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Hayles, S.F., Al, T., Cornett, R.J. *and* Harrison, A., *University of Ottawa, Advanced Research Complex, 25 Templeton St., Ottawa, ON K1N 6N5, shayl019@uottawa.ca*

162 A long-lived Neoproterozoic carbonate platform and its Cryogenian glacial record: Stratigraphic development of the Otavi Group in the easily accessible southern Kunene Region, Namibia
Hoffman, P.F., *1216 Montrose Ave., Victoria, BC V8T 2K4, paulfhoffman@gmail.com,* Halverson, G.P., Lamothe, K.G., *Earth & Planetary Sciences, McGill University, Montreal, QC H3A 0E8,* Pruss, S.B., *Geosciences, Smith College, Northampton, MA 01063, USA, and* Schrag, D.P., *Earth & Planetary Sciences, Harvard University, Cambridge, MA 02138, USA*

163 Depocenters on Snowball Earth: A tunnel valley, subglacial rift-valley lake, giant moraine and erratic blocks in the Sturtian Chuos Formation of NW Namibia
Hoffman, P.F., *1216 Montrose Ave., Victoria, BC V8T 2K4, paulfhoffman@gmail.com,* Hodgskiss, M.S.W., *Geological Sciences, Stanford University, Stanford, CA 94305, USA,* Lamothe, K.S., *Earth & Planetary Sciences, McGill University, Montreal, QC H3A 0E8, and* LoBianco, S.J.C., *Earth & Planetary Sciences, Harvard University, Cambridge, MA 02138, USA*

164 Expanded freshwater oligotrophy on Snowball Earth and the origin of modern marine planktonic cyanobacteria
Hoffman, P.F., *1216 Montrose Ave., Victoria, BC V8T 2K4, paulfhoffman@gmail.com,* Sanchez-Baracaldo, P., *School of Geographical Sciences, University of Bristol, Bristol, BS8 1SS, UK, and* Vincent, W.F., *Departement de biologie & Centre d'etudes nordiques, Universite Laval, Sainte-Foy, QC G1K 7P4*

165 Call for further research on the architecture and evolution of the crust during continental arc magmatism: Coast Mountains batholith, British Columbia
Hollister, L.S., *Princeton University, Princeton, NJ 08544, USA,* Woodsworth, G.J., *Geological Survey of Canada, Vancouver, BC V6B 5J3,* Rusmore, M.E., *Occidental College, Los Angeles, CA 90041, USA, and* Stowell, H.H., *University of Alabama, Tuscaloosa, AL 35487-0338, USA*

166 Mg isotope tracing of fluid migration during dolomitization
Holmden C., *chris.holmden@usask.ca, and* Kimmig S.R., *Saskatchewan Isotope Laboratory, Department of Geological Sciences, University of Saskatchewan, Saskatoon, SK S7N 5E2*

167 Mineralogical and chemical complexity in alteration in the Nechalacho rare-earth element deposit, NWT
Hoyle, J.W.B, *hoylej@uwindsor.ca, and* Samson, I.M., *University of Windsor, Windsor, ON N9B 3P4*

168 Late Mesozoic volcanism in the middle and lower Yangtze River reaches, China
Huaimin, X., *Institute of Geology,Chinese Academy of Geological Sciences, Bejing, China, huaiminx@sina.com*

169 Keynote (40 min): The stratigraphic expression of slope channel processes
Hubbard, S.M., *University of Calgary, Calgary, AB T2N 1N4, shubbard@ucalgary.ca*

170 Keynote (40 min): Transport, fate and impact of metallic and metalloid elements in mining-affected river systems
Hudson-Edwards, K.A.[1], *k.hudson-edwards@bbk.ac.uk,* Bird, G.[2], Brewer, P.[3], Byrne, P.[4], Jamieson, H.E.[5], Onnis, P.[4], Macklin, M.G.[6], Tame, C.[1], *and* Williams, R.D.[7], [1]*Department of Earth and Planetary Sciences, Birkbeck, University of London, WC1E 7HX, UK;* [2]*School of Environment, Natural Resources and Geography, Bangor University, Bangor, Gwynedd, LL57 2UW, UK;* [3]*Department of Geography and Earth Sci*

171 Overall approach for conducting a postclosure safety assessment for a deep geological repository for used nuclear fuel
Hunt, N.G., *Nuclear Waste Management Organization, 22 St. Clair Avenue East, 6th Floor, M4T 2S3, nhunt@nwmo.ca*

172 A structural investigation of the Thelon and Judge Sissons faults, northeast Thelon Basin, central Rae Domain, Nunavut
Hunter, R.C., *rhunter@laurentian.ca,* Lafrance, B., *Mineral Exploration Research Centre, Harquail School of Earth Sciences, Goodman School of Mines, Laurentian University, Sudbury, ON P3E 2C6, and* Thomas, D., *Cameco Corporation, 2121 11th Street West, Saskatoon, SK S7M 1J3*

173 The heat of orogeny: The importance of uniformly hot backarcs prior to orogenic collision
Hyndman, R.D., *Pacific Geoscience Centre, Geological Survey of Canada and SEOS, University of Victoria, BC, roy.hyndman@canada.ca*

174 Lower crust detachment and channel flow everywhere in the North American Cordillera: The crust moves independently of the mantle
Hyndman, R.D., *Pacific Geoscience Centre, Geological Survey of Canada and SEOS, University of Victoria, BC, roy.hyndman@canada.ca, and* Currie, C.A., *Dept. Physics, University of Alberta, AB*

175 Converging morphometry of Proterozoic and post-vegetation rivers
Ielpi, A., *Laurentian University, 935 Ramsey Lake Rd., Sudbury, ON P3E 2C6, aielpi@laurentian.ca,* Rainbird, R.H., *Geological Survey of Canada, 601 Booth St., Ottawa, ON K1A 0E8,* Ventra, D., *University of Geneva, 13 Rue des Maraîchers, Geneva, CH-1205, Switzerland, and* Ghinassi, M., *University of Padua, Via Gradenigo 6, Padua, 35131, Italy*

176 Keynote (40 min): Understanding the metamorphic architecture of large hot orogens: Tools and limitations with examples from the Grenville Province
Indares, A., *Memorial University, St John's, NL, aindares@mun.ca*

177 Aragonite facies in an Ordovician calcite sea
James, N.P.[1], Armstrong, A.K.R.[2], *and* Narbonne, G.M.[1], [1]*Queen's University, Kingston, ON;* [2]*International Ocean Discovery Program, Texas A&M University, College Station, TX 77845-9547, USA*

178 Compositional and diagenetic partitioning of cool-water carbonate marine and aeolianite sediments, SE Australia; Resolution of a conundrum
James, N.P.[1], Joury, M.R.F.[1], Bone, Y.[2], *and* Kyser, T.K.[1], Malcolm, I.[1], [1],*Queen's University, Kingston, ON;* [2]*Adelaide University, Adelaide, South Australia*

179 Application of automated mineralogy in human health risk assessment at the Giant Mine, Yellowknife
Jamieson, H.E., Dobosz, A., Bailey, A.S., Bromstad, M.L., Schuh, C.E., *and* Van Den Berghe, M.V., *Queen's University, Kingston, ON K7L 3N6, jamieson@queensu.ca*

180 Keynote (40 min): Cryptic structures revealed - Where and how they form, and why it matters
Jamieson, R.A., *Department of Earth Sciences, Dalhousie University, Halifax, NS B3H 4R2, beckyj@dal.ca, and* Beaumont, C., *Department of Oceanography, Dalhousie University, Halifax, NS B3H 4R2*

181 Deformation history of the Black Bay Fault
Jamison, D., *djamison@uwaterloo.ca,* Lin, S., *University of Waterloo, Department of Earth and Environmental Sciences, 200 University Ave W., Waterloo, ON N2L 3G1,* Martel, E., *Northwest Territories Geological Survey, 4601-B 52nd Ave., Yellowknife, NT X1A 2l9, and* Pehrsson, S., *Geological Survey of Canada, 601 Booth Street, Ottawa, ON S7M 1J3*

182 3D numerical modeling of mantle lithospheric removal induced by eclogitization
Janbakhsh, P., *Ph.D. Program, Dept. of Earth Sciences, University of Toronto, payman.janbakhsh@mail.utoronto.ca*

183 Indicator minerals and pathfinder elements from a regional drilling program, Lac de Gras, NT; Insights into 3-D dispersion resulting from ice flow shifts
Janzen, R.J.D., *r4janzen@uwaterloo.ca,* Kelley, S.E., Ross, M., *University of Waterloo, University Avenue West, Waterloo, ON N2L 3G1,* Normandeau, P.X., *and* Elliott, B., *Northwest Territories Geological Survey, 52nd Avenue, Yellowknife, NT X1A 2L9*

184 Structural control of mineralization and history of deformation at the Island Gold deposit, Superior Province, Ontario
Jellicoe, K.M., *k.jellicoe@gmail.com, and* Lin, S., *University of Waterloo, University Avenue, Waterloo, ON N2L 3G1*

185 Geochemical and textural analysis of the cyclic units in the Peridotite zone, Stillwater Complex, Montana
Jenkins, M.C. *and* Mungall, J.E., *University of Toronto, 22 Russell St., Toronto, ON M5S 3B1, chris.jenkins@mail.utoronto.ca*

186 Adaptive Phased Management: Canada's plan for long-term management of nuclear used fuel the role of geosciences

Jensen, M.R., *Nuclear Waste Management Organization, 22 St. Clair Ave. East, Toronto, ON M4T 2S3, mjensen@nwmo.ca*

187 Triassic transpressional deformation along the Shangdan Tectonic Zone and the tectonics of the Qinling orogenic belt in China

Jiang, D.[1], Qu, M.[1], Shi, J.[1], *djiang3@uwo.ca,* Li, Y.[2], *and* Lu, L.X.[1], [1]*Earth Sciences, Western University, London, ON N6A 5B7;* [2]*Department of Geology, Northwest University, Xi'an, 710069, China*

188 Uranium and molybdenum isotope constraints on ocean redox conditions during deposition of the Upper Devonian Kettle Point Formation, Ontario

Jieying, W., *Department of Earth and Environmental Sciences, University of Waterloo, Waterloo, ON N2L 3G1 (+2 authors)*

189 Most of the modern-day coastal zone in the upper Great Lakes was established many millennia ago during the Nipissing phase

Johnston, J.W., *jwjohnston@uwaterloo.ca,* Morrison, S., *Department of Earth and Environmental Sciences and Water Institute, University of Waterloo, 200 University Ave West, Waterloo, ON N2L 3G1,* Argyilan, E.P., *Indiana University Northwest, Department of Geosciences, Marram Hall 236, 3400 Broadway, Gary, IN 46408, USA,* Thompson, T.A., *Indiana University, Indiana Geological Survey, 611 North Walnut Grove Avenue, Bloomington, IN 47405-2208, USA,* Lepper, K., *North Dakota State University, Department of Geosciences, Optical Dating and Dosimetry Lab, PO Box 6050, Fargo, ND 58108, USA,* Baedke, S.J., *James Madison University, Department of Geology and Environmental Science, MSC 6903, Harrisonburg, VA 22807, USA, and* Wilcox, D.A., *SUNY-The College at Brockport, Department of Environmental Science and Biology, 350 New Campus Drive, Brockport, NY 14420, USA*

190 Lithostructural controls of U mineralization in the Kiggavik Main and Centre zones, north-central Rae craton: A record of long-lived tectonism and ground preparation for U ore systems

Johnstone, D., Bethune, K., *Dept. of Geology, University of Regina, 3737 Wascana Parkway, Regina, SK S4S 0A2, johnstdi@uregina.ca,* Quirt, D., Benedicto, A., *and* Ledru, P., *AREVA Resources Canada Inc., 817 45th Street West, Saskatoon, SK S7K 3X5*

191 The geochemical characterization and resultant exploration implications for the meta-sedimentary hosted Kiyuk Lake Au-prospect, Kivalliq region, Nunavut

Jones, S., *13sj34@queensu.ca,* Kyser, K., *Queen's University, 36 Union St., Kingston, ON K7L 3N6,* Fleming, A., *adrian.fleming@me.com, and* Mackie, R., *Suite 610, 1155 W. Pender St. Vancouver, BC V6E 2P4*

192 Keynote (40 min): The Ni-Cu-PGE prospectivity of mafic-ultramafic Large Igneous Province events and the use of lithogeochemistry in mineral exploration

Jowitt, S.M., *Department of Geoscience, University of Nevada Las Vegas, 4505., S Maryland Pkwy, Las Vegas, NV 89154-4010, USA, simon.jowitt@unlv.edu, and* Keays, R.R., *School of Earth, Atmosphere and Environment, Monash University, Wellington Road, Clayton, VIC3800, Australia*

193 Alteration mineralogy and pathfinder element inventory in the footprint of the McArthur River unconformity-related uranium deposit, Canada

Joyce, N., *nickjoyce@gmail.com,* Layton-Matthews, D., Kyser, K., *Queen's University, 36 Union St., Kingston, ON K7L 3N6,* Ansdell, K., *University of Saskatchewan, Saskatoon, SK,* Quirt, D., *AREVA, Saskatoon, SK, and* Kotzer, T., *Cameco Corp., Saskatoon, SK*

194 Middle-Upper Devonian of the central-northern Mackenzie Corridor: Multiproxy stratigraphic framework and sedimentary environments of a black-shale basin

Kabanov, P.[1], *Pavel.Kabanov@canada.ca,* Gouwy, S.A.[1], Percival, J.B.[2], Bilot, I.[2], Jiang, C.[1], *and* Chuen Chan, W.[3], - *Geological Survey of Canada, 3303 33rd St., NW Calgary, AB T2L 2A7;* [2]*Geological Survey of Canada, 601 Booth Street, Ottawa, ON K1A 0E8;* [3]*University of Calgary, 2500 University Dr., NW Calgary, AB T2N 1N4*

195 Cigar Lake: Geometallurgical ore characterization in support of mining and milling

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196 Stratigraphy and sedimentology of Ordovician outliers in the northern Ottawa-Bonnechere graben, central Ontario: An ongoing study of their significance for depositional systems within the Laurentian interior

Kang, H., *he.kang@carleton.ca,* Dix, G.R., *and* Oruche, N.E., *Carleton University, 1125 Colonel By Drive, Ottawa, ON K1S 5B6*

197 Field, petrologic and geochemical evidence for structurally-controlled hydrothermal dolomitization in a compressive-extensional tectonic regime: An example from the Cretaceous Qamchuqa carbonates, Zagros Basin, Kurdistan Iraq

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198 Keynote (30 min): Dating fault zones using the K-Ar decay system

Kellett, D.A., *Geological Survey of Canada, 1 Challenger Drive, Dartmouth, NS B2Y 4A2, dawn.kellett@canada.ca,* Warren, C., *School of Environment Earth and Ecosystem Sciences, The Open University, Milton Keynes, MK7 6AA UK,* Zwingmann, H., *Department of Geology and Mineralogy, Graduate School of Science, Sakyo-ku, Kyoto University, Kyoto, 606-8502, Japan,* Larson, K.P., *Earth and Environmental Sciences, University of British Columbia, Okanagan, FIP353-3247 University Way, Kelowna, BC V1V 1V7,* van Staal, C., *Geological Survey of Canada (emeritus), 1500-605 Robson St., Vancouver, BC V6B 5J3, and* Rogers, N., *Geological Survey of Canada, 601 Booth St., Ottawa, ON K1A 0E8*

199 Glacial dispersal patterns in three dimensions from a pair of buried kimberlites, Lac De Gras region, NT

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200 Physical and chemical controls on the localization and precipitation of gold at the Archean Hislop and Grey Fox deposits

Kelly, C.H., *ckelly2@laurentian.ca,* Kontak, D.J., *and* Lafrance, B., *Laurentian University, Ramsey Lake Rd, Sudbury, ON P3E 2C6*

201 Unravelling the history of high-pressure granulite-facies rocks: The metamorphic record of kyanite

Kendrick, J.L. *and* Indares, A., *Department of Earth Sciences, Memorial University of Newfoundland, St. John's, NL A1B 3X5, jkendrick@mun.ca*

202 The Molaoi Pb-Zn(-Ag) deposit in South Eastern Peloponnese, Hellas

Kevrekidis, E.[1], *eliaskevrekidis@gmail.com,* St.Seymour, K.[1], Tombros, S.[1], Koukouvelas, I.[1], Oyman, T.[2], Zhai, D.[3], Liu, J.[3], *and* Kalaitzidis, S.[1], [1]*Department of Geology, University of Patras, Rio-Patras, 26504, Greece;* [2]*Department of Geological Engineering, Dokuz Eylul University, 35100 Bornova, Izmir, Turkey;* [3]*School of Earth Sciences and Resources, China University of Geoscie*

203 1020-975 Ma LIP on the southeastern margin of the Siberian Craton: The Sette-Daban mafic magmatic event

Khudoley, A.K.[1], *a.khudoley@spbu.ru,* Prokopiev, A.V.[2], Chamberlain, K.R.[3,4], Ernst, R.E.[5,4], Lebedeva, O.Y.[6], Zaitsev, A.I.[2], *and* Kazakova, G.G.[6], [1]*St. Petersburg State University, Institute of the Earth Sciences, 7/9 University nab., St. Petersburg, 199034, Russia;* [2]*Diamond and Precious Metal Geology Institute, Siberian Branch of the Russian Academy of Sciences, 39 Lenin Ave., Yak*

204 An allochtonous terrane in the Korean Peninsula: The Neoproterozoic Sangwon unit

Kim, Y., *Chungbuk National University, Chungdae-ro 1, Cheongju, Chungbuk 28644, South Korea, yoonsup@cbnu.ac.kr (+2nd author?)*

205 Frictional-viscous deformation at the source of slow earthquakes

Kirkpatrick, J.D., *McGill University, 3450 University Ave, Montreal, QC H3A 0E8, james.kirkpatrick@mcgill.ca*

206 **A geochemical study of the intracaldera tuffs of the ca. 25 Ma Underdown caldera, western Nevada caldera belt, north-central Nevada, U.S.A.**
Klausen, K.B., *kim.klausen@carleton.ca,* Cousens, B., *Ottawa–Carleton Geoscience Centre, Department of Earth Sciences, Carleton University, 1125 Colonel By Drive, Ottawa, ON K1S 5B6, and* Henry, C.D., *Nevada Bureau of Mines and Geology, University of Nevada, Reno, NV 89557, USA*

207 **A new look at VMS and Au mineral endowment in the Slave Province through detailed bedrock mapping of the Beaulieu River Volcanic Belt at Sunset Lake, Northwest Territories**
Knox, B., *Northwest Territories Geological Survey, PO Box 1320, Yellowknife, NT X1A 1K5*

208 **Diagenetic and mineralising fluids are more than just wt. % equivalent NaCl!**
Kontak, D.J., *dkontak@laurentian.ca,* Turner, E.C., Mathieu, J., *and* Hahn, K., *Harquail School of Earth Sciences, Laurentian University, Sudbury ON P3E 2C6*

209 **Structural controls on gold mineralization at the Dogpaw and Dubenski deposits in the Rowan-Kakagi greenstone belt, western Wabigoon Subprovince, northwestern Ontario**
Krapf-Jones, A.D., *akrafpjo@uwaterloo.ca,* Lin, S., *University of Waterloo, 200 University Ave. W., Waterloo, ON N2L 3G1, and* Meade, S.R., *Earth Resources and Geosceince Mapping Section, Ontario Geological Survey, Sudbury, ON P3E 6B5*

210 **Freshwater dinoflagellate cysts as proxies of cultural eutrophication**
Krueger, A.M.[1], *akrueger@brocku.ca,* McCarthy, F.M.G.[1], Riddick, N.L.[2], Volik, O.[3], Danesh, D.C.[4], Drljepan, M.[5], Pilkington, P.M.[1], Garner, C.[1], *and* Vasseur, L.[1], [1]*Brock University, St Catharines ON L2S 3A1;* [2]*McMaster University, Hamilton, ON L8S 4L8;* [3]*University of Waterloo, Waterloo, ON N2L 3G1;* [4]*Queens University, Kingston, ON K7L ÇN6;* [5]*Western University, London, ON N6A 3K7*

211 **Searching for the Cheshire cat: Biases in Ediacaran taphonomy**
Laflamme, M., *Department of Chemical and Physical Sciences, University of Toronto Mississauga, marc.laflamme@utoronto.ca*

212 **Siderite synthesis from iron-bearing acidic solutions combined with flue gases from combustion of fossil fuels**
Lake, D.J., Groat, L.A., Gyenge, E., *University of British Columbia, Vancouver, BC V6T 1Z4, groat@mail.ubc.ca,* Carne, A., *and* Ritchie, J., *Terra CO_2 Technologies Ltd., 510 West Hastings St., Vancouver, BC V6B 1L8*

213 **Use of chromite chemistry for correlation of PGE-bearing reefs within the Bushveld Igneous Complex**
Langa, M.M., *mlanga@laurentian.ca,* Jugo, P.J., *and* Leybourne, M., *Laurentian University, 935 Ramsey Lake Road, Sudbury, ON P3E 2C6*

214 **Characterizing strain in the East Athabasca mylonite zone**
Larson, K.P., *Earth, Environmental and Geographic Sciences, IKBSAS, University of British Columbia, Okanagan, Kelowna, BC V1V 1V7, kyle.larson@ubc.ca*

215 **A diamictite dichotomy: Glacial conveyor belts and olistostromes in the Neoproterozoic of Death Valley, California, USA**
Le Heron, D.P., Tofaif, S., Vandyk, T., *and* Ali, D.O., *Department of Earth Sciences, Royal Holloway University of London, Egham, Surrey TW20 0EX, UK*

216 **Precambrian continental landscapes and paleoclimates: New perspectives from 1.2 Ga Meall Dearg Formation, Torridonian of Scotland**
Lebeau, L.E. *and* Ielpi, A., *Harquail School of Earth Sciences, Laurentian University, Sudbury, ON P3E 2C6, llebeau@laurentian.ca*

217 **Geological Survey of Canada (GSC): Peering into the future, teaming for geoscience excellence and results**
Lebel, D., *Geological Survey of Canada, Natural Resources Canada, 601 Booth Street, Ottawa, ON K1A 0E8*

218 Identification of Early Cretaceous extensional granitic domes along the southeastern China-Mongolia border and its tectonic implications
Lei, G., Tao, W., Ying, T., *Institute of Geology, Chinese Academy of Geological Sciences, Beijing, China, 100037, guolei@cags.ac.cn,* Narantsetseg, T., *and* Enkh-Orshikh, O., *Institute of Paleontology and Geology, Mongolian Academy of Sciences, Ulaanbaatar, Mongolia, 15160, POB 46/650*

219 Fault interpretation from multiple data sources in central BC
Lenauer, I.[1], *iris.lenauer@utoronto.ca,* Ugalde, H.[2], *and* Milkereit, B.[1], [1]*University of Toronto, 22 Russell Street, Toronto, ON M5S 3B1;* [2]*Paterson, Grant & Watson Ltd., 155 University Ave, Toronto, ON M5H 3B7*

220 Characterization of gold in the W-Cu skarns at Cantung, NWT: Results from in situ LA ICP-MS, SEM, and Micro-XRF analyses
Lentz, C.P.E., *carlin.lentz90@gmail.com,* McFarlane, C.R.M., *University of New Brunswick, 2 Bailey Drive, Fredericton, NB E3B 5A3, and* Falck, H., *Northwest Territories Geological Survey, 4601-B 52nd Ave, Yellowknife, NT X1A 2L9*

221 Extreme fractionation in various felsic magmatic systems: Constraints from thermal modelling with examples from ore-forming granophile-element systems
Lentz, D.R., *University of New Brunswick, 2 Bailey Drive, Fredericton, NB E3B 5A3, dlentz@unb.ca*

222 The ups and downs of magmatic Fe-Ni-Cu-(PGE) sulfide melts in large igneous complexes
Lesher, C.M., *Mineral Exploration Research Centre, Harquail School of Earth Sciences and Goodman School of Mines, Laurentian University, Sudbury, ON P3E 2C6, mlesher@laurentian.ca*

223 Crustal-scale modelling for the UK 3D Geological Model
Leslie, A.G., Schofield, D., *British Geological Survey, Edinburgh, UK,* Pharaoh, T.C., Mathers, S., Terrington, R. *and* Thorpe, S., *British Geological Survey, Keyworth, UK, tcp@bgs.ac.uk*

224 Alteration zonation associated with Au mineralization along the northern Bug Lake gold trend of the Archean La Martinière gold system, west-central Quebec
Létourneau, M., *mletourneau1@laurentian.ca,* Kontak, D.J., *and* Leybourne, M.I., *Laurentian University, Sudbury, ON P3E 2C6*

225 Radon risk management initiatives: Geoscience for geohazard risk management and public safety decision making
Leybourne, M.I. *and* de Jong, S., *Harquail School of Earth Sciences, Laurentian University*

226 Building aquifer vulnerability literacy in southern Ontario: Applying emergent technologies in groundwater geoscience education
Leybourne, M.I., Jong, S., *Harquail School of Earth Sciences, Laurentian University, and* Russell, H., *Geological Survey of Canada, Natural Resources Canada*

227 South China as an accretionary orogen
Lin, S.[1], *Shoufa@uwaterloo.ca,* Xing, G.F.[2], Davis, D.W.[3], Yin, C.Q.[4], Wu, M.L.[1], Li, L.M.[5], Fang, H.[6], Jiang, Y.[2], *and* Chen, Z.H.[2], [1]*University of Waterloo, Waterloo, ON N2L 3G1;* [2]*Nanjing Institute of Geology and Mineral Resources, Nanjing 210016, China;* [3]*University of Toronto, Toronto, ON M5S 3B1;* [4]*Sun Yat-Sen University, Guangzhou 510275, China;* [5]*Hefei University*

228 A collision of Avalonia and Cadomia at 540 Ma?
Linnemann, U., Gärtner, A., Hofmann, M., Zieger, J., *Senckenberg Collections of Natural History Dresden, Königsbrücker Landstr. 159, Dresden, O1109, Germany, ulf.linnemann@senckenberg.de*

229 Deciphering the crystalline metasedimentary rocks exposed in the Hellenic Volcanic Arc, Santorini, Greece
Lion, A., *alion103@uottawa.ca,* Schneider, D.A., *Univerity of Ottawa, 75 Laurier East, Ottawa, ON K1N 6N5,* Grasemann, B., *and* Tsevairidou, K., *University of Vienna, A-1090 Vienna, Austria*

230 Tectonic affinities of microcontinents in the Central Asian Orogenic Belt: A case study from the Chinese Tianshan Orogenic Belt
Long X.P., *State Key Laboratory of Continental Dynamics, Department of Geology, Northwest University, Northern Taibai Str. 229, Xi'an 710069, China, longxp@nwu.edu.cn*

231 Keynote (30 min): Diagenetic yearnings and learnings from light stable isotopy of clay minerals – Looking backward and going forward

Longstaffe, F.J., *The University of Western Ontario, Earth Sciences, London, ON N6A 5B7, flongsta@uwo.ca*

232 Relevance of fluid:rock interaction in Proterozoic pegmatites near Sudbury, Ontario to mineralization in rare-metal pegmatite settings

Lorenzo, R.I. *and* Kontak, D.J., *Harquail School of Earth Sciences, Laurentian University, 935 Ramsey Lake Rd., Sudbury, ON P3E 2C6, rlorenzo@laurentian.ca*

233 An exquisitely diverse assemblage of organic-walled microfossils from the Proterozoic of Arctic Canada and implications for the early evolution of eukaryotes

Loron, C., Javaux, E.J., *Palaeobiogeobiology-Palaeobotany-Palaeopalynology, Geology department, University of Liège, Liège, Belgium, c.loron@ulg.ac.be,* Rainbird, R., Greenman, W., *Geological Survey of Canada, Ottawa-Carleton Geoscience Centre, Carleton University, Ottawa, ON, and* Turner, E., *Earth Sciences Department, Laurentian University, Sudbury, ON*

234 Fine fraction indicator mineral signatures of porphyry, VMS and other deposits

Lougheed, H.D.[1], *5hdl@queensu.ca,* McClenaghan, M.B.[2], *and* Layton-Matthews, D.[1], [1]*Queen's University, Department of Geological Sciences and Engineering, 36 Union Street, Kingston, ON K7L 3N6;* [2]*Geological Survey of Canada, 601 Booth Street, Ottawa, ON K1A 0E8*

235 Genesis and petrology of the Antamina Cu-Zn skarn deposit, Peru

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236 Automatic estimation of aquifer parameters using long-term water supply pumping and injection records from a highly heterogeneous glacial deposit

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237 Hyperspectral characterization of mineralogy and mineral chemistry across the Canadian Malartic gold deposit, Quebec, Canada

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238 Microstructural style and relative timing of deformation along the Bathurst fault, western Nunavut

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239 Sedimentary-hosted Pb-Zn mineralization in the Paleoproterozoic Karrat Group, west Greenland

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240 Regional distribution of arsenic in soil in the Yellowknife region

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241 Till provenance discrimination using iron oxides physicochemical characteristics; Case studies from Kiggavik uranium district (Nunavut, Canada)

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242 Geochronological constraints on the dextral strike-slip motion along the Acadian Grand Pabos fault in Gaspé Peninsula, Canadian Appalachians

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243 Facies analysis of Ediacaran deposits in southern Namibia

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244 Replacement textures in arfvedsonite granite and associated HFSE-enriched felsic veins in the Eastern Cobequid Highlands, Nova Scotia

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245 Ultramafic arc cumulates in an accretionary orogen: Tracing the geochemical evolution of the Giant Mascot ultramafic suite in the southern Coast Plutonic Complex of southwestern British Columbia

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246 A novel approach using detrital apatite and till geochemistry to identify buried mineral deposits from the Nechako Plateau, central British Columbia

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247 Geodynamic development of the South China block from Precambrian to Cretaceous: Constraints from geochemistry, geochronology and geology

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248 Timing of deformation in the Central Metasedimentary Belt boundary zone (CMBbz), southern Ontario, Canada from electron microprobe dating of monazite

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249 Globules of fluxed silicocarbonatitic melt at Otter Lake, Quebec: A new complication in the Grenville Province

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250 Environmental (subglacial melt water) and glass compositional controls on the geochemistry of palagonite formed from Pleistocene glaciovolcanic sideromelane at Wells Gray (Canada) and Helgafell (Iceland Large Igneous Province).

