{Ar}/^{39}\text{Ar}$ ). In the eastern part of study area ( $67^{\circ}13'\text{W}$  and  $26^{\circ}50'\text{S}$ , normal faults are identified by abrupt changes in the steepness of river channels and cut through Neogene fluvial strata and Quaternary conglomerated alluvial sediments. These faults range in length from 1.5 to 4 km and they are mostly E-W striking. In the northern part of the study region, laterally offset modern river channels mark a right-lateral fault, which is 2 km long and strikes  $\text{N}45^{\circ}\text{E}$ . Additional normal faults and right-lateral strike-slip faults, with the similar characteristics, have been identified in other parts of study area. In addition to these small faults, which recently developed, several large faults also cut through the study area. Those faults strike mostly ENE or NE. Previous studies identified these as Miocene reverse faults recently reactivated as normal faults. Our study shows that they are

now undergoing both normal faulting and right-lateral strike-slip displacement, indicating an approximately N-S extensional direction. The vertical offset of the basaltic cinder cone cut by fault PVW-01 is 7.4–24.7 m. The 0.3 Ma age of this cinder cone yields a minimum vertical displacement rate of  $\sim 0.02\text{--}0.08$  mm/a. In the same way, the average vertical displacement rate across fault PVW-02 is estimated as a minimum of  $\sim 0.01\text{--}0.02$  mm/a. Considering possible degradation of the cinder cones by erosion, these estimates could be smaller than the true vertical displacement rate, but regardless, indicate that the vertical displacement rate, and therefore the extension rate, must be very slow. Kinematic analysis of both the newly developed and reactivated faults indicates that the Pasto Ventura region on the southern plateau margin is undergoing N-S to NNE-SSW extension. The extension rate, though currently very slow, appears to be accelerating. These structures may reflect the upper lithospheric extension related to the proposed recent lithospheric foundering beneath the Puna Plateau.

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