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251 Intact paleocaves linked to sediment fluidisation structures at the Precambrian-Cambrian boundary (Victoria Island, NWT)

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252 Bioremediation of a hydrocarbon plume using biostimulation
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253 The significance of Mn-rich ilmenite in the determination of P-T paths from zoned garnet in metamorphic terranes
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254 Metasomatic formational conditions of gehlenite in Crestmore, California as determined by mineral associations and textural relationships
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255 Surficial and whole rock geochemistry of the Racecourse Cu-Au porphyry prospect, NSW, Australia
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256 A tale of two massifs: Geochemical and geothermometric constraints on the history of the Nahlin ophiolite, Cache Creek terrane, northwestern British Columbia
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257 A long term study of a oxidant injection into a fractured limestone aquifer
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258 Recovery of legacy marine geoscience data in the Great Lakes Basin: Application to Canada 3D
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259 Till provenance across the terminus of the Dubawnt Lake Ice Stream, central Nunavut
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260 The identification of reworked sedimentary contexts and stratigraphic provenance of bones: A novel quantitative method for Pleistocene archaeological and palaeontological sites
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261 Sedimentary provenance of the Matinenda and Ramsay Lake formations in Drury Township using laser ablation detrital zircon analysis
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262 Continental lithosphere was a warm blanket on the Archean Earth
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263 Hydrothermal alterations from Vulcano and Campi Flegrei volcanoes, Italy
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264 Geochemical baselines and metal(loid) mobility in a changing northern climate
Miller, C.B.[1], Parsons, M.B.[2], Jamieson, H.E.[1], Galloway, J.M.[2], *and* Patterson, R.T.[3], [1]*Department of Geological Sciences and Geological Engineering, Queen's University;* [2]*Geological Survey of Canada, Natural Resources Canada;* [3]*Ottawa - Carleton Geoscience Centre and Department of Earth Sciences, Carleton University*

265 Paleoproterozoic metamorphism of the Thelon Tectonic Zone and margins of the Slave and Rae Archean cratons - insights into the nature and timing of the Slave-Rae Collision
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266 Aeromagnetic modelling of the sub-Athabasca basement
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267 The last gasp of the Skaergaard intrusion as recorded by zircon textures and trace element geochemistry
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268 (U-Th)/He thermochronology of the Aishihik batholith, central Yukon: Resolving Cretaceous tectonism
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269 3D regional geological modelling in structurally complex and data sparse environments: Benefits, challenges and strategies from the northern Labrador Trough, Kuujjuaq, Quebec
Montsion, R.M.[1], *rebecca.montsion@gmail.com,* de Kemp, E.A.[2], Corrigan, D.[2], Hillier, M.J.[2], *and* Schneider, D.A.[1], [1]*University of Ottawa, FSS Hall, Ottawa, ON K1N 6N5;* [2]*Geological Survey of Canada, Ottawa, ON*

270 Reconstruction of the metamorphic P-T-t path of garnet-bearing rocks from the Snowcap Assemblage in the Stewart River area, west-central Yukon
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271 Past Great Lakes water level fluctuations elucidated by the sediments of the Ipperwash strandplain, southern Lake Huron
Morrison, S.M.[1], *sean.morrison@uwaterloo.ca,* Johnston J.W.[1], Lepper, K.[2], Jol, H.[3], Zamperoni, A.[1], *and* Garcia, C.[4], [1]*University of Waterloo, 200 University Ave West, Waterloo, ON N2L 3G1;* [2]*North Dakota State University, Optical Dating and Dosimetry Lab, 218 Stevens Hall, Fargo, ND 58105, USA;* [3]*University of Wisconsin Eau Claire, 105 Garfield Avenue, Ea*

272 The Zircon and Accessory Phase Laboratory (ZAPLab); A Canadian advance in nano- to atom-scale geochronology applied to resource and planetary evolution
Moser, D.E., Barker, I., Arcuri, G., Hey, J., Hyde, B., Jones, G., Morissette, L., *and* Rolleman, J., *Department of Earth Sciences, University of Western Ontario, London, ON N6A 5B7*

273 Mountain lakes: Eyes on global environmental change
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274 Revisiting the role of shear heating in Himalayan inverted metamorphism using thermomechanical models
Mukherjee, S., *Department of Earth Sciences, Indian Institute of Technology Bombay, Powai, Mumbai 400076, Maharashtra, India*

275 Drumlinized tunnel valleys in Simcoe County, southern Ontario
Mulligan, R.P.M., *riley.mulligan@ontario.ca,* Bajc, A.F., *Ontario Geological Survey, Sudbury, ON P3E 6B5, and* Eyles, C.H., *McMaster University, Hamilton, ON L8S 4K1*

276 **New insights on ice dynamics in central and eastern Ontario from the spatial arrangement and morphology of glacial landforms**
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277 **A tectonic history of the Meliadine Gold Trend, Nunavut from aeromagnetic data modelling and interpretation**
Mundreon, S.A.*, sm11fg@brocku.ca, and* Ugalde, H.*, Brock University, 1812 Sir Isaac Brock Way, St. Catharines, ON L2S 3A1*

278 **Keynote (40 min): The LIP record on the rifted margins of the Superior Craton**
Mungall, J.E.*, University of Toronto, 22 Russell St, Toronto, ON M5S 3B1, mungall@es.utoronto.ca*

279 **Late-tectonic magmatic-hydrothermal systems of Abitibi: Contribution of regional-scale fluid reservoirs to the Duquesne, Dolodau, Lac Shortt and Canadian Malartic gold deposits**
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280 **The ins and outs of Ediacaran discs**
Narbonne, G.M. *and* Dececchi, T.A.*, Department of Geological Sciences and Geological Engineering, Queen's University, 36 Union Street, Kingston, ON K7L 3N6 (+ 1st author)*

281 **Celebrating geoheritage: Canada's newest UNESCO World Heritage Site, Mistaken Point, NL**
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282 **External controls on the evolution of stratal architecture in the transition from basin floor to slope, Neoproterozoic Windermere turbidite system, southeastern Canadian Cordillera**
Navarro, L.*, lnava074@uottawa.ca, and* Arnott, R.W.C.*, University of Ottawa, Ottawa, ON K1N 6N5*

283 **Automated optical gold grain counting: A quantum leap**
Néron A.*, neron.alex@gmail.com,* Girard, R.*, IOS services Géoscientifiques Inc, 1319 Boulevard St-Paul, Saguenay, QC G7J 3Y2, rejeang@iosgo.com, and* Bédard, P.*, Sciences de la terre, LabMaTer, Université du Québec à Chicoutimi, Saguenay, QC, Paul_Bedard@uqac.ca*

284 **Geochemical controls on vanadium mobility in oil sands fluid petroleum coke deposits**
Nesbitt, J.A.*, jan999@mail.usask.ca, and* Lindsay, M.B.J.*, University of Saskatchewan, 114 Science Place, Saskatoon, SK S7N 5E2*

285 **Regulatory research on coupled Thermal-Hydrological-Mechanical Chemical processes in natural and engineered barriers for geological disposal of radioactive wastes**
Nguyen, T.S.*, Canadian Nuclear Safety Commission 280 Slater, Ottawa, ON K1P 5S9, son.nguyen@canada.ca*

286 **Pearce element ratio diagrams and cumulate rocks**
Nicholls, J.*, University of Calgary, Department of Geoscience, 2500 University Drive NW, Calgary, AB T2N 1N4, jim.nicholls@shaw.ca*

287 **Clearing the muddy waters: A detailed sedimentological analysis of matrix-rich sandstones in the Windermere turbidite system and comparison with equivalent deposits**
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288 **Keynote (30 min): Cascading, compound, multi-fault ruptures: A new class of earthquake**
Nissen, E.*, School of Earth and Ocean Sciences, University of Victoria, Victoria, BC V8P 5C2, enissen@uvic.ca*

289 **Litho-, δ^{13}C, and ash-bed (Millbrig) stratigraphies redefine the foreland Blackriveran-Trentonian boundary succession, Ottawa Embayment: Significance for extrabasinal correlation**
Nkechi, E.O.*, NkechiEgboka@cmail.carleton.ca,* Dix, G.R.*, Department of Earth Sciences, Carleton University, Ottawa, ON K1S 5B6, and* Kamo, S.L.*, Jack Satterly Geochronology Laboratory, Department of Earth Sciences, University of Toronto, ON M5S 3B1*

300 Geochemical and structural analysis of Slide Mountain Terrane in south-central Yukon: Insights into the early development of the NW Cordilleran orogen

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301 Stratigraphy of the Paleoproterozoic Karrat Group, Greenland: Defining sedimentary-tectonic cycles on the "far east" Rae craton

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302 Kinetic controls on staurolite-Al_2SiO_5 mineral assemblages, with implications for Barrovian and Buchan metamorphism

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303 The Strange Lake dispersal train: A product of a hard-bedded ice stream

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304 Mineralogical signature of the St. Lawrence Columbium Mine at Oka, Québec

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305 Detrital U-Pb and $^{40}Ar/^{39}Ar$ geochronology of Silurian-Devonian sedimentary rocks of the Connecticut Valley-Gaspe trough: Tectonic implications for the southern Quebec and northern Vermont Appalachians

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306 A wish for wings that work: The use of aerodynamic modelling to unravel the origins of avian flight

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307 The source and paleofluid evolution of secondary minerals in low-permeability Ordovician limestones of the Michigan Basin

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308 Complex fault reactivation history and style of the East Irish Sea Basin, offshore UK

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309 Heterogeneous stress distributions within shallow subduction mélanges: Do they control the distribution of seismic features?

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310 Relative timing between the Canadian Malartic footprint and the regional metamorphism of the northeastern Pontiac Subprovince, Abitibi, Québec
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311 A tale of two lakes: Algal palynomorphs record the history of Walden Pond and Sluice Pond since the Pilgrims landed in eastern Massachusetts
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312 Petrographic, geochemical, and isotopic fingerprint and economic potential of the ca. 780 Ma Gunbarrel LIP
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313 Structural and petrological constraints on the metamorphic evolution of the foreland-hinterland transition in the northern New Quebec Orogen, Nunavik
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314 Holocene record of climate and marine primary productivity change in the Santa Barbara Basin, southern California
Pospelova, V.[1], *vpospe@uvic.ca,* Mertens, K.N.[2], Hendy, I.L.[3], *and* Pedersen, T.F.[1], [1]*School of Earth and Ocean Sciences, University of Victoria, OEASB A405, PO Box 3065 STN CSC, Victoria, BC V8W 3V6;* [2]*Ifremer, LER BO, Station de Biologie Marine, Place de la Croix, BP40537, F-29185 Concarneau Cedex, France;* [3]*Department*

315 Identifying the hanging wall of the West Cycladic Detachment System, Aegean region, Greece
Powell, C.D.[1], *cpowe072@uottawa.ca,* Schneider, D.A.[1], Grasemann, B.[2], Soukis, K.[3], Rogowitz, A.[2], *and* Camacho, A.[4], [1]*Department of Earth Sciences, University of Ottawa, Ottawa, ON;* [2]*Department of Geodynamics and Sedimentology, University of Vienna, Austria;* [3]*Faculty of Geology and geoenvironment, National and Kapodistrian University of Athens, Greece;*

316 Diagenesis in the Mg-carbonate system: Implications for carbon sequestration
Power, I.M.[1], *ipower@eoas.ubc.ca,* Wilson, S.A.[2], Morgan, B.[2], Burton, C.A.[2], Williams, T.B.[2], Harrison, A.L.[3], *and* Dipple, G.M.[1], [1]*The University of British Columbia, 2020-2207 Main Mall, Vancouver, BC V6T 1Z4;* [2]*Monash University, Clayton, VIC 3800, Australia;* [3]*Université de Toulouse, 14 Avenue Edouard Belin, 31400 Toulouse, France*

317 Transformation of the Geological Survey of Canada and Canadian Geoscience during the second half of the Twentieth Century --- A personal perspective
Price, R.A., *Department of Geological Sciences and Geological Engineering, Queen's University, Kingston, ON K7L 3N6*

318 Keynote (40 min): Giant economic iron formation and phosphorite deposits: Applied sedimentology of ancient upwelling systems
Pufahl, P.K., *Acadia University, 12 University Avenue, Wolfville, NS B4P 2R6, peir.pufahl@aacdiau.ca*

319 A new map database of glacial geomorphological landforms in Finland
Putkinen, N., *niko.putkinen@gtk.fi,* Putkinen, S., *Geological Survey of Finland (GTK) PO Box 97, Kokkola, 67101, FIN,* Palmu, J-P., Ojala, A.E.K., *GTK, PO Box 96, Espoo, 02151, FIN,* Sarala, P., *GTK, PO Box 77, Rovaniemi, 96101, FIN, and* Ahtonen, N., *GTK, PO Box 1237, Kuopio, 70211, FIN*

320 **Fate of adsorbed molybdate during reductive transformation of iron(III) (hydr)oxides under advective flow conditions**
Qin, K., Das, S., Lindsay, M.B.J., *Department of Geological Sciences, University of Saskatchewan, Saskatoon, SK, S7N 5E2, matt.lindsay@usask.ca*

321 **Keynote (30 min): Athabasca Basin diagenesis and diagenetic-hydrothermal alteration: What it is and how it was characterized**
Quirt, D.H., *AREVA Resources Canada Inc., Saskatoon, SK, david.quirt@areva.com*

322 **Lead isotopes in exploration for basement-hosted uranium deposits at Kiggavik, Nunavut**
Quirt, D.H.[1], *david.quirt@areva.com,* Millar, R.[2], *and* Benedicto, A.[1], [1]*AREVA Resources Canada, Saskatoon, SK;* [2]*Saskatchewan Research Council, Saskatoon, SK*

323 **Effects of marine inundation on till composition in permafrost terrain South of Wager Bay, central Mainland Nunavut**
Randour, I.[1], *randour.iyse@courrier.uqam.ca,* McMartin, I.[2], *and* Roy, M.[1], [1]*Université du Québec à Montréal, Montréal, QC;* [2]*Geological Survey of Canada, Ottawa, ON*

324 **Glacial dynamics of the Quebec-Labrador sector of the Laurentide Ice Sheet in northcentral Quebec/Labrador**
Rice, J.M., *j4rice@uwaterloo.ca,* Ross, M.A., *University of Waterloo, Earth and Environmental Dept., 200 University Ave., Waterloo, ON N2L 3G1,* Paulen, R.C., McClenghan, M.B., *Geological Survey of Canada, 601 Booth St. Ottawa, ON K1A 0E8,* Neudorf, C.M., *and* Lian, O.B., *University of the Fraser Valley, 33844 King Road, Abbotsford, BC V2S 7M8*

325 **Rocks are Us – 175 years of the Geological Survey of Canada**
Riddihough, R., *327 Ferndale Avenue, Ottawa, ON K1Z 6P9 robin.riddihough@sympatico.ca*

326 **Gravitationally-driven extensional collapse of a large hot orogen: Evidence from the western Grenville Province**
Rivers, T., *Department of Earth Sciences, Memorial University, St. John's, NL A1B 3X5, and* Schwerdtner, F., *Department of Earth Sciences, University of Toronto, Toronto, ON M5S 3B1*

327 **Constraining the thermal evolution of the UG2 reef, Bushveld Complex, South Africa**
Robb, S.J., *Department of Earth Sciences, University of Toronto, 22 Russell St, Toronto, ON M5S 3B1, samuel.robb@mail.utoronto.ca*

328 **Subglacial landscape zones and their glacial dynamics based on surficial geology, till geochemistry, and detrital ^{10}Be: Hall Peninsula, southeastern Baffin Island**
Ross, M.[1], *maross@uwaterloo.ca,* Grunsky, E.[1], Gosse, J.C.[2], Johnson, C.L.[1], Tremblay, T.[3], *and* Hodder, T.J.[1], [1]*University of Waterloo, Waterloo, ON N2L 3G1;* [2]*Department of Earth Sciences, Dalhousie University, Halifax, NS B3H 4R2;* [3]*Canada-Nunavut Geoscience Office, 1106 Ikaluktuutiak Dr., Iqaluit, NU X0A 0H0*

329 **Using susceptibility modelling to determine terrain sensitive to subsurface water pressurization in permafrost landscapes**
Rudy, A.C.A.[1], *ashley.rudy@queensu.ca,* Holloway, J.E.[2], Lamoureux, S.F.[1], *and* Treitz, P.[1], [1]*Queen's University, Kingston, ON K7L 3N6;* [2]*University of Ottawa, Ottawa, ON K1N 6N5*

330 **Rivers Mile 183.6: A deep seated landslide in the clay-shale of the Riding Mountain Formation**
Ruel, M., *Queen's University, 99 University Ave, Kingston, ON K7L 3N6, Melissa.ruel@cn.ca,* Edwards, T., *CN, and* Hutchison, J.

331 **A 3-D framework of surficial geology for Canada**
Russell, H.A.J.[1], *hazen.russell@canada.ca,* Atkinson, N.[2], Bajc, A.F.[3], Brodaric, B.[1], Keller, G.[4], Lo, K.[5], Parent, M.[1], Pyne, M.[1], Smith, R.[1], *and* Todd, B.[1], [1]*Geological Survey of Canada;* [2]*Alberta Geological Survey;* [3]*Ontario Geological Survey;* [4]*Manitoba Geological Survey;* [5]*Saskatchewan Water Security Agency*

332 **Communicating 3D geological models to a broader audience: A case study from southern Ontario**
Russell, H.A.J.[1], *hazen.russell@canada.ca,* Brodaric, B.[1], Brunton, F.R.[2], Carter, T.[3], Clark, J.[4], Logan, C.E.[1], *and* Sutherland, L.[4], [1]*Geological Survey of Canada;* [2]*Ontario Geological Survey;* [3]*Carter Geoscience;* [4]*Oil Gas and Salt Resources Library, Ontario*

333 **Modelling the MOHO for the Canada3D initiative: An integrated approach using refraction seismic, teleseismic and gravity data**
Schetselaar, E.M., *Geological Survey of Canada, 615 Booth Street, Ottawa, ON K1A 0E8*

334 **Mineral surface coatings in contaminated soils: Records of environmental processes and sinks of metal(loid)-bearing incidental nanoparticles**
Schindler, M.[1] *and* Hochella, Jr., M.F.[2,3], [1]*Department of Earth Sciences, Laurentian University, Sudbury, ON;* [2]*Department of Geosciences, Virginia Tech, Blacksburg, VA 24061, USA;* [3]*Geosciences Group, Pacific Northwest National Laboratory, Richland, WA 99352, USA*

335 **The solid-phase speciation and post-depositional mobility of arsenic in lake sediments impacted by ore roasting at Giant Mine, Yellowknife, NT, Canada**
Schuh, C.E., *c.schuh@queensu.ca,* Jamieson, H.E., *Queen's University, Kingston, ON K7L 3N6,* Palmer, M.J., *Carleton University, Ottawa, ON K1S 5B6, and* Martin, A.J., *Lorax Environmental Services, Vancouver, BC V6J 3H9*

336 **Large-area SEM imaging in geosciences: Bringing the world of multiscale and multisource correlative microscopy to classrooms as a tool for teaching and learning**
Schumann, D., Unrau, D., Laquerre, A., Murray, A.J., Collins, R., *and* Phaneuf, M.W., *Fibics Incorporated, 1431 Merivale Road, Ottawa, ON K2E 0B9, dschumann@fibics.com*

337 **Silicocarbonatite melt inclusions in fluorapatite from Otter Lake (Quebec): Evidence of carbonate melts in the Central Metasedimentary Belt of the Grenville Province**
Schumann, D., *Fibics Incorporated, 1431 Merivale Road, Ottawa, ON K2E 0B9, dschumann@fibics.com,* Martin, R.F., *McGill University, 3450 University Street, Montreal, QC H3A 0E8,* de Fourestier, J., *Mineralogical Research, 28 Broad Street, Gatineau (Aylmer), QC J9H 4H3, and* Fuchs, S., *GEOMAR – Helmholtz Centre for Ocean Research Kiel, Wischhofstrasse 1-3, Geb. 8A-112, D-24148, Kiel, Germany*

338 **Tectonic significance of late-orogenic cross-folds in a high-grade gneiss terrane - formation during transtensional collapse**
Schwerdtner, W.M., *Department of Earth Sciences, University of Toronto, Toronto, ON M5S 3B1, and* Rivers, T., *Department of Earth Sciences, Memorial University, St. John's, NL A1B 3X5*

339 **The Muskox intrusion and the connection between LIPs and layered intrusions**
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340 **Till stratigraphy in the drumlinized terrain of the McArthur River uranium mine area in the eastern Athabasca Basin**
Scott, S.[1], *shawn.scott@uwaterloo.ca,* Ross, M.[1], Chouteau, M.[2], Shamsipour, P.[2], Chen, H.[1], Campbell, J.E.[3], Kotzer, T.[4], Quirt, D.[5], *and* Kyser, K.[6], [1]*University of Waterloo, 200 University Ave W, Waterloo, ON N2L 3G1;* [2]*École Polytechnique, 2900 Edouard Montpetit Blvd, Montreal, QB H3T 1J4;* [3]*Geological Survey of Canada, 601 Booth St, Ottawa, ON K1A 0E8;* [4]*Cameco Corporation, 2121 11*th

341 **Hadean-Archean transition: Implications of a global continental reconstruction**
Sears, J.W., *University of Montana, Missoula, MT, USA 59812, james.sears@umontana.edu*

342 **Deformation of the subduction plate interface beneath the seismogenic zone: An example from the Leech River Shear Zone**
Seyler, C.E., *caroline.seyler@mail.mcgill.ca, and* Kirkpatrick, J.D., *McGill University, 3450 Rue University, Montreal, QC H3A 0E8*

343 **Geochronology and genesis of the Andrew Lake uranium deposit, Thelon Basin, Nunavut, Canada**
Shabaga, B.M.[1], *Brandi.Shabaga@umanitoba.ca,* Fayek, M.[1], Quirt, D.[2], Jefferson, C.W.[3], Camacho, A.[1], [1]*University of Manitoba, Dept. of Geological Sciences, Winnipeg, MB R3T 2N2;* [2]*AREVA Resources Canada Inc., PO Box 9204, 817 45th Street W., Saskatoon, SK S7K 3X5;* [3]*Geological Survey of Canada, 601 Booth Street, Ottawa, ON K1A 0E8*

344 **A unified hydrogeological framework for southern Ontario: A progress report on surficial geological stratigraphy**
Sharpe, D.R.[1], *david.sharpe@canada.ca,* Bajc, A.F.[2], Hinton, M.J.[1], *and* Russell, H.A.J.[1], [1]*Geological Survey of Canada;* [2]*Ontario Geological Survey*

345 **Timing of post-collisional Pan-African Orogeny granitic magmatism within south-central Chad**
Shellnutt, J.G.[1], *jgshelln@ntnu.edu.tw,* Pham, N.H.T.[1], Denyszyn, S.W.[2], Yeh, M-W.[1], *and* Lee, T-Y.[1], [1]*National Taiwan Normal University, 88 Tingzhou Road Section 4, Taipei 11677, Taiwan;* [2]*University of Western Australia, 35 Stirling Highway, 6009 Australia*

346 **A geochemical explanation for the absence of environmental contamination by heavy metals in the region of the Athabasca bituminous sands**
Shotyk, W., *shotyk@ualberta.ca,* Bicalho, B., *bicalho@ualberta.ca,* Cuss, C.W., *cuss@ualberta.ca,* Donner, M.W., *mdonner@ualberta.ca,* Grant-Weaver, I., *igrantwe@ualberta.ca,* Javed, M.B., *mjaved@ualberta.ca,* Mullan-Boudreau, G., *mullanbo@ualberta.ca, and* Noernberg, T., *noernber@ualberta.ca, University of Alberta, AB*

347 **Selenium stable isotope ratio measurements as a tool for determining processes in groundwater**
Shrimpton, H.K., *hshrimpt@uwaterloo.ca,* Jamieson-Hanes, J.H., Ptacek, C.J., *and* Blowes, D.W., *Department of Earth Sciences, University of Waterloo, Waterloo, ON N2L 3G1*

348 **REE geochemistry of cumulate clinopyroxenites, wehrlites and mantle rocks and their REE-clinopyroxene concentrations, from W. Chalkidiki ophiolites, N. Greece**
Sideridis, A.[1], Tsitsanis, P.[2], Tsikouras, B.[3], Boucher, B.[4], McFarlane, C.[4], Grammatikopoulos, T.[5], *Tassos.Grammatikopoulos@sgs.com, and* Hatzipanagiotou, K.[1], [1]*University of Patras, University Campus, Rio, 265 04, Greece;* [2]*Hellas Gold Exploration, Stratoni, Halkidiki, 630 82, Greece;* [3]*Universiti Brunei Darussalam, Jalan Tungku Link, BE 1410 Gadong, Brunei Darussalam;* [4]*University of New*

349 **Marine palynology of the Miocene–Pliocene Rees Borehole, Belgium: biostratigraphy and paleoenvironments at the southern margin of the North Sea**
Silwadi, S., *saifsilwadi@gmail.com,* Head, M.J., *Department of Earth Sciences, Brock University, 1812 Sir Isaac Brock Way, St. Catharines, ON L2S 3A1, and* Louwye, S., *Research Unit Palaeontology, Krijgslaan 281/S8, B-9000 Ghent, Belgium*

350 **Paleomagnetic directions from the Pretoria Group of South Africa: Hints at the position of the Kaapvaal Craton at 2.2 – 2.1 Ga**
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351 **Natural and anthropogenic controls of groundwater geochemistry on the Niagara Peninsula**
Smal, C.A., *caitlin.smal@gmail.com,* Slater, G.F., *McMaster University, Hamilton, ON, L8S 4L8, and* Hamilton, S.M., *Ontario Geological Survey, Sudbury, ON, P3E 6B5*

352 **Construction and destruction of some North American cratons interpreted using 3-D lithospheric models**
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353 **Exploring the origins of drumlins and megascale glacial lineations**
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354 **Direct dating of a shear fabric: An example from a Himalayan shear zone**
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355 Abrupt along-strike variations in the P-T-t evolution of the Himalayan middle crust: Insights from western Nepal klippen
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356 Geochronology and geochemistry of calcite-filled fractures, southern Ontario: Insight into Cretaceous plate reorganization?
Spalding, J.[1], *jspal066@uottawa.ca,* Schneider, D.A.[1], Gautheron, C.[2], Sarda, P.[2], Davis, D.[3], *and* Petts, D.[1], [1]*University of Ottawa, 25 Templeton Street, Ottawa, ON K1N 6N5;* [2]*Université de Paris-Sud, 91405 Orsay;* [3]*University of Toronto, 22 Russell Street, Toronto, ON M5S 3B1*

357 On the trail of the Great Stone Chief
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358 In situ dating of multiple events in Neoproterozoic granulite-facies rocks of the Larsemann Hills, Prydz Bay, East Antarctica using electron microprobe analysis of monazite
Spreitzer, S.K.[1], Williams, M.L.[2], Yates, M.G.[1], Jercinovic, M.J.[2], Grew, E.S.[1], esgrew@maine.edu, *and* Carson, C.J.[3], [1]*University of Maine, Bryand Center, Orono, ME 04469, USA;* [2]*University of Massachusetts, Morrill Center, Amherst, MA 01003, USA;* [3]*Geoscience Australia, Canberra ACT 2601 Australia*

359 Supracrustal rocks of the Tehery-Wager area: Distinct packages and their metamorphic assemblages
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360 Stable and radiogenic Sr isotope systematics of magmatic-meteoric hydrothermal systems
Stevenson, R., *Geotop and Sciences de la terre et de l'atmosphere Université du Québec à Montréal, Station Centre-Ville, PO Box 8888, Montreal, QC H3C 3P8*

361 Architecture of Upper Cretaceous faulting within the Great Plains polygonal fault system
St-Onge, A., *PFS Interpretations Ltd., 427 28 Avenue NW, Calgary, AB T2M 2K7*

362 Tectonic map of Arctic Canada (TeMAC): A first derivative product from the Canada-in-3D geological compilation work
St-Onge, M.R.[1], *marc.st-onge@canada.ca,* Harrison, J.C.[1], Paul, D.[1], Tella, S.[1], Brent, T.A.[2], Jauer, C.D.[3], *and* Maclean, B.C.[3], [1]*Geological Survey of Canada, Ottawa, ON;* [2]*Geological Survey of Canada, Calgary, AB;* [3]*Geological Survey of Canada, Halifax, NS*

363 Evolving crustal architecture in magmatic arcs: An example from Fiordland New Zealand
Stowell, H.H., *University of Alabama, Tuscaloosa, AL 35487, USA, hstowell@ua.edu,* Klepeis, K., *University of Vermont, 308 Delehanty Hall, Burlington, VT, USA, and* Schwartz, J., *California State University Northridge, 18111 Nordhoff St., Northridge, CA, USA*

364 Volcanic, structural, and hydrothermal controls on mineralized environments at the Onaman Property, northern Ontario
Strongman, K.S., *kstrongman@laurentian.ca,* Gibson, H.L., *Laurentian University, 935 Ramsey Lake Road, Sudbury, ON P3E 2C6, and* Howard, A.E., *Nebu Consulting LLC, Williamsville, NY, USA*

365 Simulating 100kyr glacial cycles over North America within the University of Toronto Glacial Systems Model (UofTGSM) framework
Stuhne, G. *and* Peltier, W.R., *Dept. of Physics, University of Toronto, 60 St. George St., Toronto, ON M5S 1A7, gordan@atmosp.physics.utoronto.ca*

366 Keynote (40 min): Big models need big data: Integrated hydrosystem modelling in Canada
Sudicky, E.A., *Department of Earth & Environmental Sciences, University of Waterloo, Waterloo, ON, sudicky@uwaterloo.ca*

367 Paleokarst features below the Silurian-Devonian unconformity, southwestern Ontario

Sun, S.[1], *ssun224@uwo.ca,* Brunton, F.R.[2], *and* Jin, J.[1], [1]*Department of Earth Science, Western University, London, ON N6A 5B7;* [2]*Earth Resources and Geoscience Mapping Section, Ontario Geological Survey, Sudbury, ON P3E 6B5*

368 Hydrothermal alteration of the crater-lake sediments in the Ries impact structure, Germany

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369 Identification an accretionary orogen by amount of juvenile compositions: An examples from SW Central Asia Orogenic Belt

Tao Wang, Ying Tong, He Huang, Lei Zhang, Lei Guo, Jianjun Zhang, *Institute of Geology, Chinese Academy of Geological Sciences, Beijing, China, taowang@cags.ac.cn*

370 Unknown knowns: A multidiscipline approach investigation previously unknown amber samples and their paleoecological implications

Tapscott, M.[1], Handyside, E.[1], Narbonne, G.M.[1], Kyser, K.[1], Tahara, R.[2], Larsson, H.C.E.[2], *and* Dececchi, T.A.[1], [1]*Department of Geological Sciences, Queen's University, Bruce Wing/Miller Hall, 36 Union Street, Kingston, ON K7L 3N6;* [2]*Redpath Museum, McGill University, 859 Sherbrooke Street West, Montreal, QC H3A 2K6*

371 3D geological modeling of quaternary sediments for seismic shaking assessment on a regional scale

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372 Thelon Tectonic Zone: Crustal origins, tectonic setting, and implications for the Thelon-Taltson orogenic belt -- An oxygen isotope perspective

Taylor, B.E., *Bruce.Taylor@canada.ca,* Berman, R.G., Whalen, J.B., *and* Davis, W.J., *Geological Survey of Canada, 601 Booth Street, Ottawa, ON K1A 0E8*

373 Oxygen isotope zoning at the Archean Izok Zn-Cu-Pb-Ag VMS deposit, Nunavut, Canada: Hanging wall vector to mineralization

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374 In-situ sulphur isotope study of the Prairie Creek deposit, southern Mackenzie Mountains, NWT: Deciphering the conundrum of three deposit styles in one

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375 Deformation and extensional exhumation of Paleoproterozoic high-pressure granulites along the Wholdaia Lake shear zone, south Rae craton, Northwest Territories

Thiessen, E.J.[1], *ericjamesthiessen@gmail.com,* Regis, D.[2], Gibson, H.D.[1], *and* Pehrsson, S.J.[2], [1]*Simon Fraser University, Burnaby, BC;* [2]*Geological Survey of Canada, 601 Booth Street, Ottawa, ON*

376 Faults in the late Paleozoic Antigonish sub-basin, Nova Scotia, reinterpreted as potential salt welds

Thomas, A.K. *and* Waldron, J.W.F., *Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB T6G 2E3*

377 Keynote (40 min): From geoscience to metallurgy – improving mining, processing and sustainability

Thompson, J.F.H., *Cornell University, Ithaca, NY 14853, USA, jft66@cornell.edu*

378 Paleoenvironmental implications of rugose coral growth ridges in the Middle Devonian Hungry Hollow Member, Michigan Basin

Thomson, A.M., *agrouchy@uwo.ca,* Tsujita, C.J., *and* McCausland, P.J.A., *Department of Earth Sciences, Western University, London, ON N6A 5B7*

379 Keynote (40 min): Geological mapping in the US

Thorleifson, L.H., *Minnesota Geological Survey, 2609 West Territorial Road, St Paul, MN 55114-1009 USA, thorleif@umn.edu*

380 Polyphase structural deformation of low- to medium-grade metamorphic rocks of the Liaohe Group in the central segment of Jiao-Liao-Ji Orogenic Belt, North China Craton: Correlations with tectonic evolution

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381 What small Earth Science institutions can do for education: An example from the Quartermain Earth Science Centre, Fredericton, New Brunswick

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382 Basaltic lava flow field analog at Craters of the Moon National Monument and Preserve

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383 Two contrasting crustal blocks revealed by Nd-Hf isotope data from Paleozoic granitoids on either side of Erlian-Hegenshan suture

Tong, Y.[1], *Yingtong@cags.ac.cn,* Wilde, S.A.[2], Jahn, B-m.[3], Wang, T.[1], Guo, L.[1], Enkh-Orshikh, O.[4], *and* Tserendash, N.[4], [1]*Institute of Geology, Chinese Academy of Geological Sciences, Beijing, China, 100037;* [2]*Department of Applied Geology, Curtin University, Perth 6102, Australia;* [3]*Department of Geosciences, National Taiwan University, Taipei 106;* [4]*Insti*

384 A geochemical and petrographic study of Postshield volcanism and the generation of trachyte on West Maui, HI

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385 Till compositional inheritance and overprinting in the Hudson Bay Lowland and across onto the Precambrian Shield

Trommelen, M.S.[1], *michelle.gauthier@gov.mb.ca,* Kelley, S.E.[2], Hodder, T.J.[1], Wang, Y.[2], *and* Ross, M.[2], [1]*Manitoba Geological Survey;* [2]*University of Waterloo, Waterloo ON*

386 Reconstructing the depositional environment of the Late Ordovician Rouge River Member, lower Blue Mountain Formation, southern Ontario

Truong, R., *rtruong@uwaterloo.ca,* Kendall, B., *University of Waterloo, Department of Earth and Environmental Sciences, 200 University Ave W., Waterloo, ON N2L 3G1*

387 Sulfur isotope fractionation in the Eastern Equatorial Pacific derived from reaction-transport models

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388 Lithostratigraphy, chemostratigraphy, and detrital zircon geochronology of the Mesoproterozoic Hunting Formation, Somerset Island (NU)

Turner, E.C., *Harquail School of Earth Sciences, Laurentian University, Sudbury ON P3E 2C6, eturner@laurentian.ca*

389 Litho- and chemostratigraphic transect of the Cambro-Ordovician Franklin Mountain Formation across the interior plains, NWT

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390 Neoproterozoic lithofacies control ore distribution at the Kipushi Cu-Zn deposit (Democratic Republic of Congo) and Gayna River Zn camp (NWT)

Turner, E.C., *Harquail School of Earth Sciences, Laurentian University, Sudbury, ON P3E 2C6,* Brooks, T., *and* Broughton, D.W., *Ivanhoe Mines, 654-999 Canada Place, Vancouver, BC*

391 Mineralogy and geochemistry of fracture coatings in Athabasca Group sandstone as records of primary and secondary elemental dispersion

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392 Keynote (40 min): From fault dates to orogenic rates

van der Pluijm, B., *Univ of Michigan-Ann Arbor, vdpluijm@umich.edu,* Haines, S., *Ohio State Univ.,* Hnat, J., *Shell Exploration & Production, and* Pana, D., *Alberta Energy Regulator, Alberta Geological Survey*

393 Effects of orthogonal compression and dextral transpression on metamorphic evolution of the Paleoproterozoic New Quebec orogen

Van Rooyen, D., *Department of Mathematics, Physics, and Geology, Cape Breton University, Sydney, NS B1P 6L2, deanne_vanrooyen@cbu.ca, and* Corrigan, D., *Geological Survey of Canada, 601 Booth St., Ottawa, ON K1A 0E8*

394 Keynote (40 min): Tectonic evolution of the Newfoundland Appalachians

van Stal, C.R., *Geological Survey of Canada, 1500-605 Robson Street, Vancouver, BC V6B 5J3, cees.vanstaal@canada.ca, and* Zagorevski, A., *Geological Survey of Canada, 601 Booth Street, Ottawa, ON K1A 0E8*

395 Geometallurgical analysis of the Decar nickel deposit, British Columbia: Implications for tailings management and CO_2 sequestration

Vanderzee, S., Dipple, G., Power, I., *University of British Columbia, Main Mall, Vancouver, BC V6T 1Z4, svander@eoas.ubca.ca, and* Bradshaw, P., *First Point Minerals, Pender St., Vancouver, BC V6E 2P4*

396 Structural analysis and shear zone thermometry in the southeastern Churchill Province

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397 Searching for a deep biosphere, hydrocarbon fingerprint in hydrothermal vent sediments at Guaymas Basin

Ventura, G.T.[1], *todd.ventura@smu.ca,* Nelson, R.K.[2], Walters, C.C.[3], Higgins, M.B.[3], Reddy, C.M.[2], Dalzell, C.[1], *and* Sievert, S.M.[2], [1]*Saint Mary's University, Halifax, NS B3H 3C3;* [2]*Woods Hole Oceanographic Institution, Woods Hole, USA;* [3]*ExxonMobil Research and Engineering, Clinton, NJ, USA*

398 Tracking the solidus of cumulates in layered intrusions related to LIPs using trace elements in zircon and rutile from the Bushveld Complex

Ver Hoeve, T.J.[1], *tverhoev@eoas.ubc.ca,* Scoates, J.S.[1], Wall, C.J.[2], Weis, D.[1], *and* Amini, M.[1], [1]*Pacific Centre for Isotopic and Geochemical Research, Department of Earth, Ocean, and Atmospheric Sciences, University of British Columbia, Vancouver, BC V6T 1Z4;* [2]*Department of Geosciences, Boise State University, 1910 University Drive, Boi*

399 Late Cretaceous to Paleocene tectono-metamorphic evolution of southwest Yukon

Vice, L., *lvice@sfu.ca,* Gibson, H.D., *Simon Fraser University, Burnaby, BC,* Israel, S., *Yukon Geological Survey, Whitehorse, YT, and* Crowley, J., *Boise State University, Boise, ID, USA*

400 From a tide- to storm-dominated depositional system in a mixed carbonate-siliciclastic succession: The Upper Ordovician Vauréal Formation, eastern Anticosti Island, Québec

Vincent-Couture, M. *and* Desrochers, A., *University of Ottawa, Department of Earth and Environmental Sciences, ON K1N 6N5, mvinc083@uottawa.ca*

401 **Characterization of the mode of occurrence and compositions of strategic elements in the Vazante willemite ore and hematite-rich breccia, Minas Gerais, Brazil**
Waberi, S., *shawna.waberi@gmail.com,* Olivo, G.R., *and* Layton-Matthews, D., *Queen's University, Kingston, ON K7L 3N6*

402 **Tectonic versus sedimentary mélanges, mélanges within mélanges, and megathrust slip accommodation in subduction complexes**
Wakabayashi, J., *Department of Earth and Environmental Sciences, California State University, Fresno, 2576 E. San Ramon Avenue ST-24, Fresno, CA 93740-8029, USA, jwakabayashi@csufresno.edu*

403 **Diachronous Palaeozoic accretion of peri-Gondwanan terranes in the Caledonides and northern Appalachians**
Waldron, J.W.F., *Department of Earth & Atmospheric Sciences, University of Alberta, Edmonton, AB T6G 2E, john.waldron@ualberta.ca,* Schofield D.I., *British Geological Survey, The Lyell Centre, Research Avenue South, Edinburgh EH14 4AP UK,* Murphy, J.B., *Department of Earth Sciences, St. Francis Xavier University, Antigonish, NS B2G 2W5,* Ady, B.E., *and* Whittaker, R.C., *GeoArctic Ltd., 3300, 205-5th Avenue SW, Calgary, AB T2P 2V?*

404 **Large layered intrusions in LIPs as amalgamated stacks of out-of-sequence sills from high-precision dating of the Stillwater Complex**
Wall, C.J., *cwall@eoas.ubc.ca,* Scoates, J.S., Weis, D., Friedman, R.M., Amini, M., *Pacific Centre for Isotopic and Geochemical Research, Department of Earth, Ocean and Atmospheric Sciences, 2020-2207 Main Mall, University of British Columbia, Vancouver, BC V6T 1Z4, and* Meurer, W.P., *ExxonMobil Upstream Research, Houston, TX, USA*

405 **Differentiating tills in the Hudson Bay Lowland; Gillam area, northern Manitoba**
Wang, Y., Kelley, S.E., Ross, M., *University of Waterloo, 200 University Ave W, Waterloo, ON N2L 3G1, y649wang@uwaterloo.ca,* Trommelen, M.S., *and* Hodder, T.J., *Geological Survey of Manitoba, Manitoba Mineral Resources, 360-1395 Ellice Avenue, Winnipeg, MB R3G 3P2*

406 **290–270 Ma volcanism along the Central Asian Orogenic belt: Reworked or a process of the accretionary orogeny?**
Wang, Y., Luo, Z., *and* Hao, J., *Institute of Earth Sciences, China University of Geosciences, Beijing 100083, wangy@cugb.edu.cn*

407 **Keynote (40 min): When does monazite crystallise in metamorphic rocks?**
Warren, C.J.[1], *clare.warren@open.ac.uk,* Roberts, N.M.W.[2], Greenwood, L.V.[1], Parrish, R.R.[2], Argles, T.W.[1], *and* Harris, N.B.W.[1], [1]*School of Environment, Earth and Ecosystem Sciences, The Open University, Walton Hall, Milton Keynes, MK7 6AA;* [2]*NERC Isotope Geoscience Laboratories, British Geological Survey, Kingsley Dunham Centre, Keyworth NG12 5GG*

408 **Age and preliminary paleomagnetic assessment of the Silurian Mavillette gabbro, Meguma terrane, Nova Scotia, Canada**
Warsame, H.S., *hwarsame@uwo.ca,* McCausland, P.J.A., *Western University, 1151 Richmond St, London, ON, N6A 5B7,* White, C.E., *Nova Scotia Department of Natural Resources, PO Box 1003, Halifax, NS B3J 2T9,* Barr, S.M., *Acadia University, 15 University Ave, Wolfville, NS B4P 2R6, and* Dunning, G.R., *Memorial University, 230 Elizabeth Ave, St. John's, NL A1B 3X5*

409 **Vertical stacking patterns of matrix-rich and matrix-poor sandstones in a deep-marine channel-margin succession, Isaac Formation, Windermere Supergroup, British Columbia**
Wearmouth, C.D., *cwear099@uottawa.ca, and* Arnott, R.W., *University of Ottawa, Ottawa, ON K1N 6N5*

410 **Sulfur cycling over the past 70 million years**
Weiqi, Y., *University of Toronto, 22 Russell Street, Toronto, ON M5S 3B1*

411 **Deep and long-lasting mantle plumes with enriched mantle-1 signatures**
Weis, D., Harrison, L., *and* Scoates, J.S., *Pacific Centre for Isotopic and Geochemical Research, Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, 2020-2207 Main Mall, Vancouver, BC V6T 1Z4, dweis@eos.ubc.ca*

412 **Fluids in the Los Azufres Geothermal Field, Mexico traced by noble gas isotopes and $^{87}Sr/^{86}Sr$**
Wen, T., *Penn State University, University Park, PA, USA, jaywen@umich.edu,* Pinti, D.L., *GEOTOP, Université du Québec à Montréal, QC,* Castro, M.C., Hall, C.M., *University of Michigan, Ann Arbor, MI, USA,* Shouakar-Stash, O., *Isotope Tracer Technologies Inc., Waterloo, ON,* López-Hernández, A., *UMSNH, Morelia, Mich., México, and* Sandoval-Medina, F., *Gerencia de Proyectos Geotermoeléctricos, CFE, México*

413 **The Silurian-Devonian Rockville Notch Group, Nova Scotia, Canada – unique to Meguma**
White, C.E., *Nova Scotia Department of Natural Resources, Halifax, NS B3J 2T9, whitece@gov.ns.ca,* Barr, S.M., *Department of Earth and Environmental Science, Acadia University, Wolfville, NS B4P 2R6, and* Linnemann, U., *Senckenberg Naturhistorische Sammlungen Dresden, Königsbrücker Landstr. 159, D-01109 Dresden, Germany*

414 **Keynote (30 min): The varieties of fault experience (with apologies to William James)**
White, J.C., *University of New Brunswick, 3 Bailey Dr., Fredericton, NB E3B 5A3*

415 **The foreland basin offshore western Newfoundland: Concealed record of northern Appalachian orogen development**
White, S.E., *sewhite@ualberta.ca, and* Waldron, J.W.F., *Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB*

416 **Keynote (40 min): High-temperature metamorphism and Grenville orogenesis in the Adirondack Highlands, New York, USA**
Williams, M.L.[1], Grover, T.W.[2], Jerconivic, M.J.[1], Pless, C.R.[1], *and* Regan, S.P.[1], [1]*University of Massachusetts, Amherst, MA 01003, USA;* [2]*Castleton University, Castleton, VT 05735, USA*

417 **Comparing climate signals obtained from encrusting and free-living Southwest Greenland coralline algae**
Williams, S.M., *University of Toronto, 27 King's College Circle, Toronto, ON M5S 3B1, siobhan.williams@mail.utoronto.ca*

418 **Compositional evidence for magma recharge and mixing in CFB reservoirs: Evidence from melt inclusions in HALIP basalts**
Williamson, M-C., Jackson, S.E., Yang, Z., Venance, K., *and* Hunt, P., *Geological Survey of Canada, 601 Booth St., Ottawa, ON K1A 0E8*

419 **Volcanology and geochemistry of HALIP flood basalts, Axel Heiberg Island, Nunavut**
Williamson, M-C., Saumur, B-M., *Geological Survey of Canada (Central), 601 Booth St., Ottawa, ON K1A 0E8,* Evenchick, C.A., *Geological Survey of Canada (Pacific), 1500 – 605 Robson Street, Vancouver, BC V6B 5J3,* Little, K.J., *and* Cousens, B.L., *Department of Earth Sciences, Carleton University, 1125 Colonel By Drive, Ottawa, ON K1S 5B6*

420 **Geochemistry of shield basalts from the island of Kauaʻi and the emergence of the Hawaiian geochemical trends**
Williamson, N.M.B., Weis, D., *and* Scoates, J.S., *Pacific Centre for Isotopic and Geochemical Research, Department of Earth, Ocean and Atmospheric Sciences, 2020-2207 Main Mall, University of British Columbia, Vancouver, BC V6T 1Z4, nwilliam@eoas.ubc.ca*

421 **Keynote (40 min): Quantitative mineralogy of gossans and stream sediments in the High Arctic Large Igneous Province (HALIP) via SEM-MLA: Implications for economic potential**
Wilton, D.H.C., *Department of Earth Sciences, Memorial University, St. John's, NL A1B 3X5, dwilton@mun.ca,* Williamson, M-C., *and* McNeil, R.J., *Geological Survey of Canada, 601 Booth Street, Ottawa, ON K1A 0E8*

422 **The beginning and end of metallogeny in the Labrador Central Mineral Belt; 1868 to 1064 Ma Re-Os molybdenite dates bracket the widespread polymetallic mineralization**
Wilton, D.H.C., *Department of Earth Sciences, Memorial University, St. John's, NL A1B 3X5, dwilton@mun.ca, and* Selby, D., *Department of Earth Sciences, Durham University, Durham DH1 3LE, UK*

423 **Neoarchean to Paleoproterozoic evolution of the south-central Rae margin, Tehery-Wager area, Nunavut: Insights from field mapping, U-Pb geochronology, and Sm-Nd isotope data**
Wodicka, N.[1], *natasha.wodicka@canada.ca,* Steenkamp, H.M.[2], Peterson, T.[1], Whalen J.[1], *and* Lawley, C.J.M.[1], [1]*Geological Survey of Canada, Ottawa, ON K1A 0E8;* [2]*Canada-Nunavut Geoscience Office, Iqaluit, NU X0A 0H0*

424 **Using integrated zircon U-Pb-Hf-O isotopes to unravel Archean crustal evolution: Example from the Southern Jilin Complex in the North China Craton**
Wu, M., *geowumeiling@gmail.com,* Lin, S., *University of Waterloo, Waterloo, ON N2L 3G1,* Wan, Y.S., *Beijing SHRIMP Center, Institute of Geology, Chinese Academy of Geological Sciences, Beijing 100037, China,* Gao, J-F., *State Key Laboratory of Ore Deposit Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550002, China, and* Stern, R.A., *Canadian Centre for Isotopic Microanalysis, Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB*

425 **Tectonic transformation from the Paleo-Pacific to west Pacific plate subduction – based on the geologic evidence of the southeastern China continental margin**
Xie, Y., Wang, Y., *and* Zhou, L., *China University of Geosciences, 29 Xueyuan Road, Haidian District*

426 **Episodic subduction of the Proto-Tethyan Ocean along the NE Tibet-Qinghai Plateau: Evidence from Lajishan ophiolites and arc-related magmatism**
Yan, Z., *Institute of Geology, Chinese Academy of Geological Sciences, Beijing 100037, China, yanzhen@mail.iggcas.ac.cn*

427 **Numerical investigation into reducing mechanisms in the precipitation of unconformity-related uranium deposits**
Yang, J. *and* Aghbelagh, Y.B., *University of Windsor, 401 Sunset Avenue, Windsor, ON N9B 3P4, jianweny@uwindsor.ca*

428 **Flotation mechanism of sulphide melt on vapor bubbles in crystal mush**
Yao, Z.S., *yaozhuosen@163.com, and* Mungall, J.E., *Department of Earth Sciences, University of Toronto, ON M5S 3B1*

429 **Early Cretaceous metamorphism of the Fiordland magmatic arc, Fiordland, New Zealand**
Yelverton Jr., J.W., *jwyelverton@crimson.ua.edu, and* Stowell, H.H., *Department of Geological Sciences, University of Alabama, Box 870338, Tuscaloosa, AL 35487, USA*

430 **Terrane boundaries and terrane boundary displacements: Application of Appalachian concepts to British Columbia and Yukon**
Zagorevski, A., *Geological Survey of Canada, 601 Booth St., Ottawa, ON K1A 0E8, alex.zagorevski@canada.ca,* Mihalynuk, M.G., *Geological Survey and Resource Development Branch, BC Ministry of Energy and Mines, PO Box 9333 Stn Prov Govt, Victoria, BC V8W 9N3, and* McGoldrick, S., *School of Earth & Ocean Sciences, University of Victoria, Victoria, BC V8W 3P6*

431 **Novel approaches to 3D geologic mapping using kinematic mobile laser scanning and LiDAR intensity**
Zanetti, M., *michael.zanetti@uwo.ca,* Osinski, G.R., Neish, C.D., *University of Western Ontario, Dept. of Earth Sciences, Dept of Physics and Astronomy, and the Centre for Planetary and Space Exploration (CPSX), 1151 Richmond St N, London, ON N6A 5B7, and* Kukko, A., *National Land Survey of Finland (NLS), Finnish Geospatial Research Institute (FGI), and the Centre of Excellence in Laser Scanning Research (CoE-LaSR), Geodeetinrinne 2, 02460 Masala, Finland*

432 **Cambrian to Silurian ophiolite in the northern Tibetan Plateau**
Zhai, Q-g.A.[1], *zhaiqingguo@126.com,* Wang, J.A.[1], Li, C.B.[2], Hu, P-y.A.[1], *and* Tang, Y.A.[1], [1]*Institute of Geology, CAGS, Beijing, China;* [2]*School of Earth Science, Jilin University, Changchun, Jilin, China*

433 **Ocean-climate system and bioevents from Hirnantian-Wenlock conodonts and integration with graptolite biozones, Cape Phillips Formation, Cornwallis Island, Canadian Arctic Islands**
Zhang, S., *Canada - Nunavut Geoscience Office, PO Box 2319, 1106 Inuksugait IV, 1st floor, Iqaluit, NU X0A 0H0,* Jowett, D.M.S., *15 Somerglen Place SW, Calgary, AB T2Y 3L5, and* Barnes, C.R., *School of Earth and Ocean Sciences, University of Victoria, PO Box 1700, Victoria, BC V8W 2Y2, crbarnes@uvic.ca*

434 **New insights into Ordovician stratigraphy and petroleum potential on Akpatok Island and in Ungava Bay**

Zhang, S., *Canada-Nunavut Geoscience Office, PO Box 2319, Iqaluit, NU X0A 0H0, shunxin.zhang@canada.ca*

435 **On the importance of geological data for three-dimensional transient hydraulic tomography at a highly heterogeneous multi-aquifer-aquitard system**

Zhao, Z., *z58zhao@uwaterloo.ca, and* Illman, W.A., *willman@uwaterloo.ca, University of Waterloo, 200 University Avenue W, Waterloo, ON N2L 3G1*

436 **The mid-lower-crustal Chinese Central Tianshan: Implications for continental growth and accretionary orogenesis**

Zhong, L.L.[1], Wang, B.[1], *bwang@nju.edu.cn,* Liu, H.S.[1], Kapp, P.[2], Worthington, J.R.[2], Cao, Y.C.[1], *and* He, Z.Y.[1], [1]*School of Earth Sciences and Engineering, Nanjing University;* [2]*Department of Geosciences, University of Arizona*

437 **Joint inverse modeling of groundwater level and multi-extensometer data for improved characterization of heterogeneous aquitards**

Zhuang, C.[1], *zchao1990@hhu.edu.cn,* Zhou, Z.[1], *zhouzf@hhu.edu.cn,* Illman, W.A.[2], *willman@uwaterloo.ca,* Guo, Q.[1], *guoqiaona2010@hhu.edu.cn, and* Wang, J.[1], *wang_jinguo@hhu.edu.cn,* [1]*Hohai Univeristy, No.1 Xikang Road, Nanjing, China, 210098;* [2]*University of Waterloo, University Avenue, Waterloo, ON N2L 3G1*

Abstracts / Résumés

Reduction of AMD generation and availability of metals from sulfidic mine tailings through biochar application: A laboratory scale study

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Biochar is a carbonaceous substance produced from pyrolysis of biomass whose addition to environmental media reportedly confers many benefits, including aiding in carbon sequestration, reducing greenhouse gas emissions, raising pH, and immobilizing organic and inorganic contaminants. This study investigated whether applying biochar to acidic mine tailings could simultaneously help to decrease acidity and increase immobilization of toxic metals. To this end we conducted a series of experiments with shake flasks and columns involving fast pyrolysis biochar (FB) and mine tailings (MT) from the Vale mine at Voisey's Bay, NL. Additional MT from an abandoned mine site at Gullbridge, NL were used in the shake flask experiments only. The study also included admixtures of a product formulated by Virotec Global Solutions Pty Ltd called Terra B (TB), added to biochar (1:19 w/w) to see whether it can further increase efficacy.

With Voisey's Bay MT, pH increased with both shaking time and rate of FB or FB+TB application, whereas in Gullbridge MT, pH is affected only by the rate of application. The increase in pH was about 0.8 unit for FB only (35% w/w) treatment, but the increase was doubled when FB+TB was applied. In case of Gullbridge MT the increase in pH was about 1.6 units at the FB only (35% w/w) treatment, which further increased to 2.2 units with FB+TB treatment at the same application rate. With the column experiment 30% FB application leads to a pH increase of 1.3 units while 30% FB+TB treatment increased the pH by 2.2 units. Immobilization of a number of metals (Fe, Mn, Ni, Cu, Co, Al, etc.) increased relative to control with the increasing rates of FB or FB+TB applications. In general, FB+TB performed better than FB treatments alone. Percent immobilization of metals also varied depending on residence time and type of MT. At the highest residence time (4 weeks for shake flasks and 14 weeks for columns), with the highest FB+TB treatment, >90% immobilization was achieved for Fe, Ni, Cu, Co and Al. The experimental results therefore suggest that biochar has the potential to decrease acidity and increase the immobilization of toxic metals in sulfidic mine tailings. These effects can further be enhanced through by applying biochar along with Terra B.

An investigation of apatite as an indicator mineral that recorded hydrothermal fluid chemistry at the Cantung tungsten skarn deposit, NWT, Canada

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The Cantung tungsten deposit, District of Mackenzie, NWT, Canada, is a complexly zoned, high-grade exoskarn hosted in metacarbonate of the Selwyn Basin and spatially associated with the monzogranitic Minestock Pluton. Multiple, overprinting anhydrous (pyroxene and/or garnet) and hydrous (amphibole or biotite) skarn units comprise the deposit and contain variable amounts of scheelite, pyrrhotite and apatite, with trace plagioclase, allanite, and tourmaline. Hydrothermal apatite is a potential indicator mineral for W-skarn deposits, as it can accommodate a variety of trace elements in its crystal structure and thus record the evolution of fluid chemistry during skarn development. Using petrographic and LA-ICPMS methods, this study (i) resolves the paragenesis of apatite in different skarn types, (ii) characterizes and differentiates trace element abundances in apatite from skarn and the monzogranite, and (iii) elucidates the distribution of trace elements in zoned apatite, through the interpretation of multielement maps. Apatite occurs as euhedral, zoned crystals and is paragenetically early in all skarn types. Apatite occurs in trace amounts in garnet skarn, but is abundant in amphibole skarn, and ubiquitous in biotite skarn, occurring with coarse-grained (<0.5 cm) scheelite. Garnet skarn contains apatite with low Sr (55.4 to 153 ppm), variably high As (up to 14.6 ppm), Mn (417 to 5000 ppm), and Fe (150 – 9200 ppm) and Ce_N/Y_N ratios from 2 to 6. Apatite from amphibole skarn contains relatively low Sr (55.1 to 132 ppm) and As (up to 4.0 ppm), with high Mn (797 to 4450 ppm) and Fe (196 to 6460 ppm) and Ce_N/Y_N ratios ranging 3.0 to 48. Apatite from biotite skarn contains low Sr (55.4 to 171 ppm), variably high As (up to 21.8 ppm), Mn (470 to 4090 ppm) and Fe (470 to 4280 ppm), with Ce_N/Y_N ratios ranging 1.8 to 49. Magmatic apatite contains high Sr (189 to 286 ppm), As (up to 14.1 ppm), and relatively low Mn (616 to 2300), Fe (89.0 to 885 ppm) and Ce_N/Y_N ratios from 0.6 to 1.4. Using ternary diagrams, these compositional parameters allow discrimination between apatite of different skarn types and origin. Most apatite exhibit negative Eu anomalies; however, some hydrothermal apatite is zoned with cores exhibiting positive Eu anomalies. These anomalies are explained by the partial dissolution of plagioclase during the early stages of skarn development. Current work is ongoing to identify elemental associations using trace element maps in order to understand the evolution of the hydrothermal system during skarn development.

Early Cenozoic evolution of the Gurla Mandhata core complex, NW Nepal Himalaya

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The Gurla Mandhata dome is an amphibolite to granulite facies metamorphic core complex of uncertain lithotectonic affinity exposed in the hinterland of the Himalaya in NW Nepal. Subsequent to crustal thickening, exhumation occurred along a system of local detachment and strike-slip faults associated with a Middle Miocene transition from dominant N-S directed contraction to orogen-parallel extension identifiable across the Himalayan orogen. Previous work has disparately assigned the rocks of the core complex to two different Himalayan lithotectonic units, the Lesser Himalayan sequence or the Greater Himalayan sequence. This introduces first-order structural and petrological uncertainties regarding the position of the Main Central thrust and the Main Himalayan detachment. Studies have also identified major shear zones with top-to-the-W shear fabrics along the margins of the core complex, interpreted to be associated with Middle Miocene doming. These fabrics are observed to dominate the core complex such that much of the evidence for its pre-Middle Miocene prograde tectonic history has likely been overprinted by progressive shear. To gain a more complete structural and temporal understanding of the core complex, fieldwork was performed in Spring 2016 along a 40 km N-S transect across the core complex, traversing and sampling a new segment of the dome previously only mapped remotely.

The core complex contains abundant quartzo-feldspathic (± Grt ± Sill) schist with some augen gneiss, calc-silicate, and leucogranite bodies. Metamorphic units are slightly to moderately migmatized, up to diatexite migmatite. Structural elements are constant across the core complex, with foliation in most units striking NW to NE and with E-plunging mineral lineations defined by sillimanite and by biotite and quartz aggregates. Strained metamorphic units display abundant top-to-the-W macro- and microscopic shear fabrics. These lineations and foliation are consistent with the interpretation that they are associated with the exhumation of the core complex, though the lack of convincing retrogressive mineral assemblages allows for the possibility that the top-W shear fabrics are the initial peak-metamorphic top-to-the-S structures rotated by late Miocene extension. Furthermore, the constant orientation of all structural elements observed across the core complex challenges previous interpretations that the Gurla Mandhata core complex has a domal geometry throughout. Our Sm/Nd isotope analysis and bulk rock geochemical analyses, complemented by in situ U-Th/Pb monazite geochronology and microstructural analysis, will help constrain the Gurla Mandhata core complex's lithotectonic affinity and enable the reconstruction of the prograde early Cenozoic history and crustal-scale geometry of the dome.

Diffusion research: Lab scale to field scale – recent advances

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The geology that surrounds a proposed deep geological repository (DGR) represents the ultimate barrier to migration of contaminants toward surface receptors. Geologic systems with very low permeability where solute transport is dominated by diffusion are a prerequisite, so the requirement to understand the diffusive transport properties of the rocks is fundamental to site characterization for a DGR. Diffusion research is therefore a key component of the Canadian geoscience research program directed by the Nuclear Waste Management Organization. The research involves development of lab- and field-scale methods for measuring diffusion and reaction properties of crystalline and sedimentary rocks. Goals of lab-scale studies include determination of pore- and effective-diffusion coefficients (Dp and De) for gases (He and CH_4) and chemical (Cl^-, Br^-, I^-) or isotopic (^{18}O, $^{1}H^{3}HO$) tracers in response to variables such as lithology, confining pressure and degree of partial gas saturation. Lab-scale investigations also allow for quantification of important transport properties for both non-reactive and reactive solutes such as tracer-accessible porosity, cation-exchange capacity (CEC) and ion-exchange selectivity coefficients. These measurements must be complimented by experiments that investigate the larger-scale integrated transport properties of the surrounding geosphere. The best approach for scaling up from lab to field involves natural analogues whereby numerical diffusion models are used to match profiles of naturally-occurring chemical and isotopic tracers to obtain formation-scale parameters and to estimate residence time in the subsurface. Site investigations for the DGR proposed by OPG for low- and intermediate-level waste at the Bruce nuclear site in Ontario provided opportunities to apply methods, including the natural analogue approach. This presentation will review the variety of methods that have been developed and applied at the lab and field scales, and will describe ongoing efforts to improve and expand methods for application in the near future at sites that will be evaluated for potential to host a DGR for used nuclear fuel.

The zircon record of granitic continental crust subjected to tectonic burial, from 0 to ≥ 60 km, the Eastern Segment, Sveconorwegian orogen

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The Eastern Segment of the Sveconorwegian orogen in Scandinavia exposes the deeply eroded remnants of a 1.0 Ga collisional orogen. It constitutes the foreland facing, easternmost segment of the orogen, which also exposes the most deeply buried sections of continental crust. New mapping, U-Th-Pb zircon, and bulk geochemical data combined with a previously existing extensive data set, demonstrate that the Eastern Segment almost entirely consists of deformed and metamorphosed rocks of the 1.87–1.66 Ga Transscandinavian Igneous Belt; a magmatic belt that forms a major part of the pre-Sveconorwegian continent also east of the orogen. The Eastern Segment exposes a ca 150 km wide section of the Transscandinavian Igneous Belt at westwards successively deeper levels of Sveconorwegian tectonic burial, including also an eclogitized unit (≥ 60 km). Detailed studies of field relations at 18 selected localities across this section, combined with careful imaging and U-Th-Pb ion microprobe analyses of zircon, in both unmetamorphosed and strongly reworked rocks, allows for recognition of a first order tectonometamorphic and temporal build-up of this part of the orogen. It also allows discrimination between Sveconorwegian and pre-Sveconorwegian metamorphism and deformation structures. Texturally and isotopically identical zircon phases are found in undeformed granites at shallow tectonic levels along the orogenic front, and in intensely deformed veined orthogneiss in the internal parts of the Eastern Segment. The secondary zircon in these rocks dates two intervals of pre-Sveconorwegian high-grade metamorphism and associated magmatism at 1.47-1.44 Ga and 1.42-1.38 Ga, respectively (both events related to Hallandian orogenesis). The data highlights the necessity of full control of field relations for interpretation of zircon data. In the internal parts of the Eastern Segment, pre-Sveconorwegian ductile deformation and vein structures are strongly deformed and transposed. High-pressure metamorphism in a distinct eclogitized tectonic unit is dated at 0.99-0.98 Ga. Partial melting and ductile deformation at granulite to amphibolite facies conditions (including the eclogitized unit) is dated at 0.98-0.96 Ga. Felsic dykes cross-cutting high-grade features are dated at 0.96-0.94 Ga. The Sveconorwegian migmatite zircon is chemically and texturally different from the older Hallandian migmatite zircon. This reflects differences in pressure, temperature and/or melt composition during migmatization, to be further explored by systematic study of partially molten rocks and zircon behaviour across the Eastern Segment traverse.

Mineralogical and geochemical characterization of spilled tailings from the Mount Polley Mine: Implications for remediation and rehabilitation

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A breach of the Mount Polley Mine (MPM) Tailings Storage Facility embankment occurred on August 4, 2014, releasing tailings, supernatant and pore water, as well as dam construction materials, into the environment. Variable mixtures of tailings, dam construction materials, and scoured natural soil and glacial sediments, were deposited into two lakes (Polley and Quesnel) and in the valley of Hazeltine Creek. An understanding of the regional and local geology, as well as the mineralogical and geochemical characteristics of materials released (i.e. tailings), and an understanding of how these materials will weather and what processes will control the release of constituents, is required to inform remediation and rehabilitation of the area impacted by the breach.

Located approximately 55 km northeast of Williams Lake, British Columbia, the MPM is located in Quesnellia, an accreted terrane in the Intermontane Belt of the Canadian Cordillera. Hosted in the Mount Polley Intrusive Complex, the MPM is an alkali copper-gold porphyry deposit consisting of alkalic, marginally silica-undersaturated intrusions, and magmatic-hydrothermal breccias. The country rocks are predominantly mafic to intermediate volcanics. The mineralization is hosted mainly within a monzonitic intrusion. Hydrothermal alteration is dominantly potassic, with pervasive calcite, natural oxide alteration, and a lack of pronounced pyrite haloes.

A geochemical characterization program, including laboratory kinetic testing (humidity cells and columns), was developed and carried out on spilled tailings; and background geology, mineralogy and geochemistry information was reviewed to provide context for analytical results. Copper and selenium were the main focus of continued investigations as they were identified to be enriched in the initial study of tailings geochemical characteristics. However, all parameters with guidelines for the protection of freshwater aquatic life in British Columbia are being monitored. Kinetic testing results are now available for up to 90 weeks. Results support the assessment that acid rock drainage (ARD) is not expected from the tailings and leaching will be under neutral to alkaline conditions. Leaching rates are now either stable or slowly declining, which is expected to continue. Variability in leaching rates has also been established and some kinetic testing is ongoing. The relative geochemical stability of the MPM tailings indicates that they are not likely to pose a chemical contamination problem, particularly those that were deposited under water. The results of these geochemical and other investigations are being used to inform the ongoing remediation planning and rehabilitation activities at the mine, as well as current and future monitoring programs.

Ice streams within the last Cordilleran Ice Sheet

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The Cordilleran Ice Sheet (CIS) in western North America is the least understood of all late Wisconsin Northern Hemisphere ice sheets. It reached its maximum extent (~2.5 x 10^6 km^2) as late at c. 14,500 ybp when it was broadly similar in size and basal topography to today's Greenland Ice Sheet. High resolution geomorphic mapping has the object of identifying subglacial landforms below the ice sheet to gain insights into its paleoglaciology, bed rheology and mode of flow. Some 80% of the ice sheet's bed consists of high mountains and alpine terrain. The remainder consists of subglacially-streamlined rock and sediment at lower elevations within outlet valleys and across broad intermontane plateaux of the Intermontane Belt of interior British Columbia and coterminous parts of Washington State and Montana of the northern USA. Mapping and field work in these areas contrasts so-called 'mixed beds' consisting of variably-streamlined patches of bedrock protruding through discontinuous drumlinized till, from drumlinized 'soft beds' underlain by deformation till reworked from overridden glaciolacustrine and glaciofluvial sediment. Drumlins on soft beds are erosional features cut into till and underlying sediments, and are transitional downglacier to megascale glacial lineations (MSGLs) that identify the trunks of at least 10 large fast-flowing (< 400 m yr^{-1}) paleo-ice streams. The location of ice streams primarily reflects topographic funneling of outflows from plateau surfaces through outlet valleys and lowland 'gateways' underlain by thick deformation till. Other marine-based ice streams were present within overdeepened offshore troughs fed by fiords along the Pacific coast but their geomorphic footprint is largely unexplored. CIS disintegrated in < 1000 years after c. 13,000 ybp and released large volumes of meltwaters and sediment through interior valleys to the Pacific. Abrupt collapse may reflect the rapid onset of ice streaming when the ice sheet reached its maximum volume leading to unsustainable ice losses from calving ice streams terminating in the ocean or in deep interior 'fiord' lake basins.

Post-accretionary uplift of the Meguma Terrane relative to the Avalon Terrane in the Canadian Appalachians

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Accreted terranes are discrete crustal blocks with distinct geological histories normally bounded by long-lived fault zones with complex histories. These fault zones are the locus for relative and repeated movements during the initial docking and post-accretionary tectonism. The Avalon and Meguma terranes are the two most outboard accreted terranes in the Canadian Appalachians. These terranes were located along the Gondwanan margin in the Early Paleozoic. Accretion to the Laurentian margin followed as Iapetus Ocean closed, either as separate crustal blocks during the Early or Late Devonian respectively, or during a single event as a contiguous terrane in the Early Devonian. The Minas Fault Zone delineates the boundary between these peri-Gondwanan terranes. Exposures of the fault zone at various localities in mainland Nova Scotia crop out over a length of ca. 300 km and include the Chedabucto Fault, to the north of which lies the Avalon Terrane, and the West River St. Mary's Fault, to the south of which lies the Meguma Terrane. Between these faults lies the St. Mary's Basin, a Late Devonian-Early Carboniferous basin containing almost entirely continental clastic rocks and contains clasts of Meguma terrane lithologies. An unnamed, elongate and foliated granite pluton exposed along the West River St. Mary's Fault intrudes Meguma Supergroup metasedimentary rocks. The well-developed foliation consists of a shallowly (<10°) westerly plunging stretching lineation, and C-S fabrics with muscovite aligned in the S fabric. New U-Pb (zircon) geochronological data yield a crystallization age for the intrusion of 375.0 ± 4.6 Ma that is indistinguishable from previously reported Late-Devonian intrusions in the Meguma Terrane. $^{40}Ar/^{39}Ar$ (muscovite) age data will be presented during this conference to help constraining the timing of deformation and exhumation of these rocks into the upper crust. The presence of abundant granite clasts in St. Marys Basin strata indicated the granites were exposed by ca. 360 Ma. Taken together, these data document the Upper-Devonian tectonic history of the region and the relationship between the Avalon and Meguma terranes following their accretion to the Laurentian margin.

Modal, textural and chemical variations in the vanadiferous magnetite deposit of the Lac Doré Complex (Québec) and their implications on the chemical purity of magnetite concentrates

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Vanadium extraction from magnetites is very sensitive to the presence of contaminating elements (e.g., Si, Ca and transition metals). Consequently, a good knowledge of the distribution of these contaminants in rocks and a good understanding of ore behavior during comminution and beneficiation processes are critical to optimise the extraction process. Geometallurgy, an emerging approach within the mining industry, aims to integrate geological and metallurgical data to develop predictive models for the improvement of ore processing. Knowingly, geometallurgical modeling proves to be an efficient tool to optimize the production of very clean magnetite concentrates.

VanadiumCorp Resources Inc. plans to extract the vanadium contained in magnetites from its Lac Doré property (Lac Doré Complex, a layered intrusion in the north of Québec, Canada) to produce high-purity vanadium chemicals (99.99%) for the industry of vanadium flow redox batteries. However, contaminants from gangue minerals and magnetites themselves cause recovery losses and expensive purification steps. Therefore, obtaining cleanest magnetite concentrates must be optimized for the beneficiation process, either it is alkali roasting, smelting or else. The purpose of this PhD research project is to assess the effects of mineralogical variations on the purity of magnetite concentrates produced from a transect line across the stratigraphy of the East deposit (Lac Doré property). Two issues will be investigated: (1) the implication of modal and textural variations on magnetite liberation during comminution processes; and (2) the implication of mineral composition and its variations on the incorporation rate of contaminating elements. This will be achieved by using in situ quantitative mineralogical analyses (based on backscattered electron imagery, plus EDS and LA-ICP-MS analyses) combined with laboratory-scale comminution and magnetic separation tests. Results from our preliminary petrographic study reveal that magnetite is preferentially associated with (1) ilmenite produced by oxy-exsolution processes and primary crystallization, (2) actinolite and chlorite derived from the metamorphism of plagioclase with water interaction, and (3) chlorite formed by the replacement of magnetite itself along fractures and grain margins. Two types of oxy-exsolutions are present in magnetites: (i) ilmenite exsolutions resulting from the oxidation of the ulvöspinel component at temperatures above the solvus of the magnetite-ulvöspinel solid solution; and (ii) ilmenite exsolutions resulting from the oxidation of exsolved ulvöspinels. Since the abundance, attachments and composition of the associated minerals vary greatly in the studied transect due to changes in rock formation and metamorphism conditions, they are suspected to affect the chemical constancy of magnetite concentrates.

Revisiting the composition of Hawai‘i’s most geochemically enriched shield basalts

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Intraplate volcanism linked to mantle plumes produces basalts with diverse radiogenic isotope signatures, which can be juxtaposed along a single hotspot, demonstrating a high degree of geochemical heterogeneity in the deep mantle. On the Hawaiian Islands, a unique geochemical signature occurs in basalts that erupted late in the shield-building stage of Ko‘olau volcano on O‘ahu. These tholeiites evolved from a ‘Loa-trend’ composition, which prevails on the southwest side of the Hawaiian Island chain, to a more geochemically enriched ‘Makapu‘u-type’ signature, similar to the EM-1 mantle component. This signature, the most enriched observed in Hawaiian Island shield basalts, is recognized by high concentrations of incompatible trace elements that are correlated with low $^{143}Nd/^{144}Nd$ and $^{176}Hf/^{177}Hf$, and with high $^{87}Sr/^{86}Sr$ and $^{208}Pb^{*}/^{206}Pb^{*}$. Despite their significance as an end-member composition, there are no Makapu‘u basalt samples for which a full, high-precision suite of major element oxides, trace element concentrations, and isotopic ratios has been characterized on the same aliquot of rock powder—a deficiency that significantly limits robust interpretations. We have established a comprehensive geochemical dataset with new samples from the sequence of basalt flows exposed at Makapu‘u Point in southeast O‘ahu, the classic Makapu‘u-stage basalt type section. Complementary samples from intracaldera mafic dykes (H3) and from 160 metres of inland basaltic drill core (WAF) allow for an assessment of the temporal and aerial extent of the enriched Makapu‘u signature in Ko‘olau basalts. The new analyses show tight correlations among radiogenic isotopes of Sr, Nd, Hf and Pb. Compared to the Makapu‘u section, the trace element signatures of the WAF drill core samples exhibit greater variability in light rare earth element (LREE) concentrations, while the H3 dykes have, on average, slightly more LREE-depleted trace element patterns. All analyzed samples (Makapu‘u, H3, and WAF) have Makapu‘u-like trace element characteristics, with high Sr/Nb and La/Nb, and low Th/La in comparison to Mauna Loa basalts. Our geochemical and isotopic study confirms the presence of the Makapu‘u end-member in late-stage basalts across Ko‘olau volcano. It also provides greater precision for modelling the contribution of the EM-1 mantle component to the geochemistry of Hawaiian shield volcanoes, and ultimately for modelling the role of the anomalous large low shear velocity province (LLSVP) at the core-mantle boundary in the structure of the Hawaiian mantle plume.

Organic-rich (source) strata in deepwater rocks of the Neoproterozoic Windermere Supergroup – Mudrocks but sandstones too

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Petroleum source rocks generally occur in Phanerozoic strata as fine-grained, organic-rich lithologies. Organic-rich deep marine sedimentary rocks of the Neoproterozoic Windermere Supergroup are enriched not only in the thin mudstone caps of thin-bedded turbidites deposited on the levees of slope channel, but also in intercalated thick- and very thick-bedded turbidites. Organic-rich sediment associated with thin-bedded turbidites represents fine suspended sediment that was carried high above the channel bottom and overspilled onto the levee. Organic-rich sediment in thick- and very thick-bedded turbidites, on the other hand, occurs in the thin, fine-grained cap to the bed, but significantly also as discrete layers within the medium-grained, typically parallel-laminated sandstone that comprises most of the bed. The intercalated organic-rich and quartz-rich layers indicate that the organic material particles were hydraulically equivalent to medium quartz sand grains that were either originally in-situ bound or partly lithified and preferentially sorted on the bed just prior to deposition. Moreover the sedimentation style in these thicker beds suggests deposition by more energetic flow stripping processes at channel bends. Collectively the preferential organic matter preservation in levee deposits indicates higher local sedimentation rates and more rapid burial, which together would have enhanced source rock preservation potential. Contemporaneously, common bed scour preferentially removed fine-grained bed tops, and exposed buried organic material to oxidation in the adjacent channels. Additionally, the abundance of mineral matter (grains) in channel fills would have diluted and therefore further reduced the organic content.

Organic-rich deep marine strata of the Windermere Supergroup were episodically resedimented from an upflow source area, indicating that they are unrelated to either water column anoxic events or a quasi-permanent rain of hemipelagic or pelagic organic matter to the sea floor. Instead, the vertically spaced and paleogeographically controlled occurrence of organic-rich beds is due to recurring episodes of high organic productivity in the upflow source region subsequently enriched by sediment sorting processes during transport and deposition on the seabed.

Alteration assemblages and gold mineralisation styles in the Archean Miller dyke complex, Abitibi greenstone belt, Ontario

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The Miller property, located 15 km south of Kirkland Lake in the southern part of the Archean Abitibi greenstone belt, contains Au with minor Cu and Mo mineralisation within a multi-phase dyke complex that intrudes mafic to intermediate metavolcanic rocks. The intrusive phases making up the complex include: 1) equigranular quartz-monzodiorites to tonalites; 2) porphyritic tonalites to granodiorites; and 3) fine-grained porphyritic gabbros. Core logging complemented with detailed petrography and SEM-EDS analysis indicate the presence of several alteration assemblages that are classified into four groups: 1) a first group controlled by Au-bearing quartz veinlets with proximal albite-pyrite selvages which grade to chlorite-calcite-pyrite and then to distal calcite-chlorite; 2) a pervasive and extensively distributed albite-sericite-hematite assemblage which affects most of the intrusive rocks. The primary plagioclase in these dykes has been albitized with fine-grained inclusions of sericite and hematite, which lends the rocks a characteristic red-brick colour. This albitic alteration is occasionally accompanied by porous-episyenitic textures due to dissolution of quartz and mafic minerals; 3) alteration adjacent to the intrusions and hosted by the metavolcanic wallrock includes sericite-albite-calcite-chlorite-pyrite, and garnet-chlorite-calcite-epidote-pyrite±chalcopyrite (skarn-like) which forms veins and irregular patches; and 4) an alteration assemblage which post-dates mineralisation and is represented by either chlorite-clay veins and breccias or silica-hematite in small breccia bodies and fault zones. Two mineralisation events are identified in the Miller dyke complex. The earliest and most important is represented by veinlets of quartz ± tourmaline ± pyrite ± Au hosted by the dykes, and the altered contacts between the dykes and volcanic rocks. The veins are generally centimetric, planar, low-angled, and sheeted, but with local stockworks. This Au mineralising event has Au grades of hundreds of ppb to several ppm and represents the main exploration target for the project. A later event, probably sub-economic is characterised by disseminated sulfides (pyrite-chalcopyrite-molybdenite) associated with dissolution features, such as cavities in the episyenites and dissolved margins of earlier quartz veins. The Au values of this event are erratic and Cu and Mo grades rarely reach 0.5 wt. %. The integrated study of alteration-mineralisation features in the Miller dyke complex will not only help to define the exploration potential of the project, but also to better understand the magmatic-hydrothermal evolution of the south part of the Kirkland Lake camp.

The geochemistry and geochronology of the End Deposit, NE Thelon region, Nunavut Canada: Insight to the Athabasca basin's closest relative

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The Paleoproterozoic, intracratonic Thelon Basin, located ~100-500 km west of Baker Lake, Nunavut, has been studied over the past few decades by various researchers, but it is still relatively poorly understood. It displays many stratigraphic, sedimentological and metallogenetic similarities to the uranium-producing Athabasca Basin located in Northern Saskatchewan that have made it an attractive target for uranium exploration.

The Kiggavik uranium project area is located in the NE region, in sub-Thelon Formation basement rocks, just south the Thelon Basin, ~80 km west of Baker Lake. The project area contains a series of uranium deposits generally located along a NNE-trending structural corridor known as the Andrew Lake-Kiggavik structural trend. The End deposit, within this structural trend, is hosted by Neoarchean metasedimentary rocks interpreted to belong to the Pipedream Assemblage of the Woodburn Lake group.

Three paragenetic stages of uranium mineralization are preserved, with the third stage comprising 3 sub-stages. The oldest dated stage is disseminated uraninite (U1) (~1500 Ma). This is transected by vein-type uraninite (U2) (~1300Ma). These in turn were remobilized as foliation-parallel (U3a), infill-type (U3b) (~970 Ma) and micro-roll-front style (U3c) (~750Ma). All uranium oxide minerals are highly altered and the U-Pb ages obtained are fairly discordant, suggesting that Pb-loss has occurred. Therefore, these ages are interpreted to represent thermal or tectonic resetting events. The U-Pb ages of uranium minerals from the End deposit are similar to the ages of uranium mineralization at the Bong deposit, which coincide with regional and tectonic thermal events.

Three alteration events were also dated using $^{40}Ar/^{39}Ar$ geochronology of muscovite and illite with ~1600, ~1474 and ~1300 Ma. A ~1600 event is slightly younger than the 1.67 Ga age of fluorapatite cement in the Thelon Basin, consistent with replacement of fluorapatite by uraninite in the Kiggavik Main Zone. The ~1474 and 1300 Ma events coincide with ages of uranium minerals from the End deposit. The fluid that deposited U1 and illite (Il1) had a temperature of 210 ± 16 °C with a $\delta^{18}O$ and δD +1.6 to 6.8 ± 0.7 ‰ and -131 ± 4‰ respectively. The stable isotope systematics of the uranium deposits of the Athabasca and McArthur River Basin (Australia) suggest that these deposits formed from interaction of basinal brines with basement fluids, whereas deposits from the Kiggavik camp, like the Bong and End deposits, appear to have formed from hydrothermal-meteoric fluids.

Optimal density to fractionate organic and mineral particles of Québec boreal lake sediments

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Bottom lake sediments geochemistry is a widely used exploration method, although little is known about the metal accumulation process in such sediment. The present project aims to address the issue of where the various metals are accumulated. The study of the organic and mineral particles from lakes sediments may be realized with a physical or chemical technique. The chemical techniques bring the elements out of their chemical structures. Those techniques are not as selective as they are suppose to be and can bring to the formation of nonexistent complexes in the natural material. Physical techniques keep the chemicals bond untouched. This is why those techniques are named non-destructive techniques. In the case of fixation site study of the metal trace elements in lake sediments, it is important to keep the chemical bounds intact. Density separation and scanning electron microscope (SEM) are physical techniques. Density separation allows separating organic and mineral particles from lake sediments. Various densities are recommended in scientific literature to separate organic and mineral particles from lake sediments, and tests were conducted to select the optimal one for the purpose of conducting non-destructive analyses with a SEM to assess metal trace elements fixation sites.

For this study, a composite sample made from metal rich boreal lake sediment was used. The material was mixed up with a dense liquid adjusted at four different densities. Three repetitions were made for each density tested. The separation was applied twice on the light fraction to make sure that all the particles were gathered. Both light and heavy fractions were rinsed to make sure no density liquid was left. Material from various density fractions has been scanned a SEM in order to obtain a mosaic of high resolution elemental X-ray images. The images were imported in ImageJ software and a 5 mm^2 surface was select randomly. Particle analysis has been conducted and each particle types were color-coded, measured and cataloged. Variance analyses (ANOVA) were applied on the particles population, with the use of R software. It had been found out that a density of 1,8 g cm^{-3} was the best to separate organic and mineral particles. A fair amount of diatoms particles, made of pure silica, is present in the composite samples. About 40% of all the particles were impossible to classify due to their small size. Metal deportment among the various type of particle is currently being investigated.

Keynote (30 min): Hematite textural and (U-Th)/He thermochronometry constraints on seismic and aseismic fault damage zone processes

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Hematite-coated slip surfaces in fault damage zones archive the thermal and mechanical processes operative within fault systems. Hematite is amenable to (U-Th)/He (hematite He) thermochronometry and hematite mineralization occurs over a range of depths within the Earth, forming above or below its nominal hematite He closure temperature (~25-250 °C), which is a function of the aliquot grain-size distribution. Accurate interpretation of hematite He data requires hematite grain-size distribution information, textural characterization, and constraints on the ambient thermal conditions during and after hematite formation from apatite (U-Th)/He (apatite He) thermochronometry. These data from the Wasatch fault damage zone, Utah, and basement-hosted fault damage zones in the Mecca Hills, California, provide insight into seismic and aseismic deformation processes, respectively, accommodated on these hematite-coated slip surfaces.

A network of high gloss, light reflective hematite "fault mirrors" in the exhumed, seismogenic Wasatch fault zone preserve textural and thermochronometric evidence for elevated temperatures during paleo-nanoearthquakes. Polygonal hematite crystal morphology, coupled with hematite He data patterns from these surfaces and host rock apatite He data, are best explained by friction-generated heat at slip interface geometric asperities. These observations inform thermomechanical models of flash heating at frictional contacts and resulting fractional hematite He loss over generated fault surface thermal histories. Temperatures of ~>700-1200 °C, depending on asperity size, are sufficient to induce 85-100% hematite He loss within 200 µm of the fault surface. Preserved events occurred <4.5 Ma and restricted to ~2 km depth or the upper boundary of the seismogenic zone in this setting. Prior slip caused progressive hematite comminution, reduction in the He diffusion domain length scale, and a lower closure temperature, making the hematite He system susceptible to subsequent flash heating resetting.

In the Mecca Hills, adjacent to the southernmost San Andreas Fault, faults cut Plio-Pleistocene sedimentary rocks and underlying crystalline basement and accommodate active deformation and exhumation. Damage zones comprise metallic, striated, undulatory hematite-coated minor fault surfaces. Reproducible mean hematite He dates from these faults in the Painted Canyon Fault damage zone range from ~0.7-0.4 Ma and are younger than ~1.2 Ma apatite He dates from adjacent crystalline basement host rock. These data reveal synchronous Late Pleistocene episodes of fault slip, fluid flow, and syn-kinematic hematite mineralization. Hematite fault coatings comprising anastomosing, stacked, hematite platelets akin to a "scaly fabric" and hematite He data patterns imply some damage zone deformation occurred via aseismic creep processes.

Characterization of arsenic-hosting solid phases in tailings and tailings dust from Giant Mine, Yellowknife, NT

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Mining and ore processing at Giant Mine, a gold mine in northern Canada, occurred for over 50 years (1948 – 1999). Roasting the arsenopyrite-bearing gold ore generated As-bearing maghemite, As-bearing hematite, and arsenic trioxide (As_2O_3). Arsenic trioxide is considered the most bioaccessible arsenic compound. After spring thaw in May the temperature is too low to apply any chemical surfactant to the Giant Mine tailings, thus there is a window of time when the tailings are exposed to surface conditions. This window coincides with north-north-westerly high velocity wind events (> 8.0 m/s) in May and June. There has been growing concern regarding the potential arsenic concentration and arsenic speciation of the dust from Giant Mine, particularly from the residents of N'Dilo – a community of Yellowknives Dene First Nations (YKDFN) located southeast of Giant Mine. The objective of this research is to characterize the mineralogy of the fine fraction of the tailings (particles <20um in diameter) to determine what arsenic-hosting solid phases are present, and to identify the arsenic-hosting species. Samples of surface tailings (0-10cm) were taken from locations within the tailings ponds where dust generation has been observed in the past. These samples have been sieved to <63um to isolate the finest fraction for analysis. From May to July of 2016, a total suspended particulate (TSP) high volume air sampler was set up at the south end of the south-most tailings pond to continuously sample the airborne material being transported from the mine property to local communities. For all of the surface tailings and dust samples, we collected bulk chemical and mineralogical data via inductively coupled plasma-optical emission spectrometry (ICP-OES) and -mass spectrometry (ICP-MS), scanning electron microscopy-mineral liberation analysis (SEM-MLA), and synchrontron-based microanalytical work. Bulk chemical data show that As concentrations in the <63um fraction of the tailings range from 3000 – 9300 ppm. Arsenopyrite and roaster-generated Fe-oxides (maghemite) appear to be the predominant arsenic-hosting minerals. Arsenic trioxide has not been found in the samples processed. Both arsenopyrite and Fe-oxides are commonly found in the <10um fraction of the surface tailings and tailings dust. In the sieved tailings samples, these <10um arsenic-bearing particles are present as aggregates. In the dust samples, however, the <10um particles exist both within aggregates and liberated from the aggregates. Protecting these aggregates through development of an undisturbed crust at the surface of the tailings would therefore significantly limit emission of fine-grained As-bearing minerals.

An overview of the Boothia Peninsula of northern Nunavut obtained from airborne magnetic data modelling and interpretation

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The Boothia Peninsula is a land mass found in the central region of Nunavut. The geology of the region consists of mostly granite, biotite-hornblende gneiss and quartz feldspar gneiss. The region also is covered by some till scattered over the peninsula and carbonates on the western coast. Historically very little in-depth study has been done of the area with the first extensive survey being conducted in the early 1960's, most of which was summarized by Arthur S. Dyke in 1984 for the Geological Survey of Canada in a memoir called Quaternary Geology of Boothia Peninsula and Northern District of Keewatin, Central Canadian Arctic, and nothing since then up until the previous few years.

Recently a magnetic survey was flown over the area by the Geological Survey of Canada (GSC). The survey, flown by Sander Geophysics Limited with north-south lines spaced at 400m and 150 m above the ground, is providing with a wealth of data to complement the existing geological knowledge of the area.

The data was gridded at 80 m (1/5 of the line spacing), and interpreted at 1:100,000 scale. This contribution shows the litho-structural interpretation of the SE corner of the survey. The structural interpretation shows several deformation events that resulted in 2 generation of folds and 3 main orientations of brittle faults. From younger to older, the main structural trends are ENE, NE and NW.

The lithological interpretation of the data allows to accurately map the boundaries of the 3 main lithological units that occupy the area: biotite-hornblende gneiss, quartz-feldspar gneiss and granites all of Archean age. Gabbroic dykes of Proterozoic age are characterized by a strong magnetic response. Cross-cutting relationships between dykes allow to separate at least 2 different swarms in the area, striking NW and NE.

Forward modelling of the magnetic data is giving a good indication of dip and dip-direction of the main folded sequences and some of the main contacts in the area.

All this data will contribute to the upcoming field mapping in the area.

Investigation of the long-term influence of the Bridge-River Diversion on Sockeye Salmon nursery ecosystem production in Seton Lake, British Columbia, Canada: A comparative paleolimnological study

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Seton and Anderson lakes (British Columbia, Canada) are large and deep oligotrophic lakes that experience similar geomorphological, physical and climatic conditions. Both lakes contain anadromous populations of Sockeye Salmon (Oncorhynchus nerka) and resident Kokanee (O. nerka). In the last century, the physical and chemical conditions of Seton Lake have changed largely due to the establishment of hydroelectric dams and a water diversion (Bridge River Diversion, BRD) which introduced glacially-turbid water to this historically clear-water system, whereas disturbances to Anderson Lake have been minimal. All of the existing limnological information on Seton Lake represents the post-diversion period, and consequently the influence of hydroelectric-based activities on Seton Lake are difficult to assess. Similarly, the lack of long-term data on both Seton and Anderson lakes make the detection of any recent changes in climate on the limnology of these lakes difficult. This project uses a paleolimnological approach to assess the cumulative impact of hydroelectric activities and climate change on the primary and secondary producers in Seton Lake; Anderson Lake being used as a reference lake. We reconstructed changes in trophic status over the last centuries in both lakes using cladoceran, diatoms, algal pigments, stable isotopes and a variety of lithological indicators. Investigating the long-term changes in primary and secondary producers associated with the BRD is an important management tool to assess the potential of these lakes to sustain populations of anadromous salmon. The sedimentological analysis show that the input of glacial flour from the Bridge River diversion drastically changed the sediment composition in Seton Lake while the sediment composition in Anderson Lake remain unchanged. Diatom and cladoceran fluxes sharply decreased following the establishment of the diversion, and show evidence that Seton Lake used to be more productive than Anderson Lake. All proxies of primary and secondary producers show evidence that, prior to diversion, salmon derived nutrient was the main driver of change of the Seton-Anderson lake system production. Additionally, the diatoms assemblages in all sediment cores from Seton Lake and Anderson Lake are characterized by a distinct increase of Cylcotella comensis post- ca. 1980 that might be related to recent change in climate.

Granitoid plutons in Cape Breton Island, Nova Scotia, Canada: New age constraints and implications for correlations with peri-Gondwanan terranes in Newfoundland and New Brunswick

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Cape Breton Island occupies a key position in the northern Appalachian orogen, geologically bridging the gap between Newfoundland and New Brunswick. The complex geology of the island, developed in large part due to the compressed width of the orogen there compared to much wider areas of equivalent geology in Newfoundland and New Brunswick, has resulted in its being commonly under-utilized at best and ignored at worst in orogenic interpretations. On the other hand, its complex history has led to the preservation and exposure of rocks and relationships not seen elsewhere and essential to understanding the Appalachian story. Granitoid plutons form more than half of the area of pre-Carboniferous rocks in Cape Breton Island and hence knowledge of the timing and tectonic setting of their emplacement is crucial for understanding the geological history of the island, guiding exploration for granite-related economic mineralization, and making along-orogen correlations. The distribution of these plutons and their petrological characteristics are reasonably well known, and they have been used in the past for recognizing both Laurentian and peri-Gondwanan components in Cape Breton Island, and for subdividing the peri-Gondwanan components into Ganderian and Avalonian terranes. The relatively few well constrained ages from previous studies showed that these plutons range in age from Mesoproterozoic (ca. 1200 Ma) in Laurentian fragments to Devonian (ca. 370 Ma). However, ages of many plutons were only assumed, based on field relations and petrological features compared to dated plutons. To test the validity of these assumptions, we have undertaken a systematic re-evaluation of plutons in peri-Gondwanan terranes in Cape Breton Island with a focus on zircon U-Pb geochronology. This study has already led to refinements in our understanding of the distribution of pluton ages and geological correlations, all of which are also incorporated into a new series of updated geological maps for the island. For example, plutons previously interpreted to be latest Ediacaran in the western part of the island are now known to range from even older to as young as Late Devonian. Most significantly, they include numerous arc-related plutons with ages of ca. 490-475 Ma, likely recording the Penobscottian event recognized in the Exploits subzone of central Newfoundland and in New Brunswick, but not previously recognized in Cape Breton Island. Arc-related Silurian plutonic activity is also more widespread than previously known, and Devonian plutons formed throughout the island but in diverse geological settings.

Keynote (40 min): Thresholds, critical transitions and state shifts in the Permian carbonate system of NW Pangea

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The Permian buildup of atmospheric CO_2 resulted in the near complete eradication of carbonate sediments along the NW margin of Pangea. A critical transition occurred some ~299 Myr ago (earliest Permian) that saw the termination of aragonitic ooid, invasion of Tethyan forams and proliferation of calcareous algae. This suggests the warmest temperatures yet in the area. The loss of aragonite ooids, yet the proliferation of aragonitic biota suggest higher pCO_2 and T may have favoured algal growth and invasion of warmer species, but prevented inorganic precipitation. The principal phase of the Late Paleozoic Ice Age came to an end in the Sakmarian (293 Ma), coinciding with a rise in CO_2 and T. NW Pangea however shifted to a cooler oceanographic setting as warm photozoan carbonates gave way to cool heterozoan carbonates. The closure of the Uralian seaway may have prevented warm Tethyan waters from reaching western Pangea. However the onset of cool water sedimentation occurred while inner shelves remained under warm conditions, suggesting shoaling of the thermocline also played a role in the cooling. This shift is accompanied by a marked influx of reduced iron, suggesting amplification of upwelling. By Middle Permian (262 Ma) the thermocline had resumed its march into shallower environments, as most of the shallow shelves were again blanketed by spiculitic biofacies. Phosphatic brachiopods now appeared in large numbers. An extinction occurred among several fossil groups that had flourished in warm latitude areas (e.g. fusulinids). Massive volcanic eruptions in China are seen as a cause for this event. The extinction preferentially affected organisms that would lose their calcifying ability in a higher CO_2 environment. By latest Permian, the deep oceans had started to stratify and become anoxic, thermohaline circulation had become sluggish, a large swath of NW Pangea had fallen below carbonate saturation, only resilient biosiliceous facies were accumulating, and pCO_2 was up to 10× modern values. Marine life had not recovered from the earlier devastation. It is against this backdrop that the largest volcanic eruptions in Earth history occurred — the Siberian Traps. This was a genuine sledgehammer that tipped the world into alternate state. The world that followed had more affinity with the microbe-dominated Proterozoic. Life did recover, but one had to wait until the Middle Triassic for a healthy metazoan biosphere to take hold, following a 5 ma-long global gap in reef, coal and chert accumulation.

After the flood: Analysis of organic rich sediments exposed by the 2013 floods along rivers in southwest Alberta

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High magnitude floods in June 2013 in southwest Alberta caused considerable riverbank erosion and damage to infrastructure. Post-flood survey work was undertaken by consultants under the auspices of the Archaeological Survey primarily to assess the impact on archaeological, Quaternary palaeontological, and palaeoecological resources along several of the main affected rivers. Besides documenting the impact on known heritage sites, a further objective was to obtain information to help develop predictive modelling for heritage resources. During these surveys, organic rich layers were documented and sampled. These layers occurred in fluvial sediments, especially in slack-water or cut-off deposits, or flood debris layers. Most of the organic rich layers were highly localized and restricted in extent. The window of opportunity to collect samples from these fresh exposures was quite limited, because steep exposures are vulnerable to slumping, erosion, and revegetation. During the last eighteen months, we have analyzed samples from these organic rich layers, processing them for their macrofossil content, mainly seeds and mollusc remains. We have examined 57 samples, although most attention has been focused on 24 samples along the Highwood River. Chronologic control is provided by relative stratigraphy, in particular position in relation to the regionally significant Mazama tephra layer, and some radiocarbon dates. Samples mostly date to the mid or late Holocene, although there are a few from the early Holocene. Samples can be divided into two categories: organic rich vegetation mats and shell beds. Taxa indicative of riparian, wet meadow, and aquatic habitats are common across assemblages. Taphonomic factors related to dispersal and transport are important because many samples are primarily detrital. However, most taxa are consistent with the present regional biota, suggesting that similar vegetation communities and habitats have occurred in these watersheds through most of the Holocene. The biotic data are being used in ongoing work to generate some climate models for the area. The project is generating some new insights into fluvial history along these rivers. This information will also be useful for future cultural resource management (CRM) initiatives because it helps to contextualize the regional archaeological record.

Chalcopyrite as an indicator mineral to fingerprint mineral deposit types: A preliminary study

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Chalcopyrite has the potential to be a useful indicator mineral for exploration. It is a common mineral in various types of mineralization and is resistant to mechanical and chemical weathering. Nonetheless, it is poorly studied compared to magnetite and other indicator minerals, as it contains low abundance of most trace elements. In this study, we report chalcopyrite trace element composition analyzed by EPMA and LA-ICP-MS from 16 deposits from a range of deposit types, including Ni-Cu, PGE, VMS, porphyry, skarn, IOCG, Opemiska Cu vein, Kupferschiefer, and orogenic gold, in order to outline the geochemical signatures characteristic of each mineral deposit type.

Samples from the 16 deposits include a variable amount of chalcopyrite grains (~4-90%). These grains vary in size (fine-grained to coarse-grained), are xenomorphic, and typically contain inclusions of oxides, sulphides, and/or silicates. EPMA data are mostly below or close to the detection limit. Among the 16 minor and trace elements analyzed, Se, Zn, Ba, Ag, Ni, and Sn display concentrations significantly higher than the detection limits (Ni-Cu: Ni, Se; PGE: Se, Zn; VMS: Ag, Se, Sn, Zn; porphyry: Se, Zn; skarn: Se; IOCG: Ba, Zn; Opemiska: Ni, Zn; orogenic gold: Ba). In contrast, the LA-ICP-MS data of 18 (Ag, As, Au, Bi, Cu, In, Mn, Ni, Pb, Pd, Ru, S, Sb, Se, Sn, Te, V, and Zn) out of 25 elements measured (including major elements, Cu, and S) contain less than 40% censored values, below the detection limits. Overall, chalcopyrite from VMS and porphyry deposits has high Ag concentrations (~100 ppm), while orogenic gold chalcopyrite is typically depleted in Ag (as well as in Se). High Zn contents (~100 ppm) are observed in VMS, Ni-Cu, and PGE deposits, whereas Zn values in skarn and Kupferschiefer deposits are low (<10 ppm). Palladium and Ni contents in Ni-Cu and PGE deposits are generally higher than Pd-Ni contents in the other deposit types. In particular, Pd concentrations in skarn deposits are very low. Furthermore, chalcopyrite from VMS, skarn, and Opemiska vein deposits contains high In contents (>10 ppm). These preliminary results indicate that Ag, Ni, Pd, Se, and Zn compositions of chalcopyrite are discriminant for different types of mineralization and suggest that chalcopyrite could be a reliable indicator mineral in exploration for various deposit types.

Sedimentary anisotropy and its impact on solute mixing in groundwater

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Complex configurations of sediments are typically observed in type-sections of Quaternary deposits. However, such complexity of bedding and structure is often neglected in hydrostratigraphic units implemented in hydrogeologic modelling. Anisotropy in porous media has been proven to induce complex groundwater flow patterns in numerical and analytical models. Yet these modelling efforts have been primarily conducted in porous media that do not correspond to sedimentary structures reported by sedimentologists.

In this study, we model groundwater flow and solute transport in realistic porous media that resemble scour-pool fills – trough-like architectural elements often observed in glaciofluvial sedimentary deposits. We generated multiple realisations of the trough fields. Sedimentary anisotropy was introduced through the rotation of the full hydraulic-conductivity tensor using parameters drawn from previous field investigations in the upper Rhine valley, Germany. We compared the effects of varying isotropic hydraulic conductivity and internal anisotropy using five model test cases.

The model results demonstrate that realistic sedimentary anisotropy does indeed produce complex groundwater flow fields, with twisting and intertwining of advective streamlines. Variability of isotropic hydraulic-conductivity values controls longitudinal spreading and mixing. Conversely, steady state advective-dispersive concentration distributions clearly show the effect of sedimentary anisotropy, with greater transverse spreading and mixing occurring in test cases where the full hydraulic-conductivity tensor was rotated.

The present work provides insight into the relevance of sedimentary anisotropy in groundwater flow and solute transport modelling. Until now, we have only modelled one architectural element – actual sedimentary deposits are composed of diverse assemblages of such elements. The next step is to extend our modelling efforts to include such assemblages. A hierarchical facies model framework will be implemented, whereby larger hydrostratigraphic units are composed of smaller sub-units. All components of the model framework will be simulated based on field observations and geological conceptual models.

Influence of vertical density structure on the stratal architecture of deep-marine levee deposits Neoproterozoic Isaac Formation, Windermere Supergroup, B.C., Canada

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Channel-levee complexes are a principal component of deep-marine systems. Previous work, particularly in the ancient sedimentary record, has tended to focus on the channels rather than the levees, mostly because these strata are typically poorly exposed and their less than decimetre characteristics are below the resolution of even high resolution industry seismic. At the Castle Creek study area, however, glacially-polished, vegetation-free levee deposits are 100% exposed over an area of ~2.6 km wide and ~90 m thick, locally covered by moraine and glacier. This, then, provides an unparalleled opportunity to describe details of the lateral and vertical lithological changes in channel-associated levee deposits and therein provide important details about their reservoir geometry and stratal continuity.

Levee deposits are generally assumed to thin and fine upward due to overspill of the progressively finer-grained upper part of channellized flows as levee relief increases. In this study, however, levee deposits are divided vertically into four packages that range from 6 to 21 m thick and are easily subdivided into lower and upper parts, the transition between being sharp and marked by a dramatic decrease in bed thickness, grain size and sandstone content.

The vertical packages are interpreted to be related to recurring changes in the vertical density structure of channellized flows, which in turn was controlled by grain size and grain sorting. Initially, channellized flows were coarse grained and well sorted, causing them to have a plug-like density structure with negligible vertical stratification and high flow efficiency. In addition, the velocity maximum generally occurred above the height of the incipient channel margins, thereby allowing the lower, coarse-grained, dense parts of flows to overspill and deposit thick-bedded, coarse-grained turbidites in the lower part of each package. The sharp contact with the upper part of each package marks the point when relief from channel-floor to levee-crest exceeded the height of the velocity maximum, allowing only the upper, finer-grained parts of currents to overspill. Later the make up of the sediment supply changed, specifically an increase in the sand fraction, which created an exponential density structure in the throughgoing currents. This promoted interfacial mixing and rapid energy loss, and accordingly deposition within the channel. These depositional conditions were then repeated with the formation of the next levee package, signalling the possible recurring influence of relative sea level change on the make-up of the sediment supply, and in turn, characteristics of continental slope sedimentation.

Crustal dynamics and tectonic assembly of the west-southwest Rae craton – What are key relationships in the Athabasca region telling us?

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The Rae craton contains rocks and structures of a remarkably wide age-range, from Paleo/Mesoarchean to Mesoproterozoic. The tectonic history of this complex craton is by no means fully resolved, but evidence is accumulating that Rae was independent of Hearne before it was incorporated in Laurentia-Nuna. A diagnostic feature of the Rae, setting it apart from both Hearne and Slave, is substantial late Neoarchean to early Paleoproterozoic reworking. Indeed, following a widespread 2.62-2.58 Ga granite bloom, whose tectonic significance remains poorly understood, the margins of Rae were subjected to seemingly continuous tectonism, with 2.55-2.5 Ga MacQuoid orogenesis in the east superseded by 2.5 to 2.3 Ga Arrowsmith orogenesis in the west. Because it holds key evidence of Rae's unique older history (Arrowsmith orogenesis), as well as its subsequent involvement in Nuna (Thelon-Taltson orogenesis), the western Rae is of key importance. The Thelon orogen of the western Rae was once ascribed to collision of Slave craton and/or Buffalo Head terrane with Rae. However, robust Arrowsmith effects have now been recognized well into the Rae interior, raising the idea Rae's western side may represent a long-lived accretionary margin. If this was the case, fundamental questions remain; for example, when did the process of accretion begin, at 2.5 Ga or 2.3 Ga or perhaps even earlier (2.6 Ga?), and what colliding blocks were involved? Furthermore, when did accretion end and what were the dynamics involved in the transition to Thelon-Taltson orogenesis? Additionally, what role did various distinctive supracrustal successions deposited in this transitional period play? The Athabasca region holds important clues to these questions. In this region, an internal block composed of dominantly Neoarchean (2.6 Ga) crust (Nolan domain) is bounded, across a high-strain zone to the south, by Mesoarchean (3.2-3.0 Ga) crust intermixed with early Paleoproterozoic (2.5-2.3 Ga) crust (Zemlak-Beaverlodge domains), including a distinctive suite of syn/post-collisional granites. Current data suggests that this hybrid crust, likely an extension of the Taltson basement complex to the west, may have been generated by 2.5-2.3 Ga accretion of a Paleo/Mesoarchean terrane. During subsequent Taltson orogenesis, 1.99-1.93 Ga I- and S-type granitoid plutons were emplaced, and this boundary zone, potentially marking an Arrowsmith-related suture, was intensively reworked. This talk will explore the significance of this boundary within the broader context of regional constraints and existing tectonic models for the dynamics along the west-southwest Rae margin from late Neoarchean to Paleoproterozoic time.

Expression of the McArthur River U deposit footprint in diverse surficial sampling media

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A conspicuous geochemical footprint is present at the surface above the McArthur River high-grade uranium deposit in the Athabasca Basin of northern Saskatchewan, Canada based on results from a multi-media orientation survey. Pine tree cores, multi-horizon soils, and boulders of local bedrock (Manitou Falls D Member sandstone) contained within glacial cover were collected on four 400x400-meter grids with 50 m station and line spacings. Three grids were placed along the NE-SW-trending P2 fault over weak to high-grade U mineralization that lies over 500 m below the surface along the fault, and one grid was placed 2 km away from the P2 fault trace in the non-U-mineralized hanging wall of the structure.

Clay alteration minerals in angular sandstone boulders determined by shortwave infrared (SWIR) spectrometry resemble those in sandstone in the subsurface, indicating the boulders are locally derived. Additionally, the boulders collected over the high-grade ore body contain the highest proportion of mobile radiogenic Pb ($^{207}Pb/^{206}Pb$ ratios as low as 0.29) and U (as high as 140 ppb) based on the results of 2% nitric acid leach, suggesting that both primary and secondary dispersion products are present throughout the thickness of the Manitou Falls Formation.

Pine tree cores also record secondary dispersion of radiogenic Pb and U over the high-grade ore body, with $^{207}Pb/^{206}Pb$ ratios as low as 0.57 in tree cores older than 1985. By comparison, $^{207}Pb/^{206}Pb$ ratios average 0.83 in trees collected away from the P2 fault. Na pyrophosphate leach of the organic-rich A1 soil horizon samples are similar to those of the tree cores, with $^{207}Pb/^{206}Pb$ ratios as low as 0.36 over the high-grade ore body, and around 0.85 away from the P2 fault. The results of both weak acid leach and aqua regia digest on B- and C-horizon soil separates reflect control by detrital minerals in the till, which mask geochemical contributions from secondary dispersion from the deposit.

The results of this study demonstrate the utility of compact, tightly-spaced surficial sampling grids as an effective and relatively low-cost exploration tool for deposits at depths in excess of 500 meters and attest to the possible role that the biosphere-geosphere interface can play in exploration geochemistry.

Keynote (40 min): Deep rivers in deep time

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Estimates of water and sediment paleodischarge, paleo-drainage area, and sediment budgets are calculated for a number of Mesozoic systems, from western North America. Extensive outcrop and subsurface data allow the largest trunk rivers to be identified, typically within incised valleys. Thickness, grain size, and sedimentary structures can be used to infer slope and flow velocities, and using width estimations, water and sediment paleodischarge can be calculated. River paleoslope can also be independently measured from stratigraphic-geometric considerations. Paleodischarge in turn is used to estimate the size of the catchment source area. Paleodischarge of rivers can also be estimated independently by integrating estimates of catchment source area, for example by using detrital zircons integrated with paleoclimate and regional paleogeographic/paleotectonic reconstructions.

The catchment areas of North America evolved significantly during the late Mesozoic. During the Jurassic-Early Cretaceous, fluvial systems consisting of continental-scale low-slope (S=0.0001), axially-drained rivers, formed the 40m-deep channels in the Mannville Group in Canada, which now host the supergiant heavy-oil-sands reserves. During times of maximum transgression of the Cretaceous Seaway, such as the Turonian and Campanian the western North American foreland basin was characterized by smaller-scale (typically 10m deep), steeper gradient (S=0.001) sand and gravel bed load rivers, dominated by transverse drainages in the rising Cordillera. This created a number of smaller river-delta systems along the coast, such as the Dunvegan, Ferron, Frontier, Lance and Cardium formations. As the Laramide Orogeny progressed, the Western Interior Seaway receded, and by the Paleocene the modern continental-scale drainage of North America was largely established with a major continental divide separating south-flowing Mississippi drainages that fed into the Gulf of Mexico, from north-flowing systems that drained into the Artic Ocean or Hudson's Bay, Canada.

This approach shows that the tectono-paleogeograhic evolution of the foreland basin fill alternates from axial to tranversely drained rivers, that ranged from continental-scale rivers to smaller scale systems. The S2S analysis predicts the size and scale of fluvial systems and associated downstream depositional systems, which host much of the hydrocarbon in these prolific basins.

Significant Fe isotope fractionation within the Kiglapait intrusion provides insight into the formation of layered intrusions

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Large igneous provinces (LIPs) are linked spatially and temporally with many of the world's most important mafic layered intrusions (e.g., Bushveld, Muskox, Skaergaard), some of which represent the high-level reservoirs for crystal fractionation and accumulation of magmas feeding flood basalts. Layered intrusions have long been recognized as natural laboratories of igneous and ore-forming processes for which non-traditional stable isotopes (e.g., Mg, Fe, Si) are an emerging geochemical tool. Despite recent successes in using Fe isotopes to investigate igneous processes, detailed Fe isotope studies exist for only three layered intrusions thus far: the Bushveld Complex, South Africa; the Baima Intrusion, China; the Ilímaussaq Alkaline Complex, Greenland. Iron isotopic measurements of whole rock (WR) samples and mineral separates from these intrusions provided insight into processes such as fractional crystallization, magma addition, and sub-solidus re-equilibration. Iron isotopes can also provide information about fluid exsolution, redox changes, temperature, and alteration processes. The ca. 1.3 Ga Kiglapait intrusion, part of the 20,000 km^2 Nain Plutonic Suite of coastal Labrador (Canada), records the complete fractionation crystallization sequence of 3500 km^3 of troctolitic magma. It is divided into the troctolitic Lower Zone (0-84 percent solidified [PCS]), the olivine gabbroic to ferrosyenitic Upper Zone (84-100 PCS), including the 80 cm-thick Main Ore Band, and the downward crystallized Upper Border Zone. We report the first Fe isotope measurements of Kiglapait WR samples, which show significant variation in $\delta^{56}Fe$ ($^{56}Fe/^{54}Fe$ relative to IRMM-14) from -0.01 ±0.06‰ to +0.18 ±0.03‰ (n=13, 2σaverage=0.04‰). The $\delta^{56}Fe_{WR}$ values are variable within the lowermost Lower Zone, increase from 68 to 89.3 PCS into the Upper Zone, and then decrease systematically across the Main Ore Band (93.5 PCS) to 97 PCS. The decrease in $\delta^{56}Fe_{WR}$ at the upper PCS is associated with the appearance of pyrrhotite and magnetite as cumulus phases (91 and 88.6 PCS, respectively), whereas the increase in $\delta^{56}Fe_{WR}$ values between 68 and 89.3 PCS likely reflects that the system was approaching magnetite saturation. These observations, coupled with the variability of the Lower Zone and a strong correlation with the radiogenic isotopic signatures of the same samples, implicates mineralogy as the primary control on the Fe isotope systematics of the Kiglapait intrusion. Using non-traditional stable isotopes like Fe will become a key approach in elucidating the mechanisms at play during the assembly and evolution of layered intrusions, the concentration of ores within them, and the magma plumbing systems of LIPs.

Fine-grained deep-marine sandstones: The turbidites that never were

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Along the base of passive continental margins, like east coast Canada, extensive deep-water clastic turbidite systems are present. These deposits are commonly classified using the Bouma turbidite model; a five-layer, upward-fining succession of predictable sedimentary structures and textures commonly observed in strata deposited by turbidity currents. The basal layer consists of massive or normally graded sandstone (Ta) overlain successively by planar-laminated sandstone (Tb) with a ripple cross-laminated sandstone (Tc), subtly parallel-laminated siltstone (Td) and lastly massive mudstone (Te). In the Neoproterozoic Windermere Supergroup, however, in addition to classical turbidites, strata often exhibit a succession of seven layers that often grade vertically into one another. Only rarely does a single bed include all layers. The basal layer (1) is a massive or planar/wavy stratified, granule- to lower very fine-grained sandstone that ranges from 1.5 – 187 cm (average 12.5 cm) thick. It, then, is overlain gradationally by a wavy- or planar-stratified, lower medium- to lower very fine-grained sandstone draped with silt- and mudstone (2) that range from 0.3 – 32 cm (average 5.6 cm) thick with rare layers of graded silty sand (3) and sandy silt (4) that, respectively, range from 0.3 – 6.5 cm (average 2.1 cm) and 0.5 – 5 cm (average 1.6 cm) thick. This is then capped by a 0.1 – 10 cm (average 1.7 cm) thick planar-laminated siltstone (5) overlain by a planar-laminated silty mudstone (6) that ranges from 0.3 – 6 cm thick (average 1.6 cm) capped by a planar-laminated or massive mudstone (7) that ranges from 0.5 – 22 cm (average 3.6 cm) thick.

Stratigraphically upward, thick, graded Ta sandstones (1) consistently fine and thin over 2-5 m and the proportion of mudstone (7) increases. Similarly, individual layers of Unit 1, in addition to the stack of beds composed of units 1 to 7, fine an thin upwards. Also, compared to classical turbidites, strata are ubiquitously planar stratified, which becomes better developed in the finer-grained layers (5-7), and rather than being high-angle, cross-stratified is distinctively low-angle and wavy even though the grain size can easily support the development of current ripples. Thus, it is clear that although composed of similar grain sizes, these gradational, multi-layered beds are very much different than classical turbidites, and accordingly suggest very different depositional conditions, and therein the aim of this research.

Characterization of landslides used in landslide susceptibility models in western Canada

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As a first step in assessing landslide hazard, compilation of the landslide inventory is essential. The second step is creating a landslide susceptibility model, which will highlight areas prone to landslide occurrence. The landslide inventory and susceptibility maps will then serve as baseline information to help stakeholders, decision-makers, and practitioners assess the hazard and risk. As part of Natural Resources Canada, the Geological Survey of Canada's Public Safety Geoscience Program has carried out four campaigns of landslide inventory and susceptibility mapping in western Canada, which are at different stages of completion. These campaigns were carried out for the Sea to Sky Highway, BC (110 km) and along the Alaska Highway, Yukon (900 km) and are ongoing along Douglas Channel (100 km) and east of Kitimat, BC (100 km) with collaboration from provincial, territorial, academic partners, and consultants.

The simplest landslide susceptibility modelling approach for a large area is the qualitative heuristic method. This approach was first tested along the Sea to Sky corridor for debris flows and rockfalls/rock slides. The historic record of debris flows and rockfalls/rock slides proved to be essential in validation of susceptibility models because debris flows recur in the same steep channels and rockfalls get cleaned up quickly. For the Yukon Alaska Highway corridor, qualitative heuristic assessments were tested for debris flows, rock slides and active layer detachment slides (ALD). Validation of the ALD susceptibility model proved to be difficult as ALD are small, localized, and have a short lifespan (~30 years). In an area close to Kluane Lake, a quantitative debris flows susceptibility model was tested using Flow-R software. This proved to be successful as the debris flow inventory was well documented and data derived from a high resolution DEM were available.

Two areas presently being assessed are Douglas Channel fjord southwest of Kitimat and the Kitimat-Morice River corridor. For Douglas Channel, the landslide inventory reveals that folic debris slides are the most abundant types of landslides. Folic debris slide susceptibility modelling, however, is proving somewhat difficult as these are small and triggered during rainy periods as a thin layer of organic debris on steep glacially polished bedrock. The model still needs adjustments. Nevertheless, the Flow-R method was investigated for debris flow susceptibility where LiDAR data were available.

Thus, each region possesses unique landslide events affecting the landscape. Understanding the characteristics of landslides help determine the types of data layers needed in the susceptibility models.

Guidelines for identifying and modelling LIP-related layered intrusions in plume centre regions using geophysical data

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Gravity and magnetic data from the global EGM2008 and EMAG2 datasets can be used to identify and characterize layered intrusions linked to large igneous provinces (LIPs). Our approach has been to focus on large anomalies that can be spatially associated (and are likely genetically linked) with the LIP plume centre region. We propose guidelines for identifying previously-unrecognized layered intrusions, specifically by targeting large (diameter > 40 km, and often greater than 100 kilometres in diameter), subcircular, and high-amplitude anomalies located within a 500 km radius from a mantle plume.

Our guidelines have been applied to do detailed modelling to estimate depth, size, and physical properties of intrusions associated with four LIPs: the 1.27 Ga Mackenzie LIP (North America), 1.38 Ga Lake Victoria portion of the Kunene?Kibaran LIP (East Africa), 66 Ma Deccan LIP (India), and 130?80 Ma High Artic LIP (Arctic Canada). Modelling supports that the anomalies are produced by mid-lower crustal intrusions with densities consistent with mafic-ultramafic rock and magnetic susceptibilities that suggest high magnetic mineral contents or serpentinized ultramafic rock, except in the Deccan LIP where the intrusions tend to be positioned at shallow levels in the crust and are mainly mafic in composition. We find that layered intrusions linked to LIPs can occur in recognizable spatial distribution patterns within the plume centre region, and are exemplified by these four case studies. These are (1) intrusions emplaced along a circular fault system (hundreds of kilometres in diameter) that circumscribes the plume centre, and likely formed as a result of plume-induced uplift and subsequent subsidence. (2) Linearly aligned intrusions emplaced along rifts that, in some cases, converge towards the plume centre. (3) Unclassified groups of intrusions, whose geometric distribution is unclear.

Understanding how layered intrusions are distributed in the vicinity of mantle plumes is critical for understanding the geometry of LIP plumbing systems, and is important for mineral exploration in plume centre regions where shallow intrusions are often sourced from these deeper intrusions. Exposed intrusions can be linked with a LIP on the basis of geochemistry and/or geochronology. These methods, however, are not applicable when investigating buried intrusions that have not been accessed via drillcore. Using gravity and magnetic data affords an opportunity for preliminary studies of these inaccessible targets.

New precise U-Pb geochronological data and stratigraphic interpretation for the Raglan belt, Northern Quebec

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At Raglan, a generally north-dipping sequence of volcanic and sedimentary rocks, overlying basement of the northern Superior craton, has long been viewed as a thrust belt imbricated by multiple major thrusting events. For the para-autochthonous belt this model was based on an over-simplified stratigraphic template with significant sedimentary units restricted to the base of the Povungnituk Group. Reappearance of sedimentary panels at higher (tectono)stratigraphic levels then indeed requires major thrusts at the base of these panels. Instead, many of these sedimentary panels are unique stratigraphic units intercalated within and overlying the Povungnituk Group, and also within the Chukotat Group. No major thrusts are required, nor is there obvious field evidence for such thrust. In short, more stratigraphy, less thrusts.

Specifically this applies to thin units of quartz-rich sedimentary rocks within the continental Povungnituk basalts. More importantly, the mostly deep water, turbiditic, greywackes and mudstones of the Nuvilik Formation represent a distinct formation at the stratigraphic top of the Povungnituk Group, not a repeat of the basal sedimentary section. These sediments post-dated the main pulse of basaltic volcanism, perhaps representing the thermal subsidence phase following Povungnituk magmatism. Sulphide-bearing mudstones of this formation acted as the sulphide source for Raglan orebodies at the base of the Chukotat Group, and evidence for thermal erosion channels links Chukotat lavas to their footwall. The Nuvilik Formation is neither bounded by a major thrust at its base, nor at its top. Higher in the (tectono)stratigraphy, distinct lenses of clastic sedimentary rocks may represent syn-orogenic clastic rocks, not older basal sediments, infolded into the Chukotat Group.

We have precisely dated several gabbro sills within the stratigraphy. Differentiated sills intruding into the Nuvilik Formation were thought to be perhaps as old as ca. 1918 Ma. Careful evaluation of the variably discordant data suggest these gabbro sills may be ca. 1883 Ma. A new U-Pb zircon age on the main "footwall gabbro" sill at Katinniq, applying chemical abrasion, shows this sill to be also ca. 1883 Ma, as is a gabbro sill intruding above some of the main sulphide ore lenses within Chukotat lavas. These results tightly bracket the onset of komatiitic volcanism and ore formation.

Finally, we interpret the broad, basement-cored Kovik Antiform to the north as an extensional core complex, rather than a high-amplitude contractional antiform related to on-going shortening. Deformed leucogranite sheets on the contact of this antiform may date formation of this core complex.

Preliminary mineralogical characterization of black shale-hosted Ni-Zn sulphide mineralization at the Akie Property, northern British Columbia

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Canada Zinc Metals Corp. intersected black shale-hosted Ni-Zn sulphide mineralization in nine drill holes on the Akie property in the Kechika Trough, north-central British Columbia. These intersections are stratigraphically beneath the Cardiac Creek sedimentary exhalative Zn-Pb-Ag deposit, up to 1.17m thick (core length), and have been traced over 5.5 km of strike length. The mineralization appears to be stratigraphically controlled and occurs in the informally named Lower Devonian Paul River formation proximal to the contact of the Road River Group and the Earn Group. The Paul River formation is a carbonate debris flow interfingered with chert and black shale, and is interpreted to be the uppermost part of the Road River Group in the Akie area. The mineralized layer grades 0.39 – 2.69 wt.% Zn, 0.6 – 0.89 wt.% Ni and up to 4.36 g/t Ag.

This is the first documented occurrence of shale-hosted Ni-Zn mineralization in the Kechika Trough, but there are occurrences of similar metalliferous black shale-hosted massive sulphide in the Selwyn Basin, Yukon that are commonly referred to as "Nick-type" Ni-Zn-Mo-PGE mineralization. In the Yukon, this mineralization occurs in a stratigraphically controlled horizon, at the contact between the Road River Group and Canol Formation. The mineralized horizon characteristically occurs immediately above a carbonate concretion-rich shale and immediately below a thin-bedded, black, phosphatic/carbonaceous chert shale.

Optical microscopy and Mineral Liberation Analysis conducted on selected Akie drill core samples have identified the main Ni- and Zn-bearing phases in the sulphide horizon as millerite and sphalerite, respectively. Gersdorffite and pentlandite are minor Ni-bearing phases. These minerals typically occur in layers and stringers of fine-grained, semi-massive sulphides, together with pyrite within a discrete stratigraphic interval associated with apatite nodules and calcite gangue. Sulphide-rich layers are mineralogically zoned. The upper and lower margins of the layers are dominated by pyrite and sphalerite, whereas the interior of the layers comprises predominantly millerite and sphalerite. Framboidal pyrite (10 micron-diameter) occurs with the sulphide mineralization, and is overprinted by sphalerite, millerite and non-framboidal pyrite.

These minerals and mineral textures have also been documented in several of the Yukon occurrences, and together with the similar stratigraphic position of the Ni-Zn-Ag mineralization at Akie to Nick-type mineralization in the Yukon, some 1000 km to the north, suggests a common genesis. To confirm or refute this hypothesis, detailed stratigraphic analysis, and further geochemical and mineralogical sampling and analysis will be conducted.

Metamorphism across the Coast Mountains batholith near Mt. Waddington BC, Canada

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The Coast Mountains batholith contains a record of magmatism and metamorphism for the 1700 km long Cretaceous magmatic arc on the NW coast of North America. This makes it an ideal location to study the interplay between metamorphism and magmatism. We present preliminary garnet Sm-Nd ages, isochemical phase diagram sections, and thermobarometry for rocks near Mt. Waddington.

Metamorphic P-T paths and Sm-Nd garnet ages for pelitic rocks indicate similar P-T but variable timing across-strike 60 km NE-SW (3 samples) and 70 km along-strike NW-SE (4 samples) transects. For the across-strike NE-SW transect: (1) Approximately 20 km NE of Mt Waddington peak metamorphism occurred at 64.5±0.9 Ma and 660°C, 6 kbar. (2) Two samples 15 km SW of (1), near Mt. Waddington, yield 72.3±1.5-64.4±1.0 Ma and 72.3±1.2-67.1±1.6 Ma garnet core-rim ages with corresponding P-T paths of 515°C, 4 kbar at 72 Ma to 630°C, 5.3 kbar at ca. 65 Ma. (3) Metamorphism in the western batholith along Bute Inlet reached 660°C, 6.6 kbar. Cross cutting relations and zircon ages suggest metamorphism pre 100 Ma. For the along strike NW-SE transect: (1) 30 km SE of point (2) for the NE-SW transect yields a 79.9±2.2 Ma garnet age with a P-T path of 570°C, 5.7 kbar to 600°C, 7.6 kbar. (2) 30 km farther SW an orthogneiss yielded the oldest garnet age of 98.9±2.3 Ma. (3) Andalusite stability 10 km farther SW indicates higher structural levels.

There is little across-strike variation in pressure or temperature; however, ages vary significantly along strike. Garnet ages and P-T paths suggest that the thickest crust, > 28 km, occurred at 80 Ma; however, most crustal thickening occurred prior to garnet growth at 80 Ma. Pressures indicate ca. 15 km depths at 72 Ma and ca. 20 km depths at ca. 65 Ma. The 15 km crustal-depth at 72 Ma and P-T paths indicate 5 km of exhumation after 80 Ma.

Zircon U-Pb ages suggest a prevalence of plutons intruding at 115-90 Ma and 80-70 Ma. Therefore, plutonism was synchronous with metamorphism at ca. 99, 80, and 72. The late 64 Ma prograde metamorphism indicates that contraction may have outlasted major plutonism. Furthermore, most P-T conditions are at or below the solidus, revealing little contribution through partial melting or dehydration to magmatic flare-ups. Additional garnet geochronology and thermobarometry are currently underway for andalusite-bearing and western samples.

Geochemistry of antimony and arsenic in freshly deposited tailings at Beaverbrook Sb mine, Newfoundland

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Waste resulting from antimony (Sb) ore flotation process is an important source of metalloids pollution. As the solid waste is deposited and exposed to oxic environment, the weathering of sulphides causes the release of potentially toxic elements such as Sb, commonly accompanied by arsenic (As), into the liquid phase. Besides other environmental factors, the fate of these contaminants depends on secondary mineral precipitation. In this study, scanning electron microscopy and electron microprobe analyses were combined with synchrotron-based μ-X ray diffraction to identify the elements distribution and Sb host phases in relatively young tailings at Beaverbrook Sb deposit. Hydride generation atomic absorption spectrometry was used to analyze Sb and As speciation in pore and surface waters. In these tailings, the most common Sb and As hosts are stibnite and arsenopyrite, respectively. Antimony and As concentration in bulk tailings is relatively constant, with average values of 2940 ppm for As and 3950 ppm for Sb; however, the water samples show much lower As concentration compared to Sb. The concentration of Sb in tailings pore water is up to 26.4 mg/L and only 0.9% is in form of Sb^{3+}. In all surface water samples, Sb is most prevalent in its fully oxidized form (98.9-99.2% of total Sb) and the concentration is up to 8.71 mg/L. Arsenic concentration in tailings pore water reaches up to 2.92 mg/L and As^{3+} is the dominant form of As. Maximum As concentration in surface water is 0.5 mg/L mostly present as As^{5+}. The difference between aqueous phase speciation in pore water suggests that Sb oxidation is more rapid than As oxidation.

The Sb secondary minerals formed initially after stibnite mine waste decomposition include soluble brandholzite ($Mg[Sb(OH)_6]_2 \cdot 6H_2O$) and less soluble Sb-Fe minerals and goethite slightly enriched in Sb. The Sb-Fe secondary minerals can accommodate wide Fe/Sb ratio, but have low As concentration. Arsenic is distributed mostly in arsenopyrite and oxidation rims on pyrite and arsenopyrite. The rapid stibnite dissolution together with the periodic brandholzite dissolution contribute to high Sb concentration and over time, if conditions remain oxic, more Sb is expected to be stored by Sb-Fe oxyhydroxides.

Holocene variation of lake water balance in northeastern Ontario inferred from lacustrine carbonate stable isotopes

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Climate models suggest that temperatures will increase significantly by the end of the 21st century due to climate change. Similar patterns were observed during the mid-Holocene (also known as the Hypsithermal or the Holocene Thermal Optimum) which constitutes a potential analog period for projected changes. During this period, the Prairie region of North America displayed drier hydroclimatic conditions while the American northeast was wetter. It remains poorly understood whether the Hypsithermal resulted in drier or wetter conditions in northeast-central North America and there is a need to develop long paleohydrological records in the region to better understand future climate risks on freshwater systems.

To this end, sediment cores were retrieved from two adjacent alkaline lakes in the Timmins region of northeastern Ontario, one located upland and relatively disconnected to the local groundwater system (thus sensitive to short-term hydroclimatic change) and the other positioned lower embedded in the aquifer (therefore buffered by groundwater inflow). Sediment cores were dated with ^{14}C and analyzed for carbonate stable isotopes ($\delta^{18}O$ and $\delta^{13}C$) to reconstruct past lake-water balance.

Results show that both lakes had distinctly lower levels between 9000 and 7000 cal ^{14}C BP, implying than even hydrologically buffered lakes are sensitive to long-term hydroclimatic change. Water levels then increased abruptly in both lakes during the mid-Holocene (between 7000 and 5000 cal ^{14}C BP), reaching their highest since the lakes formed about 11,000 years ago. The isotopic record is consistent with lithological changes observed in the sediment as well as with previous pollen and geomorphic studies done in the area, suggesting that northeastern Ontario was synchronous with the American northeast in terms of hydroclimatic change during the Hypsithermal. Lake levels subsequently decreased slightly and remained relatively stable from 5000 cal ^{14}C BP to reach current intermediate water levels. However, $\delta^{18}O$ values for the last 5,000 years from the two lakes show opposing trends likely due their respective position in the landscape, suggesting that freshwater systems response to hydroclimatic change is complex and watershed-specific.

Chemostratigraphic correlation of the epicratonic Lower to Middle Cambrian Mount Clark, Mount Cap and Saline River formations, northern mainland Northwest Territories

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Lower to Middle Cambrian epicratonic strata (in ascending order, the Mount Clark, Mount Cap, and Saline River formations) are preserved across mainland northwestern Canada from the eastern Mackenzie Mountains to the Arctic coast (>500 km distance). Outcrop belts at the eastern and western extents of these strata have not been compared and correlated in detail. A cross-section of the three Cambrian formations was documented from outcrop on the eastern margin of the basin (Hornaday River Canyon), in the west-central part of the basin (Norman Range), and in two locations near the ancient Mackenzie arch (Carcajou Range). The Mount Clark Formation consists of quartz sandstone in all three regions. The Mount Cap Formation is more variable. In long-studied exposures in the Carcajou Range, it consists of a relatively thick package of mudstone, carbonate, and lesser sandstone, whereas on the eastern basin margin it is thin succession of burrowed dolostone interlayered with glauconitic sandstone. Regionally, the contact between Mount Clark and Mount Cap formations is a diachronous facies boundary. In its type area around Mackenzie Plain, the Saline River Formation is a thick succession of mudstone and evaporites, but is a thin succession of dolostone and green mudstone in the northeast. These trends suggest depositional thinning to a feather-edge against the craton in the east, but abrupt northeastward thickening adjacent to Mackenzie arch. Carbon isotope data show correlatable trends, some of which apparently differ from the established global carbon isotope curve. The Mt. Cap Formation at Hornaday River records a rising trend (-1.5‰ to 0‰VPDB) at its base that is absent in the southwestern area, suggesting that flooding of the diachronous top of the Mount Clark Formation happened earlier in the northeast than in the southwest. An ensuing negative excursion reaches -2.5‰ at Hornaday River, but -15‰ near the Mackenzie arch, suggesting that the global signal was overwhelmed by negative local (diagenetic?) values in an isolated, deep water mass adjacent to the arch. The contact between the Mount Cap and Saline River formations is a regional disconformity and cannot be evaluated meaningfully owing to a dearth of isotopic data. The Saline River Formation exhibits carbon isotope values that gradually rise from -4‰ to 0‰ at the (conformable) contact with the Franklin Mountain Formation.

Study of glacial flows and associated sediments: The case of Amaruq, Nunavut

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The Amaruq project is located in Nunavut 60 km northwest of the currently operating Meadowbank gold mine. This region has a significant mineral potential but the basement rock is largely covered by till, thus furthering our understanding of glacial dispersal processes is essential for efficient exploration in the area. This study is on the understanding of the ice-flow history and surficial geology mapping of the Quaternary deposits at the regional (1: 50,000) and detailed (1: 10,000) scales, both centered on the gold deposits at Amaruq. The study area is located about 100 km northwest of the last position of the Keewatin Ice Divide.

During the last glaciation, the Laurentide Ice Sheet covered the study area until the ice disappeared 6 000-7000 ^{14}C years ago. As a result, the area is extensively covered by various types of glacial deposits. The predominant surficial deposits are bouldery sandy till veneers, commonly forming small ridges perpendicular to ice flow, thick silty till blankets in streamlined landforms or plains, and five glaciofluvial systems containing eskers, hummocks, diamictons, kames and outwash plains. The thick silty till blankets appear to cover the sandy till veneers.

Previous reconnaissance-scale mapping indicates a main north-northwest regional ice-flow direction. In the study area, four sets of ice-flow directions were recognized based on the detailed mapping of striations, grooves and roches moutonnées. The oldest, oriented towards the NNW (N345°), is the dominant direction and is responsible for most of the glacial moulding of the landforms. The second and third ones are oriented respectively at N325° and N308° and did not have a significant influence on the landform orientation. The fourth ice-flow set is found locally along glaciofluvial systems and indicates late ice flows towards esker ridges.

A preliminary pebble count was done by ODM Ltd on 10-kg till samples collected from frost boils. The results show that the sandy till veneers material has a major local component derived from the underlying bedrock. The bouldery sandy till veneer shows a sharp change in pebble composition across the underlying lithological boundaries. The lithological package hosting the Amaruq mineralized zones is dominated by ultramafic to intermediate volcanic and sedimentary rocks, whereas the dominant lithologies up-ice and down-ice of mineralization are essentially of granitic composition. The pebbles of the thick silty till blankets over and down-ice of the mineralized zones are granite-dominated even if the lithologies beneath are of volcanic and sedimentary origins.

A newly identified P-T-t-d discontinuity along the Main Central Thrust, western Nepal Himalaya

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The India-Asia collision initiated Himalayan prograde metamorphism as early as 48 Ma and movement on a major shear zone, the Main Central Thrust (MCT), around 25 Ma. The MCT juxtaposes the Himalayan metamorphic core in the hanging wall over low metamorphic grade foreland rocks in the footwall. Broad open folds of the Karnali klippe in western Nepal expose the hanging wall of the MCT multiple times in the transport-parallel (southward) transport direction. To test whether the timing of deformation and pressure-temperature (P-T) conditions are consistent with a foreland-propagating thrust system, samples were collected in the hinterland exposure, and toward the foreland on both the north and south flanks of the klippe. Within the MCT zone, structurally higher samples contain Ky + Grt + Pl + Bt + Ms + Qz +/- St while structurally lower samples, toward the base of the shear zone, contain Grt + Pl + Bt + Ms + Qz +/- Ilm. Phase equilibria modelling are used to determine the pressure-temperature paths of these rocks. Rocks at comparable structural levels from the north flank of the klippe show higher peak pressure and temperature conditions (700C, 1.1-1.2 GPa) than those in the hinterland (650C, 0.9-1.0 GPa). SHRIMP U/Pb geochronology and in situ U-Th/Pb petrochronology on monazite in the hinterland record deformation at 18 Ma, with melt crystallization beginning at ~14 Ma and ongoing until ~8 Ma. Rocks on the north flank of the klippe record deformation as early as 47 Ma and lasting until 18 Ma, punctuated by melt crystallization at ~30 Ma. $^{40}Ar/^{39}Ar$ thermochronology on white mica indicate cooling of (1) the south flank of the klippe by 17 Ma, (2) the north flank of the klippe by 12-14 Ma and (3) the northern hinterland by 7 Ma. Despite apparent structural continuity along the studied exposures of the shear zone, the hinterland and the foreland record disparate P-T-time-deformation paths. Deformation on the Main Central Thrust is generally thought to have progressed, in sequence, from north to south, hinterland to foreland. However, we demonstrate that the shear zone in the hinterland was undergoing melting and high T deformation at 8 Ma while in the klippe the shear zone had cooled below 425 C by 12 Ma. This discontinuity between the hinterland and the foreland requires that out-of-sequence deformation occurred in the hinterland as recently as 8 Ma.

The 3D Geological Framework of Alberta: Using geomodelling to enhance and disseminate geological understanding

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The Alberta Geological Survey (AGS) is developing a "Geological Framework" for the province of Alberta (602,825 km^2). The Geological Framework provides a consistent and reliable three-dimensional (3D) representation of our current geological understanding to facilitate the integration and communication of interdisciplinary data. The Geological Framework includes a provincial-scale 3D geocellular model that represents our current regional understanding of Alberta's geology. This 3D provincial model of Alberta is a platform, capable of integrating a variety of data types from multiple sources, enabling the development of multi-scale, interdisciplinary models. This model is updated with sub-models or additional stratigraphic intervals and therefore, evolves over time, as our knowledge and understanding of the subsurface develops. High-resolution sub-models and 3D property models are being developed in strategic locations to enhance the geological characterization of the stratigraphic units within the Geological Framework.

Three-dimensional geological models are becoming increasingly useful for integrating and communicating complex geological concepts amongst multi-disciplinary teams and to support science-based decision making. The AGS produces geomodels to characterize Alberta's subsurface geology at a variety of scales to support the Alberta Energy Regulator, the Government of Alberta, or public interest. We are also investigating innovative methods (e.g. Minecraft) to disseminate the Geological Framework to a wider spectrum of stakeholders allowing them to engage and interact with our surface and subsurface data and information. Geoscientists, geostatiticians and geomodellers are essential to the development of the Geological Framework and their iterative contributions create a truly multi-disciplinary and collaborative approach to geomodelling. This approach ensures our 3D models accurately characterize the complex geology of Alberta and disclose geomodel limitations and uncertainty. We will discuss how all the modelling we do, irrespective of level of detail, is incorporated back into the provincial-scale model thereby, continuously improving the Geological Framework.

The continual improvement and maintenance of the 3D provincial model allows us to have a subsurface foundation that can integrate any geospatially referenced subsurface and surface data. This allows the Geological Framework to be used as an integrated surface and subsurface management tool. Our goal is to make the Geological Framework available in multiple dissemination formats, which will allow the AGS to communicate complex subsurface information to users and stakeholders with various levels of background knowledge.

Canada-3D: Toward national surface and subsurface compilations of the geology of Canada

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Canada has a long history of national geological compilations. Current versions include two-dimensional (2D) surface bedrock and surficial geological maps that were compiled over 20 years ago. Advancements in information technology and geological modelling enable the adoption of new approaches, and the development of new products, for a next generation view of the geology of Canada. To achieve this, the Canada-3D project comprises a national collaboration between federal, provincial, and territorial geological surveys operating under the auspices of the National Geological Surveys Committee. Expected results are new compilations for Canada, including new 2D surficial and bedrock geology maps, as well as an inaugural three-dimensional (3D) geological model. Also being developed are new 3D modeling methods, standards, and a public web portal for using and downloading the compilations. Project principles include a commitment to open and free products as well as standards, and the variable resolution and the timely ongoing integration of sources to ensure the products are authoritative and reflect the best knowledge available.

During the past two years a pilot project has generated results that include advancements toward new geology maps for the Canadian North, inaugural national 3D surfaces for depth-to-bedrock, the Phanerozoic/Precambrian boundary, the MOHO boundary, as well as advances in 3D visualization. These early results also highlight ongoing issues in (1) technology, related to the handling and viewing of massive data volumes, (2) data sources, related to gaps in geographical coverage of existing geological maps, models, and related data, and (3) limits to 3D modeling methods related to the incorporation of unconventional data, regional interpolation, and related uncertainties. Reported will be a summary of the results as well as lessons learned. Expected beneficiaries of Canada-3D are all users of geoscience information and knowledge, including industry, other federal and provincial government departments, educational institutions and non-governmental organizations.

Impact tsunami deposits of the ancient sedimentary record: Depositional regime recovery in a post-impact scenario

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Preserved ancient marine impact deposits are rarely identified in the sedimentary record. In an epicontinental paleobasin of central Australia, post-impact sediments from the Tookoonooka impact are well-preserved in the subsurface, and include crater resurge and impact tsunami deposits. The strata are lower Cretaceous in age. Impact ejecta scattered throughout the tsunami and resurge deposits include accretionary impactoclasts, altered melt clasts, basement fragments and shock metamorphosed quartz fragments. Multiple diagenetic episodes evident in the sediments were due in part to burial in the evolving marine environment and protracted impact hydrothermal conditions.
The impact deposits are host to characteristics not generally observed - in combination – in energetically 'normal' Earth depositional processes: highly sediment-saturated flow, high flow regime bedforms, bi-directional flow with sudden shifts in clast composition, rapid deposition, very thick beds, and rapidly shifting flow energies are indicated. Clast size observations are constrained by core widths, though boulder-sized clasts were discerned in core, and contrast with the pre-impact fine-medium grained sand deposition that appears to have been consistent for millions of years. The pre-impact depositional environment was persistently low-energy, low sedimentation rate, higher latitude and regionally extensive. Buried strata in the basin record both the marine impact depositional processes as well as the waning of the impact event. Strata overlying the interpreted resurge and tsunami deposits - representing the immediate aftermath of the impact – contain sediments that appear to recover relatively quickly to their pre-impact depositional regime: low energy, little reworking, and an eventual return of intense bioturbation. These are in turn buried by transgressive marine shales. Considerations affecting 'recovering' sedimentation in the post-impact basin include the new sediment source of the uplifted crater rim and the availability of large volumes of coarse debris such as melt clasts.

It is concluded that based on the Tookoonooka example, many units in the stratigraphic record deserve re-examination, as the cratering rate suggests that the occurrence of marine impacts should be much higher than the small numbers discovered in recent decades. Tookoonooka is a well-preserved example of the complex – and as yet poorly understood - processes at play following marine impacts in a shallow marine basin.

Textural and chemical characteristics of oxide minerals as a record of postmagmatic processes in the Eastern Gabbro, Coldwell Complex, NW Ontario

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Magnetite is a minor to major mineral in the mafic and ultramafic rocks of the Eastern Gabbro (EG). The EG is a complicated suite of crosscutting sills and dykes that include the unmineralized metabasalt and Layered Series, and mineralized Marathon Series. Magnetite in these gabbroic series exhibit a continuum of exsolution textures from cloth to trellis types. Cloth-textured magnetite consists of a box-like network of ulvöspinel (<1µm wide) ± thick trellis lamellae of ilmenite (5-20 µm wide) ± bladed spinel (1-5 µm wide), all hosted by magnetite. Trellis-textured magnetite consists of fine (1-5 µm wide) and coarse trellis lamellae, and always contain spinel hosted by magnetite and ilmenite lamellae.

Experimental evidence indicates that ilmenite cannot exsolve from magnetite, but must form by oxidation of ulvöspinel resulting from fluid-mineral interaction. The coexistence of these different textural varieties of magnetite throughout the EG, as well as within a given sample and even within a single crystal of magnetite is consistent with subsolidus, fluid-induced oxidation. The formation of trellis-textured magnetite by interaction of cloth-textured magnetite with Cu-rich fluids is suggested by the occurrence of trellis-like intergrowths radiating outwards from Cu-bearing fractures in cloth-textured magnetite and the intense alteration observed in many of the host rocks.

Only Ge, W, Mo, Sn, and Cu show differences in concentration between cloth- and trellis-textured magnetite on the sample scale. These elements are enriched in trellis-textured magnetite relative to cloth-textured magnetite. The enrichment is typically in the range of single-digit ppm. Their enrichment in trellis-textured magnetite, then, can be explained by the reaction of the magnetite-ulvöspinel assemblage with an oxidized fluid, in which Ge, W, Mo, Sn, and Cu were abundant, to form the magnetite-ilmenite assemblage. This suggests that within a given gabbroic series, the different magnetite types represent initial crystallization of the same high-temperature magnetite-ulvöspinel solid solution, and the different textures and trace element chemistry developed as a result of varying degrees of fluid-induced oxidation. This is also consistent with the similarity in their bulk major element composition.

These results suggest that the suite of rocks making up the EG crystallized under relatively reducing conditions capable of stabilizing ulvöspinel. These conditions were later modified by the flux of Cu-rich, oxidizing fluids, which oxidized and transformed cloth-textured magnetite-ulvöspinel assemblages to trellis-textured magnetite-ilmenite assemblages.

Giant circumferential dyke swarms: An underappreciated component of the plumbing system of Large Igneous Provinces

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Giant radiating dyke swarms are well documented as a key component of the plumbing system of Large igneous Provinces (LIPs), which have often been linked to mantle plumes and continental breakup. Magma in these dykes flows vertically in the plume centre region and then laterally outward for distances up to 2500 km from the focal point of the swarm. Through its entire length the radiating dyke swarm can feed voluminous sills, layered intrusions and flood basalts. Here we discuss another category of giant dyke swarm, termed giant circumferential dyke swarms, which has recently been recognized in association with LIPs, but has yet to be studied in detail. Giant circumferential swarms have a quasi-circular or quasi-elliptical geometry with a maximum diameter typically between 600 and 1800 km. In some instances, they are observed to circumscribe the focus of a roughly coeval giant radiating swarm. In other cases, they do not appear to have an associated radiating swarm. They may be analogues of the large quasi-circular or quasi-elliptical graben-fissure systems of coronae on Venus, which have been interpreted to be underlain by dykes, and which sometimes occur in association with giant radiating graben-fissure systems (also underlain by dykes) and flood basalts. Here we examine the giant circumferential swarms associated with the ca. 125-80 Ma High Arctic LIP, the ca. 130 Ma Parana-Etendeka LIP of South America and Africa, the ca. 250 Ma Siberian Trap LIP of Asia and the ca. 1380 Ma Kunene-Kibaran LIP of Africa, as well as possible segments of circumferential swarms associated with the ca. 60-55 Ma North Atlantic LIP, the ca. 65 Ma Deccan LIP of India and the ca. 1780 Ma Xiong'er-Taihang LIP of China. We catalogue their characteristics including geometry, diameter, width, arc length, vertical or dipping dykes, age relationship with radiating swarms, evidence for related topographic features, and association with rifting and flood basalts, and compare these characteristics with those of coronae. We assess the usefulness of the giant circumferential swarm characteristics as a guide to identifying further circumferential swarms, and in understanding their emplacement mechanism(s), possible role as feeders for flood basalts, and potential links to Ni-Cu-PGE and other types of ore deposits.

The cobalt-nickel rule, tholeiitic magma series and large impacts

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Central Manitoba is underlain by the Kisseynew Domain, a large basin structure of 250 × 300 km extent. This structure, occupying a central part of the Trans Hudson Orogen, is flanked by the Palaeoproterozoic Flin Flon- and Snow Lake volcanic belts to the south and the Lynn Lake and Leaf Rapids volcanic belts to the north. They host important VHMS type copper-zinc-gold deposits, including the large Flin Flon, Ruttan and Lalor deposits in bimodal tholeiitic volcanic rocks. Ages of hosting rocks cluster in the 1.90-1.89 Ga range. A cobalt>nickel ratio is common to all deposits, which is unusual, when considering the crustal abundances of 25 ppm for cobalt and 86 ppm for nickel.

For the Central African Copper Belt the empirical cobalt>nickel rule states that (nearly) all mines have in their copper ore more cobalt than nickel. Within the tholeiitic Skaergaard Layered Series in Greenland cobalt increases from the bottom up whereas nickel decreases upward. Near the top of the Series, nickel is depleted, the ratio being cobalt>nickel. Could a similar process have taken place in the extensive tholeiitic gabbro horizons of the Central African Copper Belt before mineralizing the sulfur-rich sediments?

Many porphyry copper deposits have in their copper concentrates a similar cobalt>nickel ratio pointing clearly to an early nickel-depleting magmatic process.
According to Bowen forsteritic olivine crystallizes at high temperature before other minerals. Forsterite will incorporate nickel for magnesium, to include 0.4-0.5 % nickel in the forsterite crystal lattice. Cumulates with this amount of nickel are common in some komatiites.

Magma of komatiitic composition is a prime candidate to become tholeiitic by nickel depletion. Does this process take place in impact melt?

An historical drill hole intercept of the Sudbury impact melt sheet shows a near perfect section of a tholeiitic melt in a 200 m segment near the transition zone between underlying norite and overlying granophyre.

I believe that in the Trans Hudson Orogen of Central Canada the Kisseynew Basin with its flanking 1.90-1.89 Ga tholeiitic volcanics and ore deposits is an example of a Palaeoproterozoic marine impact.

Three-dimensional dispersal patterns of illitic alteration pathfinders through thick multi-till stratigraphy in the Thelon Basin, Nunavut

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There are a number of regions prospective for mineral exploration that are characterized by glacial cover tens of meters thick where the application of conventional drift exploration techniques may be limited or particularly challenging. The Thelon Basin in Nunavut is one example where some areas being explored for unconformity-type uranium mineralization are covered by a succession of till units of contrasting provenance. Whether the subcropping alteration haloes surrounding deeper uranium mineralization can be detected through the nearly continuous cover of Quaternary sediments is a question of great importance for those conducting exploration in the area. The main purpose of this study is to identify in the tills the geochemical signature of subcropping alteration associated with a deep-seated basement-hosted unconformity-type uranium mineralized body, located southeast of Aberdeen Lake. Mineralization in this area is hosted at depths of over 100m, and the subcropping illitic alteration halo is covered by a multi-till sequence ranging from 12 to 34m in thickness.

Multivariate statistical analysis was carried out on both whole rock and till geochemical data from a drilling and surface sampling program. Comparison of unaltered and altered whole rock data guided the creation of 4 alteration indices that were used to amplify the signature of altered material in surface and subsurface tills. The alteration indices were constructed by dividing elements relatively enriched by alteration processes by elements that have been relatively depleted. Geochemical trends associated with the alteration are the enrichment of Fe_2O_3, K_2O, Al_2O_3, P_2O_5, TiO_2, B, Ni, U, Cr, and Sc, and depletion of CaO, MnO, Na_2O, Mo, Zn, Ba, and Sr (analysis following HF-$HClO_4$-HNO_3 digestion), and the enrichment of U and depletion of V, Zn, Y, and Yb (analysis following HNO_3-HCl digestion). Results show that the lower till units have a clear alteration signature, whereas the surface expression of the alteration footprint is greatly diluted by the youngest surficial till; however it is still detectable. The analysis also discriminated the tills based on their overall matrix geochemistry, yielding groups that are consistent with the stratigraphy established using other methods (e.g. facies and pebble lithology). This study highlights the need for a detailed understanding of both the geochemical signatures being sought and the glacial history of the area being examined.

Relative timing of sediment failures within slide-valley complexes in the Kugmallit Fan area of the central Beaufort Slope

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Hydrocarbon related activities on the Beaufort Slope raises concerns about slope geohazards. Ubiquitous seabed and shallow sub-surface sediment slide complexes have been identified on the Beaufort Slope, from multibeam bathymetry and high-resolution sub-bottom sonar data collected mainly in 2009 and 2010. Multiple shallowly-buried failures indicate a long-term history of periodic failure.

Two geologically recent, large, multiple-event failure complexes have been identified; the Ikit and Kugmallit slide-valley complexes. Neither have appreciable overlying sediment despite continuous Holocene deposition recognized from sonar profiles in nearby parent sediment. The Ikit complex is about 24 km wide, along the shelf break and about 54 km downslope, with undefined total run-out, covering over 1900 km^2. The Kugmallit complex is narrower at 14 km wide and 68 km long, with undefined total run-out, covering 1550 km^2.

Some failure scarps exceed 100 m relief and evacuated volumes exceed 100 cubic km, placing these amongst Canada's largest surficial failures. Stratified Holocene and largely glacigenic blankets, tens to over 100 m thick including presumably LGM material, have been removed in the deepest valleys. Failures span the entire post-glacial sediment sequence, but an underpinning buried interval appears more prone to collapse.

Large and numerous retrogressive failure types are identified within the slide valley complexes. Blocky to disintegrated rotational slumps have been identified and occur near the top of the valleys. Numerous and thick (10s to 50m) debris flows have been identified with cross-cutting lobes and tongues which have runouts from 100s of m to 100 km. Relative timing of as many as five failure events is recognized, based on cross-cutting relationships. Maximum failure event age is constrained locally by recognition of translated parent blocks as young as 1300 years BP cal. in shallow cores. Minimum ages are pending from Pb 210 age dating of 8 to 25cm thick post-slide mud in push cores.

Removal of confining sediments presents opportunity for continued retrogressive failure. Failure-prone unit behavior suggests sediment preconditioning in the subsurface. The state of in-situ or introduced excess pore pressures in the region is not known. Proximity to an earthquake cluster suggests a trigger mechanism for episodic and widespread failure, but temporal and causal relationships are not yet established.

Regional glacial history, paleo-dynamics and dispersal patterns, South Rae craton, Northwest Territories

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The southern Rae area in southeast Northwest Territories lies within one of the most poorly mapped and least understood regions of the Keewatin Sector of the Laurentide Ice Sheet (LIS). This region is heavily covered by glacial sediments, which impede both bedrock mapping and mineral exploration. To fill in this geoscience knowledge gap, recent regional-scale (1:250 000) mapping and till sampling in four NTS map sheets (75A, B, G and H) have been undertaken.

The glacial landscape records a complex history of changing glacial flow dynamics and subglacial conditions during deglaciation, as reflected by superimposed landforms, juxtaposed streamlined terrain (fast flow) and non-streamlined terrain (sticky spots/sluggish flow) and a network of WSW to SW trending subglacial meltwater corridors. Sediment/landform associations reflect variations in sediment transport/deposition processes and history.

Field-based measurements of erosional ice-flow indicators (e.g. striations, roches moutonnées) and imagery mapping of streamlined landforms record at least four regional flow sets. The oldest flow is recorded at a few sites as striations with unknown sense (SSE/NNW). Well-defined indicators reveal a clockwise rotation in regional ice-flow directions during Late Wisconsin glacial/deglacial events, shifting from southward to southwestward flow. A late westward flow is recorded in the north half of the study area. The prevailing regional ice-flow direction is to the southwest.

Till composition data (clast lithology, indicator minerals, matrix geochemistry and texture) combined with ice-flow indicators are examined to establish sediment dispersal patterns as well as the varying degrees of till inheritance/ hybridization. Preliminary results indicate that at the regional scale, till composition predominantly reflects the underlying bedrock domains with sharp changes in lithological and geochemical constituents across domain boundaries. Distinctive erratics and exotic clast lithologies in the till are used as tracers for glacial dispersal patterns and compositional inheritance. Clasts, such as Dubawnt Supergroup lithologies, derived from sources located to the north-northeast of the study area, indicate sustained transport of glacial debris by the older southward flow.

This research will provide much needed input for the paleoglaciological reconstruction of the Keewatin Sector of the LIS, and a Quaternary geological framework for mineral exploration and land resource management in the southwest region of the Rae geological province.

U-Pb geochronology of detrital zircons from the Mazinaw and Bancroft domains, Composite Arc belt, Grenville Province, Ontario

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Although a wealth of geochronologic information exists for the Composite Arc Belt (CAB), the depositional age and provenance of clastic metasedimentary rocks is largely unknown, with a few exceptions. To address this gap, using single-grain U-Pb geochronology on detrital zircons, we examined two samples from the Mazinaw domain to further unravel the history of the Flinton Group and one sample from western Bancroft domain where only limited U-Pb geochronology exists. These age data are compared with published detrital zircon data to constrain correlations and provenance of clastic formations, and terrane linkages within the CAB.

Of 15 zircons analyzed from 2 quartzite cobbles from the Bishop Corners Formation (Flinton Group) metaconglomerate at the Ore Chimney Mine: half the ages are Mesoproterozoic (1187-1463 Ma), half are Paleoproterozoic (1660-1981 Ma) and one is Neoarchean (2708 Ma). Younger zircons (<1660 Ma) are generally euhedral whereas older ones are rounded. The cobbles have a zircon population similar to that reported for the underlying quartzite, but they apparently lack the youngest (1157 to 1134 Ma) zircons found in the quartzite.

Quartzite of the Ompah Formation, Flinton Group, has an apparently restricted zircon population dominated by 1201 to 1186 Ma grains. The oldest crystal is 1253 ± 10 Ma. This restricted population indicates that Ompah Formation sediments were not the source of quartzite cobbles in the metaconglomerate at the Ore Chimney Mine, and that the two samples have different sources although they apparently have the same depositional age. The likely source region for the Ompah Formation is to the west (rocks now in Quebec) or south, from exhumed rocks of the Frontenac-Adirondack Belt.

Quartzite near Crystal Lake in Bancroft domain has a detrital zircon population dominated by 1910 to 1871 Ma ages. The oldest grain is 2626 ± 1 Ma. The likely source region is the pre-Grenvillian Laurentian margin. The maximum depositional age of this rock is uncertain, but the data suggest that some metasedimentary rocks in Bancroft domain may be older than those in the CAB and have populations distinct from the Flinton Group. Quartzites in eastern Bancroft domain, between Palmer Rapids and Renfrew, have either yielded detrital zircon populations dominated by Grenvillian zircons (1224 ± 10 Ma, 74 grains) or have yielded metamorphic ages only (circa 1044 Ma based on monazite and zircon). Comparison with the Crystal Lake sample indicates that sandstone deposition may have occurred more than once in Bancroft domain.

What can exhumed blueschist and eclogite blocks tell us about P-T and stress conditions along the subducting plate interface?

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Subduction zones provide us with an opportunity to study the geologic and seismic processes that occur at depth. Previous and current studies have used seismic data to analyze subduction zone earthquakes, however, the stress conditions at depth cannot be directly observed, so they are poorly understood. Blueschist and eclogite form from mafic rock at depths of >30 km in the subduction zone, and when exhumed, have been used to study the record of the pressure and temperature conditions at these depths. I will be studying the structural and metamorphic conditions of high grade blocks in the Franciscan Complex with the intention of tying temperature, pressure and time conditions to a location at depth along the plate interface. These blocks have been well-characterized in metamorphic studies, but since they occur in mélange terranes and can't be oriented with respect to the Mesozoic plate boundary, past researchers have not made use of structural information. I am developing a novel mapping method using a unique internal reference frame for each individual boulder to reveal 3-D rotations in the strain ellipse within each reference frame. We build 3D models from 100s of field photos using AGIsoft Photoscan Pro software. I use georeferenced orthophotos projected from the 3D model to create a unique reference frame for each of the boulders to document the structural fabrics. Relative changes in the orientation of deformation, and transitions between pure and simple shear, correspond to changes in metamorphic assemblage. These metamorphic-deformational events identified from detailed field mapping and thin section petrography may correspond to important events in the 'biography' of the high grade blocks, such as detachment from the downgoing slab. If we are able to successfully study these samples with our new approach, it will create opportunities to obtain structural data and information from high-P metamorphic rocks from mélanges which have been previously ignored.

3D geologic and hydrogeologic modelling of the Paleozoic bedrock of southern Ontario

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This multiyear initiative will produce the first 3D model of the Paleozoic bedrock for all southern Ontario west of Frontenac Arch. Derivative outcomes include: 1) a revised lithostratigraphic chart; 2) a revised regional bedrock topography surface, including Lake Ontario; 3) QA/QC improvements in formation contacts recorded in the Ontario petroleum well database; 4) revised formation subcrop boundaries and; 5) a model of the regional occurrence of groundwater in bedrock, focussing on potable groundwater within shallow bedrock.

Preliminary 3D geologic models have been developed using Leapfrog™ Hydro implicit modelling software based principally on digital data for approximately 300,000 formation contacts from 26,700 petroleum wells, recorded in Ontario's petroleum well database. The model area covers approximately 110,000 km^2, extending across southern Ontario and beneath the Great Lakes to the US border, but not Manitoulin Island. The model currently comprises 61 layers and attempts to render the bedrock topography, the Precambrian-Paleozoic contact, and the regional variability of 58 Paleozoic bedrock formations plus drift. It is a product of an ongoing, iterative process of interim modelling, model review by project geologists, and QA/QC editing of formation picks. Leapfrog™ modelling software is used to produce 3D models based upon Radial Basis Functions primarily using the formation depth picks. Leapfrog™ lends itself to iterative data QA/QC because revised data inputs can be readily reloaded without re-constructing the formation contact structure and model chronostratigraphy. With further development and improved data support, the lithostratigraphic model will be finalized to support a hydrostratigraphic model suitable for numeric modelling.

The study integrates classic outcrop/field/lab-based protocols and petroleum subsurface mapping techniques, with GIS/database queries, and digital modelling techniques. Efforts to date have focused on refining formation contacts and geographic distributions of Paleozoic formations. Project geologists have reviewed over 50,000 formation picks by examination of geophysical logs, core, and drill cuttings, and approximately 100,000 digital water well records have been reviewed. Issues resolved include: well location, formation assignment, anomalous data points, and wells with missing or incorrect formation picks. Development of the hydrostratigraphic model will incorporate data for: 35,000 water records from petroleum wells, 440,000 water well records, hydraulic conductivity measurements, karst mapping, drill core analyses, compositional analyses of produced water from petroleum wells, isotopic and compositional analyses of deep to intermediate groundwater, nearly 300 stratigraphic boreholes completed by the Ontario Geological Survey, and field observations. Additional data includes published geology, structure and isopach maps, ground surface DEM, and Great Lakes bathymetry.

Mineral recrystallization reactions and trace element availability in the metasedimentary contact aureole surrounding the Dublin Gulch reduced intrusion-related gold system (RIRGS); implications for metal sources for RIRGS hosted in the Selwyn Basin

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Abundant evidence exists that precious (Au, Ag), semi- (As, Te, Sb, Bi) and base metals (Mo, Cu, Zn, Pb) are mobile in metasedimentary rocks during prograde metamorphism related to orogenesis. Metamorphic mineral reactions control which elements are available to be mobilized (e.g., pyrite to pyrrhotite: Au, As, Ag, Bi, Sb, Te, Mo, Cu, Zn and Pb; rutile to titanite or ilmenite: W; chlorite to biotite: Zn). Trace elements released by this process are the source of metals in turbidite-hosted orogenic gold systems (i.e., Au, As, Ag, Bi, Sb, Te, Mo, Cu, Zn, Pb and W). The same elemental enrichments are observed in reduced intrusion-related gold systems (RIRGS), particularly those hosted in metasedimentary rocks of the Selwyn basin, northwestern Canada. In contact metamorphosed metasedimentary rocks surrounding these mineralizing systems, the same mineral recrystallization reactions occur. However, no assessment has previously been attempted to determine whether mineral recrystallization reactions in contact aureoles make the same suite of elements available to be mobilized from the rock-pile, and thus could represent an important metals source for these systems.

In this study, we assess the availability of elements from mineral recrystallization reactions occurring in contact metamorphosed metasedimentary rocks of the Yusezyu Formation which surround the Dublin Gulch RIRGS (3.6 Moz at 0.63 g/t Au). Regional Yusezyu Formation rocks that have not experienced contact metamorphism are used to characterize the original mineral compositions. In the regional Yusezyu Formation samples, Au, As, Ag, Bi, Sb, Te, Mo, Cu and Pb are predominantly hosted in pyrite, whilst W and Zn are predominantly hosted in rutile and chlorite, respectively. In the contact metamorphosed samples, pyrrhotite and chalcopyrite form after pyrite, whilst ilmenite and biotite form after rutile and chlorite, respectively. These mineral phases all contain significantly lower concentrations of metals compared to the minerals from which they formed from (except Cu, Ag, Zn and Cd in chalcopyrite, and Zn in ilmenite). No other important host minerals where observed for these elements. Results of this study suggest that metals enriched in RIRGS are available to be mobilized from the surrounding metasedimentary rocks through mineral recrystallization reactions in contact aureoles (except Cu and Ag, which are likely retained). Since these mineral recrystallization reactions occur concurrent with the formation of RIRGS they may represent a metal source not previously considered.

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Keynote (40 min): Wyoming-Superior Neoarchean to Paleoproterozoic sojourns

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Direct U-Pb dating of deformation coupled to paleomagnetic data from Archean and Proterozoic dyke swarms has established that southern Wyoming and southern Superior cratons sutured ca. 2.65 Ga along the Oregon Trail structural belt (OTSB) in central Wyoming and remained connected until ca. 2.1 Ga rifting. Wyoming was likely part of a much larger, high-μ craton, and this collision was a key step in formation of the supercraton Superia-Vaalbara. Superia-Vaalbara migrated to the equator by 2.45 Ga, and was intruded by a series of LIPs, which contributed to several Paleoproterozoic glaciations and oscillations in the atmospheric redox state at the early stage of the Great Oxidation Event between 2.43 and 2.24 Ga. In this reconstruction, the Huronian Supergroup, deposited along the southern margin of the Superior craton, and the Snowy Pass Supergroup, deposited along the southeastern margin of the Wyoming craton, were conjugate and coeval. Breakup of Superia-Vaalbara involved multiple rifts from 2.3 to 2.0 Ga and possibly the first separation of the high-μ cratons: Pilbara, Kaapvaal, Wyoming, Hearne, and Kola-Karelia. Rifting of Wyoming and Superior occurred ~100 km south of the OTSB suture, leaving the Southern Accreted terrane (SAT) attached to the Wyoming craton. The SAT has geological, geophysical and isotopic affinity with the Superior craton. By 1.90 Ga, Wyoming and Superior cratons were ~60° apart in longitude at mid-latitudes on the basis of the simplest drift paths and data from the Sourdough dike swarm. The Wyoming craton joined Laurentia by reconnecting with the Superior craton along the Wyoming craton's eastern margin ca. 1.72 Ga based on tectonic histories of the Hartville Uplift, in SE Wyoming and Black Hills, in South Dakota.

An Eifelian-Givetian (Devonian) drowning event followed by black-shale deposition in the Mackenzie Corridor (N.W.T.): Multi-proxy characterization

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The Givetian-Frasnian Horn River Group (HRG), along with its basal Bluefish Member, represents a significant economic unit within the Mackenzie Valley of the Northwest Territories. It sharply overlies the carbonates of the Middle Devonian Hume Formation, where the Bluefish Member forms a 10 to 25 m thick black bituminous shale at the base of the Hare Indian Formation. The Bluefish Member also contains local argillaceous limestones at the base, and thin (0.1-10mm) limestone laminae composed of dacryoconarid tentaculitids occur throughout with greater abundance in the lower half. The upper half contains abundant organic walled acritarchs. As a whole, the Horn River Group has excellent source rock potential based on TOC with thermal maturity mostly occurring in gas window. Within the Bluefish, mean TOC ranges between 1.50-7.97wt.% based on 42 wells and surface sections.

The change from the carbonate ramp system of the Hume Formation to anoxic marine deposits of the Bluefish Member can be identified through multi-proxy analysis. Molybdenum, copper, and nickel normalized to TOC show patterns that suggest an abrupt change from a relatively restricted basin during deposition of the Hume Formation, to a sudden increase in nutrient flux within the Bluefish Member. The HRG and Hume boundary also represents a change from highly oxic waters to euxinic conditions, shown by excess Mo and V. Three geochemical packages are recognized within the Bluefish Member: highly anoxic/euxinic conditions at the base, sharply overlain by more oxygenated conditions, overlain by another anoxic event. These packages can be correlated to gamma ray logs, showing similar cyclic behaviors. Combining this data with TOC/P, where ratios also increase from the Hume Formation to Bluefish Member, suggests either a drop in oxygen level in surface waters (unlikely), or an overall deepening where oxygen is not circulated to depth. The deepening event interpretation may be associated with the global Kaèak episode, pending conodont biostratigraphic constraints. Because three distinct packages are seen within gamma logs, geochemical data, and measured core and outcrop sections, a new subdivision of the Bluefish Member is proposed.

This work is a contribution to the Devonian stratigraphic framework study of the Mackenzie Project of GEM (Geomapping for Energy and Minerals) Program.

Two gold mineralisation events east of Matheson, Ontario

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The Porcupine-Destor deformation zone (PDDZ) is one of two major gold-bearing deformation corridors in the southern Archean Abitibi greenstone belt. Several gold deposits are spatially associated with the PDDZ, including the Black Fox, Grey Fox and Hislop deposits near Matheson in Ontario. These deposits are located within or south of the PDDZ, and they are hosted by mafic and ultramafic metavolcanic rocks of the Tisdale assemblage (2710-2704 Ma) and sandstone and conglomerate of the Timiskaming assemblage (2677-2670 Ma). The deformation history of the area began with tilting and steepening of the Tisdale assemblage during a D_1 deformation event prior to the deposition of the Timiskaming assemblage. The PDDZ formed during a D_2 deformation event as the regional strain and south-over-north shearing became localized along the mafic and ultramafic rock of the Tisdale assemblage, resulting in a strong penetrative fabric (S_2) with a down-dip stretching lineation (L_2). Continued south-over-north shearing during the same deformation event produced tight to isoclinal drag folds (F_3) with axial-planar cleavage (S_3), and localized narrow shear zones. The PDDZ was later reactivated as a dextral shear zone during a late D_4 deformation event, which resulted in the formation of open to tight, Z-shaped, NE-striking F_4 folds with an axial-planar (S_4) cleavage.

The deposits represent distinct types of quartz-gold vein systems. The Grey Fox and Hislop deposits are located south of PDDZ and consist of gold-bearing quartz-carbonate veins with crustiform texture, hosted within weakly deformed Tisdale metavolcanic rocks and Timiskaming sandstone. These veins are deformed along the PDDZ, suggesting that this early quartz-gold vein system formed prior to the development of the PDDZ. The Black Fox deposit formed during shearing along the PDDZ. It consists of fault-fill and extensional quartz-carbonate veins that were folded by F_3 drag folds and boudinaged parallel to S_2 and S_3. The Black Fox, Grey Fox and Hislop deposits are excellent examples of two distinct but spatially associated styles of gold mineralisation. Vein textures at the Grey Fox and Hislop deposits suggest that the deposits formed at shallow crustal level, were buried, and a new ore system, the Black Fox deposit, formed at mid-crustal during shearing along the PDDZ.

Multielement geochemical anomalies of till related to porphyry Cu deposits in southcentral British Columbia, Canada

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The Bonaparte Lake area in south central British Columbia is less than 50 km from the Highland Valley Copper, Gibraltar, and Mount Polley, and Woodjam deposits. The area also contains several showings of Au, Cu, Mo, Ag, Zn, Pb, Ni, Cr deposits. The study area is underlain by Mesozoic rocks of Quesnel Terrane including Nicola volcanic rocks and granitic intrusions. Two phases of ice flow occurred in the Bonaparte Lake area during the last glaciation. A first phase during ice advance towards the west to southwest and a second phase generally to the south which occurred at glacial maximum. Nearly continuous cover of thick glacial sediments pose difficulty to mineral exploration in the area. Principal component analysis (PCA) is conducted to the data of aqua regia leach of clay fractions (< 2 μm) of till to assess the elemental assemblages related to the porphyry-type mineralization and evaluate the mineral potential of the area. The PCA captures two element association with Cu; Cu-Au-Mo-Ag-As-Hg-Pb-Sb, accounting for 32.3% of the total Cu variance) in PC2, and Cu-Cr-V-As (accounting for 16.8% of the total Cu variance) in PC3. The interpolation maps and hot spot analysis (Getis-Ord Gi*) of PC2 and PC3 show that multielement anomalies occur close to buried granitic rocks. PC2 mapping also indicates that there is a potential for porphyry Cu mineralization in the areas close to the Raft Batholith and Thuya Batholith, located in northeast and central part of the study area. This study shows that the multivariate analysis is able to capture the elements associated with Cu mineralization in glacial sediments and delineate potential prospective areas.

Multivariate statistical identification of sandstones affected by uraniferous hydrothermal activity, Athabasca Basin, Canada

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Many unconformity-type U deposits in the Athabasca Basin occur along the unconformity between sandstones and the crystalline basement. Principal component analysis (PCA) of the lithogeochemistry of sandstones (n = 6305) from the Denison Mines' Wheeler River property shows that U is positively associated with Y+Cu+Zn+Na+W+Co+Ni+B+Mg+HREEs+Cr+Sc+Mo+V+LREEs due to hydrothermal alteration associated with U mineralization. In contrast, PCA of the regional sandstones (n = 2175) in the Athabasca Basin shows that U is positively associated with Th+Ti+Zr+Hf. This elemental assemblage suggests that detrital heavy minerals are the main hosts of U. Additional PCA was conducted to the subset of elements associated with U. Analysis of variance was used to determine 8 PCs that have good discriminating ability. Random Forest Classification (RFC) of the 8 PCs shows three groups of sandstones with high accuracy (94.6%) of discrimination; Group I (above the Phoenix ore), Group II (in the Wheeler River property excluding the sandstones above the ore) and Group III (regional background sandstones in the Basin). Several sandstones of the Wheeler River property are classified into Group I, suggesting that these samples even far (> 200 m) from the ore are cryptically altered to have similar composition as those above the ore. This study shows that PCA and RFC identify elemental assemblages associated with U and cryptically altered sandstones. The information can be useful in exploration for deeply buried U deposits elsewhere in the Athabasca Basin.

Keynote (40 min): High-resolution multilevel-monitoring systems: Key to understanding groundwater systems

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Hydrogeology is a good general term for groundwater science because it points to the importance of geology and hydrology in combination. In the quest for better understanding of groundwater systems, the importance of geology has been long recognized, although often not done well in the normal hydrogeology practice, but what needs to be done to inform the hydrologic part has lagged. There has been weakness in the integration of geology into the groundwater flow system context because of lack of recognition of what geologic information is most important to groundwater flow, travel time and water chemistry. The methods that enable most progress on this path involve use of depth-discrete, multilevel-monitoring systems (MLSs), which provide hydraulic head and water chemistry from many different levels (eg 10-30 levels) in each drill hole. This can be done at low cost per level but higher cost per monitoring location relative to a few conventional wells per location, however a cluster of a few wells generally cannot discern important features of the system. Therefore the issue should not be one of total cost per well nest if these nests are not capable of discerning parts of what is most important. The MLS technologies and understanding for their use has advanced markedly over the past decade. This talk summarizes MLS systems, provides examples of how MLS data sets inform the importance of geologic features and presents a plan for how MLSs can be used in very high resolution mode to advance understanding of the hydrogeology of the Oak Ridges Moraine beginning with a demonstration site in Clarington Municipality near Oshawa, Ontario.

Extreme compositional variation of feldspar in the Skaergaard Intrusion

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The ~56 Ma Skaergaard intrusion is one of a number of mafic layered intrusions that are related to formation of the East Greenland flood basalt province and opening of the North Atlantic Ocean. The Skaergaard intrusion, the model example for evaluating crystallization processes and Fe-enrichment in a closed-system layered intrusion, provides valuable insight into the evolution of a sub-volcanic magma reservoir to a large igneous province. A new comprehensive set of feldspar compositions from the Skaergaard intrusion, including primocrysts, symplectites, and feldspars from three types of late-crystallized melt pockets (plagioclase-quartz granophyres, orthoclase-quartz granophyres, and polycrystalline "granitic" pockets with two feldspars) is presented. Feldspars were analyzed by electronprobe microanalysis (EPMA) from the Layered Series (LS; floor cumulates) and Marginal Border Series (MBS; wall cumulates) and the results span nearly the complete range of permissible ternary feldspar compositions. Plagioclase primocrysts (An_{72-27}) record four types of zoning patterns, including (1) normal zoning in the LS and MBS, (2) unzoned crystals in the upper part of the LS and MBS, (3) rare reverse zoning, which is found only in the lower part of the LS, and (4) zoning with a mantle of decreasing An-content and a rim buffered to constant composition in the LS (Lower and Middle zones) and MBS. Plagioclase in the symplectites, which are late-stage reactive microstructures, is Ca-rich (An_{87-67}), whereas feldspar in the granophyres is distinctly Na-rich (predominantly albite-oligoclase) or K-rich (orthoclase). Interstitial polycrystalline pockets (up to 4 mm in diameter) from the Upper Zone and outermost portions of the MBS contain feldspar + quartz + apatite + pyroxenes + Fe-Ti oxides biotite rutile zircon. These highly evolved and incompatible element-enriched melt pockets contain two finely intergrown feldspars, one Na-rich and the other spanning the entire range of alkali feldspar compositions. The presence of these different Si-Na-K-rich intergrowths throughout the Skaergaard intrusion is the result of a diverse array of processes that operated at sub-liquidus to near-solidus conditions in a consolidating crystal mush (e.g., residual melt fractionation, liquid immiscibility). The EPMA results serve as a guide for trace element and lead isotope analyses of Skaergaard feldspar by laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS). These spatially controlled in situ compositions will be used to evaluate the effects of crustal assimilation and the mantle source of the Skaergaard magma with genetic links to the East Greenland flood basalts and evolution of the North Atlantic Igneous Province.

An integrated fluid inclusion and SIMS $\delta^{18}O_{quartz}$ study of a Meguma quartz vein sample reveals hidden complexities in orogenic gold settings

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Integrated fluid inclusion (FI) and O isotopic studies provide insight into the PTX conditions of ore deposit formation. When such data are combined with additional relevant information (e.g., deposit geology, mineralogy, mineral chemistry) a better understanding of ore deposit processes is possible. This study uses data from a single bedding parallel vein sample in an orogenic vein setting, the Caribou deposit in the Meguma terrane of Nova Scotia where host rocks were deformed and metamorphosed (greenschist facies) during late Devonian orogenesis. The sample was characterized using CL, microthermometry and evaporate mound analyses of FIs, and in situ SIMS for $\delta^{18}O_{quartz}$. The CL images vary from bright to dull and correspond to areas free of or inundated with FIs, respectively; all inclusions are thus considered of secondary origin. Type 1 inclusions dominate and are H_2O-CO_2 with $X(CO_2)$ ~0.03-0.15, 3-5 wt. % eq. NaCl and have $X(CH_4)$ <0.10. Type 2 inclusions are much less abundant and are three phase L-V-Halite type with salinities of 29 wt. % eq. NaCl and Th values of 150°C. Type 3 inclusions are also rare and are CO_2-rich (i.e., <5% H_2O by volume). Significantly macro-size (>100 µm) type 1 inclusions are commonly decrepitated with haloes of neonate inclusions; these inclusions are attributed to changing P_{H2O}. SEM-EDS analysis of evaporate mounds (n=260) in several quartz chips indicate three fluid types are present: 1) Na-rich with <10 wt. % SCa+K; 2) Na-K with 10 to 40 wt. % K and >5 wt. % Ca; and 3) a Na-Ca with 10-60 wt. % Ca and <10 wt. % K. Whereas type 1 fluid equates to the Na and Na-K mounds, type 2 fluid equates to the Na-Ca-(K) mounds. Results for 19 $\delta^{18}O_{quartz}$ analyses in one quartz chip indicate a range from 9.1 to 15.1‰ (avg. = 12.3 ± 1.7 (1σ)). As no relationship is noted for data in clear versus dull CL zones, the data are considered to reflect primary values. Whereas changing temperature and/or fluid mixing during vein formation are possible scenarios for the data, neither is considered viable based on the FI data. Instead, it is suggested that $\delta^{18}O_{H2O}$ changed due to quartz crystallizing in a closed system from a vein fluid with a $\delta^{18}O_{H2O}$ value ~15‰, as is typical of metamorphic fluids. The study shows the detailed work required to unravel the complexities of orogenic veins and reveals these systems are more complex than generally considered.

Re-examining the emplacement of the J-M Reef in the Stillwater Complex

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Layered mafic intrusions exhibit great exposures of rarely seen magmatic systems and host most of the worlds Ni, Cr and Platinum Group Element (PGE) deposits. Although the exact mechanism of formation has been debated, the concept of a layered younging upward sequence that was formed by crystal settling is widely accepted as the process by which these large mafic bodies form. The Stillwater Complex located in south-central Montana is a classic example of a layered mafic intrusion and hosts a major platinum-palladium deposit, the J-M Reef. Based on recent high precision dates of the Stillwater and Bushveld Complexes, another model has been suggested; subsequent lateral out of sequence sill emplacement into previously existing mafic cumulates. Here we present petrographic and lithogeochemical observations to test the idea that the J-M reef might be an ultramafic sill emplaced into older norites, gabbronorites, and anorthosites of the Lower Banded Series. Comparison of numerous exploration borehole logs offers inconclusive evidence for discordant upper contacts on the J-M Reef as lithological continuity is very poor, even between holes <10m apart. Dispersal of PGE mineralization outside the main olivine-bearing unit hinders correlation. AlphaMELTS modelling shows that gabbronorite cumulates leave anorthositic restite when melted to high degrees at temperatures of 1260 C. We suggest that above and below the contact anorthosite with increasing distance, less melting will occur ranging in composition up to the original gabbro wall rock. The model very closely mirrors lithogecochemical data for observed norite and anorthosite, implying it is possible that partially melted cumulate norite could generate anorthosite by injection of hot ultramafic sills. We are pursuing a variety of strategies to explore whether this model can be applied to the Stillwater Complex as has been done for other Layered Mafic Intrusions.

The Davis Strait BLIP: A retrospective reconciliation of igneous petrogenesis and plate tectonics

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Within a short time span of 1-2 my in the Paleocene, and coeval with the onset of sea-floor spreading in the Labrador Sea, massive outpourings of uniquely depleted picritic tholeiites produced the Davis Strait BLIP (Baby Large Igneous Province). Petrogenetically, the chemical characteristics of these picrites (MgO = 18-21 wt. %; K_2O = 0.01-0.20 wt. %; $^{87}Sr/^{86}Sri \approx 0.7030$; $\varepsilon Nd_i \approx +5.2\text{-}8.6$; $^3He/^4He \leq 49.5RA$) demand only derivation by partial melting of highly depleted mantle and rapid ascent to the surface, but do not necessarily require high temperatures or high degrees of partial melting. Tectonically, the Davis Strait BLIP clearly lies horizontally at the intersection of the Labrador Sea spreading axis and the Ungava Fault Zone or the Hudson Fracture Zone, and possibly also vertically with a deep mantle plume. Reconciling the unique petrogenetic constraints to produce the picrites, and the various tectonic elements to produce excess volcanism, continues to be the challenge. In broad terms, the Davis Strait BLIP appears to be a compositionally and volumetrically anomalous continuation of the Mesozoic magmatic activity in SW Greenland and Labrador. The particular geometric configuration of plates in this region (ridge-transform intersection) may have enhanced decompression melting in the depleted subcontinental lithospheric mantle. In this case, the depleted mantle source, the absence of any requirement for excess heat, and the absence of any pre-volcanic crustal uplift, appear to negate the involvement of a deep mantle plume. The Davis Strait BLIP failed to reach full LIP maturity because sea-floor spreading along the Labrador Sea - Baffin Bay axis yielded to more aggressive opening in the northeastern Atlantic Ocean.

Detrital geochronology of the Laguiche Complex in the Opinaca: Constraints on the provenance and tectonic setting of a metasedimentary subprovince of the Superior craton

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Metasedimentary subprovinces within the Superior craton occur mostly as linear belts separating volcano-plutonic subprovinces. They are important features, as stages of their development mark major tectonic events. We present detrital zircon geochronology from the Opinaca metasedimentary subprovince and the La Grande volcano-plutonic subprovince, to characterize events surrounding their formation. Five paragneiss samples from the Laguiche Complex in the Opinaca provide zircon ages from ca. 2695 Ma to 3385 Ma, including one major component peak at ca. 2715 Ma, and two minor peaks at ca. 2760 and 2835 Ma. Scant zircon ages at ca. 2950 and 3340 Ma provide evidence of older sources. Two paragneiss samples from the Rivière Salomon formation in the La Grande provide similar detrital zircon age distributions, yet no Paleoarchean ages. As the two metasedimentary units are contiguous and have statistically comparable zircon age populations, we interpret that they share a provenance. Their age distributions are consistent with a provenance in the La Grande and Minto subprovinces, although the major peak age is common throughout the Superior. This suggests the Opinaca is not an exotic accreted terrane. Basin formation is constrained to between 2696 and 2670 Ma by the thirteen youngest zircon grains (lower constraint, 2692 ± 4 Ma) and a granodiorite cross-cutting the regional foliation in the Laguiche (upper constraint, 2678 ± 8 Ma). The short time span between the youngest detrital zircon and its deposition, and the large proportion of young zircon grains in the age distributions, would be considered the signature of an active convergent margin, in the context of modern tectonic environments. However, formation of the Opinaca post-dates regional igneous activity and it cannot have formed in an active convergent margin. The tectonic environment of the Laguiche basin of the Opinaca may be unique to the Superior Province. The Laguiche contains very rare pillow basalt, volcanic and iron formation units within the margins of the basin, and recent mapping suggests it may overlie thinned orthogneiss, similar to the Rivière Salomon formation. This evidence suggests that the environment of deposition was extensional. However, unlike a modern rift environment the basins formed immediately succeeding the final stages of a massive plutonic event, thus providing the high proportion of detrital zircon ages scarcely older than the age of deposition. The subsequent rapid development of convergent tectonometamorphism is common to all of the metasedimentary subprovinces, yet may not universally be the mechanism for initial basin subsidence.

Paleozoic arcs with offset age distributions indicate successive accretion in the southern Central Asian Orogenic Belt, NW China

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The detrital zircon geochronological record of Permo-Triassic clastic rocks of the Beishan segment of the southern Central Asian Orogenic Belt indicates a pattern of cyclical, successive Paleozoic accretion events. Comparison of detrital zircon age spectra representative of two arc terranes reveals similar age patterns offset by 30-40 million years. The detrital samples with a provenance interpreted as the southern arc terrane indicate magmatic peaks at 275, 370 and 430 Ma, and include a 50 m.y. hiatus from 350-300 Ma. Samples with a provenance interpreted as the northern arc terrane exhibit a similar pattern that has consistently earlier component peaks at 310, 400 and 445 Ma with a 40 m.y. hiatus from 380-340 Ma. This illustrates that both subduction initiation and oceanic crust consumption developed successively between terranes. Subduction progressed until Silurian–Devonian sequential accretion of the arcs along separate sutures. Detrital geochronology of accreted sediments (single peak at 445 Ma) within the northern suture, with coincident tuff and pillow basalt U-Pb zircon ages (409 ± 2.9 and 416.6 ± 15.0 Ma, respectively), may redefine a principal amalgamation phase as Devonian, over previous Carboniferous–Permian interpreted ages. Initiation and cessation of arc magmatism correlates with regional phases of ophiolite generation and emplacement, respectively. This supports regional models that ophiolite belts in the Central Asian Orogenic Belt correlate with suture zones that were developed from multiple contemporaneous subduction systems between arcs. We explore whether a pericratonic archipelago of crustal slivers around the Tarim craton may have initiated successive arc formation.

Matachewan LIP revisited: A revised, high-resolution U-Pb age for the East Bull Lake intrusion and associated units

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A suite of Paleoproterozoic intrusions, collectively referred to as the East Bull Lake intrusive suite (EBLI), occur in a broadly E-W trending belt between Elliot Lake and River Valley, Ontario, near the boundary between the southernmost exposures of Archean Superior craton and the rift/passive margin sequence of the Huronian Supergroup (Southern Province). Many workers consider that the EBLI suite represents an early plutonic component of bimodal magmatism driven by the impingement of a mantle plume on a supercontinent precursor (Superia) during the earliest Paleoproterozoic – an event that led to rifting and eruption of bimodal volcanics, intrusion of mafic (Matachewan) dykes into the continental interior (failed rift system), opening of an ocean south of Superior craton and development ultimately of a south-facing passive margin sequence (younger Huronian sediments). Collectively, these magmatic components define the Matachewan Large Igneous Province (LIP). A benchmark early ID-TIMS U-Pb study by Krogh et al. (1984) using air abrasion techniques on zircon, and analyses of baddeleyite, was carried out on an olivine gabbronorite of the East Bull Lake layered intrusion, west of Sudbury. Although model $^{207}Pb/^{206}Pb$ ages for three multigrain fractions ranged from 2470.0 – 2476.0 Ma, the variably discordant data were regressed through a highly discordant point from another intrusion (Agnew intrusion) to yield a preferred upper intercept age of 2480 +10/-5 Ma. These workers also determined an age for the adjacent and likely associated Agnew (Shakespeare-Dunlop) intrusion based upon highly discordant zircon data, suggesting a precise result at 2491 ± 5 Ma. The other large EBLI body - the River Valley pluton - has yielded a U-Pb age (ID-TIMS; zircon, baddeleyite) of 2475 +2/-1 Ma (Heaman, in Easton et al., 1999). Recent high precision geochronology from other Matachewan LIP components (e.g. Matachewan dykes, Copper Cliff and Thessalon volcanics, Creighton granite) has collapsed originally broad spans in apparent ages to a much narrower range. Here, we present the first new results for the East Bull Lake intrusion, reinvestigating the original Krogh study separates, using chemical abrasion pretreatment techniques. Data for three single grain zircon fractions and one air-abraded baddeleyite fraction are concordant and yield a weighted mean $^{207}Pb/^{206}Pb$ age of 2472.2 ± 0.8 Ma (within error of the River Valley age), a robust age for igneous crystallization of this intrusion. We consequently view the previous ages for East Bull Lake and Agnew intrusions (and similar datasets) with skepticism, and urge caution in relying on their accuracy.

Geochemistry and isotopic character of Precambrian granitoid suites across the Nolan-Zemlak domain boundary, west-southwest Rae craton: Testing the possibility of a cryptic internal suture zone

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The Nolan-Zemlak domain boundary in Saskatchewan, a high-strain zone in the WSW Rae craton, has been proposed to represent a cryptic Arrowsmith-related suture marking collision between a 'proto-Rae' craton, characterized by ~2.6 Ga granitoids of the Nolan domain to the north and an older continental block underlying the Zemlak-Beaverlodge domains to the south comprising ~3.0 Ga granitoids and two distinctive early Paleoproterozoic suites (~2.5, ~2.3 Ga). A regional-scale geochemical-isotopic study aims to constrain the igneous petrogenesis of suites across this boundary and test this hypothesis. The oldest (~3.0 Ga) granitoid rocks, located within Beaverlodge domain, have arc-like geochemical signatures, TDMs older than 3.0 Ga and slightly positive εNd_t values. The Nolan domain, immediately north of the boundary, contains weakly deformed, ~2.6 Ga Bt-Hbl-bearing granite-granodiorites with arc-like characteristics, TDMs ranging from 2.89 to 2.83 Ga and slightly positive εNd_t values. The Nolan domain granitoids show a progressive southward increase in strain and are in abrupt contact, along a major mylonite zone, with a distinctive unit of highly magnetic Hbl-Bt gneissic granodiorites of the Zemlak domain, dated at 2517 ± 4 Ma. This rock type and similarly-aged quartz diorite to the east have arc-like geochemistry but are distinct from both the ~3.0 Ga and ~2.6 Ga (Nolan) granites with, low Th, TDMs from 2.96-2.86 Ga and slightly negative εNd_t values. The ~2.3 Ga granites are restricted to the Zemlak and Beaverlodge domains, and have syn- to post-collisional geochemical affinity with more highly negative εNd_t values (with TDMs of 3.06-2.87 Ga). The youngest suite of ~1.9 Ga anatectic leucogranites intrudes all older rocks and stitches the Nolan-Zemlak boundary; it yielded the most highly negative εNd_t values and TDMs of 3.31-2.84 Ga. A large body of ultramafic-mafic (pyroxenite-gabbro) entrained within mylonitic rocks along the Nolan-Zemlak boundary is relatively highly fractionated, has a TDM of 2.83 Ga and an εNd_t value of +0.3 calculated at 2.52 Ga.

In summary, the ~2.6 Ga (Nolan) and ~3.0 Ga suites show the most juvenile εNd_t values, and hence lowest degrees of crustal influence, which might be expected of terranes originally generated as independent crustal blocks. The younger ~2.5 to ~1.9 Ga granitoids show increased crustal involvement, with dramatic increases for the 2.3 Ga and ~1.9 Ga suites. This boundary separating the ~2.6 Ga and ~2.5 Ga suites may represent an Arrowsmith-age suture or, the ~2.5 Ga Zemlak may have been locally emplaced and related to more distal subduction.

Carbon isotope evolution within an Ediacaran mixed deep-marine continental slope system, Windermere Supergroup, Canadian Cordillera, British Columbia

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The 160-260 m-thick first Isaac carbonate (FIC) of the Neoproterozoic Windermere Supergroup is a mixed siliciclastic-carbonate unit in an otherwise siliciclastic dominated deep-water turbidite system in the southern Canadian Cordillera. Superbly exposed, steeply-dipping strata at the Castle Creek (CC), and Milk River (MR) study areas, separated by ~20 km, provide an excellent opportunity to analyze the long-term stratigraphic and geochemical trends in an ancient mixed deep-marine system and evaluate how fluctuations in climate, sea-level and ocean chemistry influenced siliciclastic sediment supply and the development and stability of a carbonate platform.

This study is the first to use chemostratigraphy to correlate base-of-slope strata between the two study areas. Detailed logging and mapping shows that the FIC accumulated during a long-term rise of relative sea-level represented by three areally extensive Dm-thick units of fine-grained calciturbidites with intercalated calcidebrites sourced from highstand shedding off a shallow-water carbonate platform. Superimposed on this trend are shorter-term episodes of lower relative sea-level marked by ~10-25 m-thick channel complexes filled with amalgamated, carbonate-cemented, coarse-grained sandstone and mud-rich, thin-bedded turbidites deposited on the adjacent levees. The FIC is truncated at its top by a sequence boundary and a thick succession of siliciclastic leveed-channel complexes.

Over 200 samples were collected for $\delta^{13}C_{carb}$ from carbonate rich intervals in the FIC. Primary carbonate cements were first identified in thin section and later confirmed using cathodoluminescence. $\delta^{13}C_{carb}$ is positive throughout much of the FIC (0.6-4.1‰) but shows a marked decrease (~-4‰) at the base of each calciturbidite horizon. A lowering of $\delta^{13}C_{carb}$ likely reflects increased shallow-water productivity, which in turn modified the pool of deep-water dissolved inorganic carbon (DIC). In the two lower calciturbidite units (CT1 and CT2) $\delta^{13}C_{carb}$ quickly rebounded to positive values, suggesting that the disturbance was only short-lived. In contrast, $\delta^{13}C_{carb}$ in calciturbidite 3 (CT3) remains negative for several metres above its base and then is truncated on its top by a >100 m thick siliciclastic channel complex, representing a major regression that terminated carbonate production and sedimentation. The maintenance of elevated productivity during CT3 deposition might be related to increased river-borne nutrient supply during regression, oceanographic conditions and/or bathymetry that sustained deep-water upwelling, and/or lowered rates of eustatic change that, unlike during CT1 and CT2, maintained shallow water bathymetry for longer.

Contractional deformation in Yukon Tanana terrane recorded by the Yukon River Thrust

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The pericratonic Yukon-Tanana terrane (YTT) exhibits a complex and enigmatic history of extension, arc magmatism and deformation associated with its separation and re-accretion to the western North American margin by early Mesozoic time. The Yukon River Thrust (YRT) is a ductile shear zone between pre-Late Devonian siliclastic rocks of the Snowcap assemblage of YTT and Mississippian Simpson Range suite orthogneiss; the character and timing of this shear zone heretofore represented a poorly understood episode of deformation in the Mesozoic history of YTT.

Data were determined from field observations and measurements combined with petrographic analysis on oriented thin sections cut in the XZ, XY and YZ principal planes of finite strain. In addition, fabric analysis was undertaken to acquire quartz crystallographic preferred orientation (CPO) fabrics. Field observations support a reverse sense of movement on the YRT that resulted in thrust duplexing of the Snowcap assemblage of the YTT. Kinematic information obtained from structural analysis of field measurements and quartz CPO fabrics indicate a southeast direction of thrusting of Simpson Range orthogneiss overtop of the Snowcap assemblage. Deformation is concentrated within the Snowcap assemblage, attributed to its lower rheological strength, which produced multiple strong CPO fabrics. In contrast, poly-minerallic Simpson Range samples failed to produce viable CPO fabrics. The presence of garnet, kyanite, staurolite, biotite and muscovite in Snowcap rocks and open angle thermometry based on the quartz CPO fabrics suggest the YRT was a mid-crustal shear zone with deformation occurring at 550° ± 50° C. A standard geothermal gradient of 25° C/km indicates depths of 22 ± 2 km.

Geologic relationships can provide some first order constraints on the timing of the YRT. Rocks in the hanging wall exhibit Early Jurassic to Permo-Triassic peak metamorphic ages related to crustal thickening under conditions of 7.5-9 kbar and 600-680° C corresponding to ~25-30 km depth according to a standard lithostatic gradient. Deformation recorded by the YRT may correspond to the later stages of this event as temperatures decreased towards 550° C. The presence of Late Triassic Pyroxene Mountain suite plutonic rocks in the hanging wall that are not present in the footwall suggests the YRT was active post-Late Triassic. Temperatures indicated by open angle thermometry were uniform across the YRT; the absence of a lower temperature overprint suggests deformation along the YRT may have ceased prior to mid-Jurassic uplift and exhumation as indicated by K-Ar and 40Ar/39Ar cooling ages in this area.

William E. Logan and the Geological Survey of Canada

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The Logan poster is an initiative of the Québec division of the Geological Survey of Canada (GSC-Québec). It is aimed at the general public and housed in a window display on the building, located a few steps away from the Logan fault. The poster is complemented by a Powerpoint presentation displaying historical photos from the GSC collection. Both the poster and the Powerpoint presentation present a historical perspective of the GSC in line with the 175th anniversary (1842-2017). NRCan's Communications group developed a graphic concept that combines past and present visuals in a 175th signature including the GSC anniversary banner. The text is in both French and English and the poster has been made available to other GSC locations across the country by eliminating local geographic references pertaining to Logan's fieldwork in the Québec City area. Below are some Logan facts of interest. 1) The beginnings: Logan founded the GSC on April 14, 1842 in Montréal, where it was run until 1881, before moving to Ottawa, the new national capital; 2) In search of coal: Logan began his explorations in Gaspésie and in Nova Scotia in 1843, in search of coal, which was considered an essential energy source for industrial revolution and economic growth. Despite determining that there was no coal in the area, he located and identified numerous sources of commonly used minerals of economic value. Logan directed the first studies of Precambrian rock formations in the Canadian Shield, exploring the regions of Temiskaming, Lake Superior and the Adirondacks; 3) Major discoveries: Logan was quick to recognize the great geological diversity of Eastern Canada. He also recognized the significant role played by the Logan's Fault, named after him, which extends from the west coast of Newfoundland and Labrador to Pennsylvania; 4) an accomplished naturalist: Logan showed an early interest in the emerging science of geology and was self-taught. He achieved international recognition at the 1856 Universal Exposition in Paris, and was knighted by Queen Victoria. Mount Logan, elevation 5,959 metres, in the heart of the Saint Elias Range in Yukon, is named in his honour in recognition of his outstanding achievements; 5) Geoscience of global importance: on the traces of Logan, the GSC supports the mineral and energy sectors' competitive edge, contributes to regulations, risk reduction in resource development, and reduction of financial, social and environmental repercussions produced by natural catastrophes.

The tectonometamorphic context of the north-west Opinaca, Superior Province, Eeyou Istchee Baie James

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The Opinaca subprovince, part of the Superior craton, is a major Neoarchean metasedimentary basin, composed mainly of migmatised paragneiss and granitoid intrusions. The monotonous nature of its lithologies have often led the region to be neglected and far less studied than the neighboring subprovinces. Geophysical surveys, however, show that the basin does possess a complex internal architecture. Models proposed in the literature to explain the formation and later deformation of the Opinaca all imply contrasting styles and intensity of metamorphism, strain regime, resulting structural features and, especially, a distinctive chronology of those elements.

The vast majority of the Opinaca subprovince has been affected by a late, strong migmatisation episode, obliterating most of the information that would have been recorded on its tectonic journey, with the exception of the northwestern corner of the complex which appears to have avoided anatexis. The presence of staurolite grade schists suggests that this section might have kept evidence of the earliest tectonometamorphic phases, which are key in reconstructing the geodynamic context of the subprovince. This study aims at characterizing the metamorphic and structural characteristics, as well as to the temporal relations between those elements, in order to test the competing models proposed for the area.

In the area of the study, planar structures are mostly east-west, dipping essentially towards the north and south. Mineral stretching lineation is rare and generally corresponds to the hinge of the regional folding. Seven distinct structural domains were delimited, using compilations of structural measurements of over 2000 outcrops, deformation degree interpolations, magnetic gradient maps and aerial photo analysis. Each structural domain shows different fold morphologies, varying from open to isoclinal, from concentric to conical and upright to recumbent.

Petrographic descriptions allowed the characterisation of the peak mineral assemblage, which most of the times involves plagioclase + quartz + biotite ± garnet ± cordierite ± muscovite ± sillimanite ± staurolite. Isogrades traced from index minerals highlight a garnet => staurolite => sillimanite => anataxis progression, indicating greenschist facies in the north-west to upper amphibolites facies in the south-east. The textural relationship between minerals indicate 4 phases of metamorphism, beginning with the growth of pre-kinematic minerals and followed by syn-tectonic recrystallisations of phyllosicate, by the development of higher grade porphyroblasts and by final retrogression to greenschist facies.

Preliminary results from multi-equilibrium thermobarometric calculations, using THERMOCALC software, give peak P-T conditions forming a coherent metamorphic gradient, transitional from Buchan to Barrovian gradients.

Late Miocene-Pleistocene evolution of India-Eurasia convergence partitioning between the Bhutan Himalaya and the Shillong plateau

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The Shillong plateau is a unique basement-cored uplift in the foreland of the eastern Himalaya that accommodates part of the India-Eurasia convergence since the late Miocene. It was uplifted in the late Pliocene to 1,600 metres, potentially inducing regional climatic perturbations by orographically condensing part of the Indian Summer Monsoon (ISM) precipitations along its southern flank. As such, the eastern Himalaya-Shillong plateau-ISM is suited to investigate effects of tectonics, climate and erosion in a mountain range-broken foreland system. This study focuses on a 2200 m-thick sedimentary section of the Siwalik Group strategically located in the lee of the Shillong plateau along the Dungsam Chu at the front of the eastern Bhutan Himalaya. We have performed magnetostratigraphy constrained by vitrinite reflectance and detrital apatite fission-track dating, combined with sedimentological and palynological analyses. We show that (1) the section was deposited between ~7 and 1 Ma in a marginal marine deltaic transitioning into continental environment after 5 Ma, (2) depositional environments and paleoclimate were humid with no major change during the depositional period indicating that the orographic effect of the Shillong plateau had an unexpected limited impact on the paleoclimate of the Bhutanese foothills and (3) the diminution of the flexural subsidence in the basin and/or of the detrital input from the range is attributable to a slowdown of the displacement rates along the Main Boundary Thrust in eastern Bhutan during the latest Miocene – Pleistocene, in response to increasing partitioning of the India-Eurasia convergence into the active faults bounding the Shillong plateau.

Keynote (40 min): Processes of gold mobility and deposition in circum-Pacific convergent zones: Yukon (Canada), southern New Zealand, and Taiwan

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Orogenic gold deposits have formed in most convergent belts around the Pacific rim since the Paleozoic, and have some common features. The active transpressive Taiwan orogen is one of the simplest of these gold-forming systems. Convergence since the Pliocene has incorporated Cenozoic sediments into a greenschist facies metamorphic pile in the centre of the island, while lower grade rocks are forming a fold-thrust belt. Orogenic gold is being emplaced in graphitic greenschist facies rocks while hydrocarbons are being generated and trapped in the fold-thrust belt. Gold is being transported beneath the orogen by remobilised connate brines that are diluted by metamorphic water, and these fluids are further diluted by meteoric water during upward migration. The active transpressive Southern Alps of New Zealand have similar geometry to Taiwan, but are being constructed from Mesozoic subgreenschist facies metasediments and higher grade equivalents. Dehydration of low grade metasediments is producing metamorphic water (+minor CO_2), which is mobilising trace amounts of Au, As, Sb and W from the metamorphic rock mass. These metals are being focussed and concentrated into structurally controlled deposits beneath the actively rising mountains, and meteoric water dilution occurs at shallow levels. Essentially identical processes and fluids affected the Mesozoic metasediments during Mesozoic metamorphism to produce a suite of orogenic deposits in the Otago Schist belt. Early Cretaceous mineralisation formed the world-class Macraes mine, which occurs in graphitic metasediments and has additional hydrothermal graphite that accompanied sulphidation and gold emplacement. In the convergent Yukon-Tanana Terrane of NW Canada, the Paleozoic basement rocks were metamorphosed to greenschist or amphibolite facies schists in the Permian. The orogen was reactivated in the Mesozoic to form a thrust-thickened pile in which gold was mobilised into structurally-controlled sites. Host rock alteration, involving sulphidation and/or graphitisation facilitated gold concentration. The Permian stage of metamorphism in the Yukon-Tanana Terrane removed much of the labile As from the rocks, and consequently the Mesozoic gold deposits have relatively low As contents compared to other orogenic systems. Common features in many of these circum-Pacific deposits include mobilisation of metals by metamorphic processes, emplacement in extensional sites during compressional deformation, and enhancement of gold deposition by fluid-rock interaction that includes sulphidation and graphite reactions. There are particularly strong parallels between Yukon-Tanana and Otago Schist metamorphic-hydrothermal systems and also subsequent uplift and erosion processes that led to the rich alluvial placers for which both regions are best known.

Contrasting metamorphic and meteoric fluid flow mechanisms and pathways in an actively deforming convergent orogen, New Zealand

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Crustal fluids can have important thermal and rheological effects on a deforming rock mass, but their presence and associated signals are ephemeral and transitory. Evidence for the amounts, compositions, and sources of fluids in ancient metamorphic belts is necessarily incomplete and sketchy at best. One way to improve our understanding of the nature of fluid flow regimes in metamorphic belts is to examine active orogens in which metamorphic processes are occurring at depth. The Southern Alps of New Zealand is one such active orogenic belt, which is well-exposed and has well-constrained tectonic context. The Southern Alps is a linear mountain belt forming in the hanging wall of a transpressional plate boundary fault, the Alpine Fault, with relative plate motion of 4 cm/year. A 1 cm/year convergence component is driving low grade Mesozoic metasedimentary rocks into thickening crust beneath the mountains. Metamorphic dehydration is occurring as the rocks are being transformed to amphibolite facies gneisses, and metamorphic fluid that is dominated by water with <5 mole% CO_2 is moving in strain-induced permeability at rates <1 m/year. Fluid flux is on the order of 10^2 mol/m^2/year and is controlled by microshears below the brittle-ductile transition (BDT). Upward fluid flow at faster rates occurs in extensional shear fractures beneath the high mountains controlled by localised stress switching. Extensional fractures in the upper 3 km also form during topographic collapse of steep mountain slopes. Gold and arsenic are mobilised into the metamorphic fluids during upper greenschist facies metamorphic transformations, and are transferred in solution to shallow levels. In contrast, high rainfall on the western slopes of the mountains causes head-driven incursion of meteoric water to the BDT and beyond. This meteoric fluid dominates the fluid budget of the orogen, with fracture-controlled fluxes on the order of 10^4 mol/m^2/year near to the plate boundary, leading to abundant warm springs. The orogen changes character along strike to deformation dominated by strike-slip faults. Fluid is dominantly meteoric, although rainfall and infiltration are lower than in the main mountain chain, and fluid flow is controlled by the main faults. Minor Hg mobilisation in these waters attests to some fluid-rock interaction at depth, and possibly some metamorphic dehydration reactions. The focused strike-slip fluid regime was superimposed on, and captured, the more diffuse flow regime of largely separate meteoric and metamorphic fluids in the main mountain chain.

Chemistry and structure of tetragonal garnets

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Most garnets exhibit cubic symmetry, but exceptions with tetragonal symmetry have been reported. Henritermierite is a rare Mn3+-bearing hydrogarnet, ideally $Ca_3Mn_2[(SiO_4)_2(O_4H_4)_1]\Sigma3$, with only two known occurrences. It has been reported with tetragonal symmetry and space group I41/acd. The tetragonal symmetry has been previously attributed to Jahn-Teller distortion of the octahedral Mn^{3+} cation. (OH,F)-bearing spessartine is a pyralspite-group garnet, ideally $Mn_3Al_2[(SiO_4)_2(O_4H_4,F_4)_1]\Sigma3$, and has been reported with either cubic or tetragonal symmetry and space group $Ia\bar{3}d$ and I41/acd, respectively. It has been reported that the cause of the tetragonal symmetry is ordering of (OH,F) groups or atoms. This study focuses on the crystal structure and chemical analyses of henritermierite and (OH,F)-bearing spessartine garnets using electron probe microanalysis (EPMA) and synchrotron high-resolution powder X-ray diffraction (HRPXRD) data. EPMA gave near end-member compositions of $Ca_{2.97}\{Mn_{1.95}Al_{0.04}Fe_{0.03}\}\Sigma2.02[(SiO_4)_{2.00}(O_4H_4)_{1.00}]\Sigma3$ and $(Mn_{2.82}Fe_{2+0.14}Ca_{0.04})\Sigma3\{Al_{1.95}Fe_{3+0.05}\}\Sigma 2[(SiO_4)_{2.60}(O_4H_4)_{0.28}(F_4)_{0.12}]\Sigma3$ for henritermierite and spessartine, respectively.

Morphodynamic evolution of the Kicking Horse River, BC; an integration of ground-penetrating radar, remote sensing, and gauging record analysis

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The Kicking Horse River is a gravel-bed stream originating from glacial meltwater supplied by the Wapta Icefields in south-eastern British Columbia. An alluvial reach extends for approximately 7 km nearby the town of Field, BC. A complex network of braided channels undergoes diurnal and seasonal fluctuations in flow as a result of variable glacial meltwater and runoff recharge. Prior studies erected the Kicking Horse River as a reference for intermountain braided systems, and documented bar formation and sediment distribution patterns from ground observations. However, a consistent model of planform evolution and related stratigraphic signature is lacking. This study's purpose is to analyse the morphodynamic evolution of mobile channels and related bars in the Kicking Horse River, and to characterize its planform evolution at the yearly to decadal scale. The study integrates the analysis of ground-penetrating radar (GPR), remote sensing, and gauging records. Remote sensing highlights rates of lateral channel migration of as much as 270 meters over eight years (~ 34 meters/year), and demonstrates how flood stages are associated with stepwise episodes of channel braiding and anabranching. Channel migration influences in turn the size and relative abundance of mid-channel bars and bank-attached bars, through repeated processes or erosion and reworking. A total of 387 ground data points across ten selected fluvial bars were used to examine grain size, local flow direction, and degree of vegetation cover. GPR analysis was conducted in order to depict the depositional stratigraphy of the fluvial bars. Preliminary GPR analyses reveal the occurrence of distinct radar facies, including: discontinuous, inclined, planar, trough-shaped, and mounded reflectors, which can be in turn related to the fluvial processes and architectural elements responsible for bar construction. Integration of sedimentological data with remote sensing, gauging records, and GPR analysis allows for high-resolution modelling of stepwise changes in alluvial morphology. Conceptual models stemming from such analyses can be employed in the future to understand the depositional history and stratigraphic signature of proximal and coarse-grained fluvial systems.

Retrogressive stacking of parasequences in a tide-dominated delta: The transgressive phase of the Changjiang (Yangtze River) Delta

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The Changjiang, the 4th largest river in the world in terms of sediment discharge, is a tide-dominated system with a mean tidal range of 2.7 m and tidal-current speeds of ~ 1 m/s at its mouth. The sediment delivered to the coast is dominated by silt and clay, creating a mud-dominated delta. During the last glacial lowstand, the Changjiang created a 90 m-deep incised valley. The lower part of the valley fill is transgressive, passing upward from fluvial and fluvial-tidal deposits into a unit previously interpreted to be "estuarine" in origin. The succession is capped by the modern delta that has prograded approximately 200 km over the last 7500 years. Detailed study of the "estuary" unit shows that this ~25 m-thick succession is mud-dominated and contains a variety of tidal-channel and tidal-bar deposits that define a seaward transition from delta-plain to delta-front and prodelta deposits with a well-developed seaward-fining trend and a facies distribution that is identical to that of the modern delta. Tidal-channel-floor deposits in more landward locations contain abundant tide-generated fluid-mud layers (1-3 cm thick), intercalated with the coarsest sand in the succession. Channel-floor and the overlying tidal-bar deposits commonly become sandier upward because of the upward loss of fluid-mud layers. The delta-front tidal-channel, tidal-bar and prodeltaic deposits are dominated by randomly organized structureless mud layers, 5-30 cm thick, that are interpreted to be storm-generated fluid-mud deposits. These mud layers become less abundant upward, generating upward-sanding successions. The entire "estuarine" succession consists of three retrogradationally stacked deltaic parasequences, each of which becomes sandier upward. The composite unit fines upward overall, because of the net transgression. Despite the rapid rate of relative sea-level rise during deposition, the enormous sediment input was capable of allowing episodic progradation. Formation of the flooding surfaces is attributed to some combination of more rapid sea-level rise, reduced sediment supply because of climate fluctuations, or avulsion. Retrogradational stacking of deltaic parasequences has been recorded in ancient successions but has not been documented in the modern because only large rivers like the Changjiang have sufficient sediment supply to prevent formation of an estuary during the rapid transgression.

Integrated high-resolution stratigraphic analysis of the paleotropical carbonates spanning the Ordovician-Silurian boundary (Katian-Aeronian), Anticosti Island, Québec

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The carbonate storm-dominated sedimentary succession superbly exposed on Anticosti Island in Eastern Canada represents one of the most complete and well-preserved paleotropical stratigraphic records spanning the Ordovician-Silurian (O/S) boundary. We sampled the nearly complete coastal outcrop exposed at low tide along the west coast of Anticosti Island for high-resolution $\delta^{13}C$ and $\delta^{18}O$ chemostratigraphy. The new isotopic curves comprise more than 800 data points (micrite samples) for a total of >500 m of strata including from the base to the top: the late Katian Vauréal Formation, the Hirnantian Ellis Bay Formation, the Rhuddanian Becscie and Merrimack formations and the early Aeronian Gun River Formation. In addition, we sampled a recent stratigraphic core to access the younger part of the Anticosti succession not continuously exposed toward the south-central coast of the island. The $\delta^{13}C$ curve displays two distinctive positive peaks in the Ellis Bay Formation; a small lower peak (+2.5‰) and an upper larger peak (+4.5‰) and a broad positive excursion (+2.5‰) in the Gun River Formation. These positive isotopic carbon excursions provide a distinctive chemostratigraphic signature for regional and global correlations with other O/S sections. The continuing descending $\delta^{13}C$ trend, at least 30 m above the currently interpreted O/S boundary, suggests a higher stratigraphic position of that boundary in the Anticosti succession. The $\delta^{18}O$ curve, similarly to the Quaternary $\delta^{18}O$ marine curve, is tightly coupled with multi-order cyclic facies changes. Our coupled lithological and oxygen isotopic data suggest that the Anticosti succession was influenced by glacio-eustatic fluctuations during the whole studied Katian to Aeronian time interval. Furthermore, the estimated duration of these multi-order cycles supports an astronomical forcing. A near pristine isotopic oxygen record is also supported by the lack of significant covariance between $\delta^{13}C$ and $\delta^{18}O$, by the excellent microfabric preservation of both macro and microfossils in petrographic, cathodoluminescence, and SEM microscopy, and by little or no diagenetic resetting as suggested by the trace element geochemistry. This is unusual in the deep geological time but possible when lithification occurred shortly after the deposition in a closed diagenetic system.

Sulfur and carbon isotopes in tree rings as a record of volcanic activity: A new approach to studying the gases at Turrialba volcano, Costa Rica

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Turrialba is an historically explosive stratovolcano located at the southern end of Costa Rica's central volcanic range. Turrialba had been quiescent for nearly 150 years when the first signs of unease, including degassing, began in 1996. Since 2010, Turrialba has emitted a near constant plume of gas and there have been increasingly frequent explosions and ash emissions as activity continues to accelerate. In this study, fluctuations of gas output in the volcanic plume are being examined using an original method in dendrogeochemistry. A robust montane species, Alnus acuminata, is found in abundance around the volcano, and a successful campaign of non-destructive sampling in 2016 has produced a suite of core showing traits suitable for dendrochronological analysis. We propose here that given their exposure to the volcanic gas plume, these trees contain a geochemical fingerprint of local atmosphere as recorded in seasonal tree rings, since pollution studies have shown that exposure to high levels of SO_2 can affect the stable carbon and stable sulphur isotopes, $\delta^{34}S$ and $\delta^{13}C$, in trees. Here, tree rings are being analysed to provide a biannual record of fluctuating sulfur output at Turrialba, spanning decades. In this way, $\delta^{34}S$ and $\delta^{13}C$ can be measured both before and throughout the degassing episode and can thus be used as indicators of the volcanic activity. Since degassing at Turrialba is well-documented, we propose that comparison between our results and the corresponding fluctuations of CO_2 and SO_2 from the plume during this time could further strengthen this proxy, which can then be applied to other volcanoes around the world. This work may provide a revolutionary method for scientists looking to obtain a temporal record of degassing, while also providing valuable information for those seeking to evaluate the direct impact of volcanism on the growth of exposed biota.

Keynote (40 min): Beta diversity, conservation paleobiogeography, and the ‘6^{th} mass extinction’

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Global change observed in the last ~200 years is causing the extinction of species at rates that rival the largest biodiversity crises of the Phanerozoic, and has been termed the ‘6^{th} mass extinction’. Consequently, ecologists and paleontologists alike are increasingly turning to the fossil record as a source of data to use in building predictive models for the future. Here, I give a brief introduction to ‘conservation paleobiogeography’, which both places conservation paleobiology in a spatially-explicit context, and gives conservation biogeography a historical and deep-time perspective. As a field, it uses the fossil, subfossil, and geological records to address the questions: How do we expect species distributions to shift with continuing global change? Where do we expect ecosystems to be worst affected? How large, and where, should we construct protected areas? I review developing techniques in this field, and present a brief case study examining changes beta diversity over the Ordovician-Silurian mass extinction at nested spatial scales. The results provide the beginnings of a space- and time-specific ‘roadmap’ for interpreting the changing distributions of species in the modern oceans, and highlight one of the many crucial roles paleontology will play in the 21^{st} century.

Evolution of fault slip surfaces with increasing displacement

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Fault slip surface roughness determines fault strength, friction and dynamic fault processes. Wear models and field observations suggest that roughness decreases with cumulative displacement. However, measurements have yet to isolate the effect of displacement from other possible controls, such as lithology or tectonic setting. We present an unprecedentedly large fault surface dataset collected in and around the San-Rafael Desert, S.E. Utah, United States. In the study area, faults accommodated regional extension at shallow 1 to 3 km depth and are hosted in the massive, well sorted, high porosity Navajo and Entrada sandstones. Existing detailed stratigraphic throw profile provide a maximum constraint for displacement. Where cross-sectional exposure is good, we measure exact displacement imparted on slip surfaces using offset in marker horizons. Thereby, we isolate for the effect of displacement during the embryonic stages of faulting (0 to 60 m in displacement). Our field observations indicate a clear compositional and morphological progression from isolated joints or deformation bands towards smooth, continuous and mirror-like fault slip surfaces with increasing displacement. To quantify these observations, slip surfaces were scanned with a white light interferometer, a laser scanner and a ground based Lidar. Together these instruments resolve more than eight decades of spatial length scale (from less than µm's to m's in scale). Results indicate that the maximum roughness is fixed—bounded a by a primordial roughness corresponding to that of joints surfaces and deformation band edges. In the early stages of fault development roughness decreases rapidly with displacement according to a power law relation. In addition, we find wear rates and processes are different at different length scales. Our results build towards a coherent model of fault wear robust to ambiguities associated to displacement estimates, spatial scaling and geological context.

Overview of major 2100-2125 Ma mafic dyke swarms and sill provinces across Archean cratonic fragments

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Prolific Paleoproterozoic tholeiitic dyke swarms and sill provinces offer key evidence through which to constrain the configuration(s) of the larger, ancestral landmasses, termed supercratons, from which the present Archean cratons originated. Studies involving geochronology, spatial analysis, paleomagnetism, petrography and geochemistry are combined in the reconstruction of these ancient supercratonic landmasses or continents.

Remnants of ca. 2100-2125 Ma large igneous provinces (LIPs) occur within numerous Archean cratonic fragments: Superior, Hearne, Slave, Nain (Canada), NAC (Greenland), Wyoming (USA), and Karelia-Kola (Finland and Russia). Although this ensemble of cratonic fragments hosts approximately contemporaneous mafic magmatism, it is not yet fully resolved which fragments share a common ancestral landmass, and/or can be related to a single magmatic centre. Recent work has expanded on the original Superia reconstruction (Superior, Hearne, Wyoming and Karelia-Kola cratons) by showing that Nain and NAC were likely attached to what is now the northeastern margin of Superior while Kaapvaal and Pilbara are positioned at Superior's southwestern margin. Sclavia, a contemporaneous reconstruction cored by the Slave craton, however, remains unattached.

Events pertaining to the Superia reconstruction include the ca. 2100 to 2125 Ma Marathon dykes (Superior); 2118 Ma Misi gabbro sills, ca. 2117 Ma Tohmajärvi dyke and ca. 2130 Ma Pirtguba dykes (Karelia); 2113 Ma Bear Mountain dykes (Wyoming); and ca. 2110 Ma Griffin sills, and 2111 Ma Kazan and 2113 Ma Chipman dykes (Hearne); 2121 Ma Tikkigatsiagak (Nain); and a 2124 Ma dyke from the Nuuk area of South West Greenland. Relevant to the Sclavia reconstruction, the Slave craton hosts the ca. 2100 Ma Indin dykes.

A precise U-Pb age of 2115 Ma is presented from chemically abraded single zircon grains of the Nieminen dyke, Tohmajärvi swarm, Karelia. The Nieminen dyke's flat, MORB-like REE pattern matches trends reported from the Pirtguba swarm in Eastern Karelia. Notably, contemporaneous Misi gabbro sills and Sipojuntti dyke within Karelia are enriched in LREE and Ti but depleted in Nb-Ta. A similar dichotomy in trace element patterns is observed in Marathon and Chipman dykes but, among these, MORB-like signatures are rare. The enriched patterns in Karelia compare to those of Tikkigatsiagak, Indin, Marathon, Kazan, and the Chipman dykes and Griffin sills. Future work aims to clarify whether these block-specific geochemical nuances can be traced across formerly adjacent blocks in space and time to improve the paleogeographic reconstruction of these cratons and their breakup history.

Secondary calcite as a useful U-Pb geochronometer: An example from the Paleozoic sedimentary sequence in southern Ontario

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U-Pb dating of fracture calcites within a Cambrian to Devonian age sedimentary sequence that straddles the Michigan and Algonquin Basins in southern Ontario has been successfully conducted using LA-ICPMS and ID-TIMS.

Results from Devonian (Lucas Formation) samples collected at surface indicate a prolonged period of secondary calcite growth with major age peaks at about 100 Ma and 80 Ma and smaller peaks extending to about 50 Ma. Deeper (<200 m) Devonian and upper Silurian samples show a variety of younger ages with apparently distinct events at about 50 Ma, 30 Ma, 12-20 Ma, 7.6 ± 1.3 Ma and 0.7 ± 1.5 Ma but no evidence of the Cretaceous events dated at surface. Horizontal Lower Silurian veins, collected above evaporate formations (330 m), record vertical extension at 315 ± 10 Ma. Deeper Ordovician carbonate samples (650-800 m) give indistinguishable ages for veins, vugs and host rocks that average to 434 ± 5 Ma. This indicates mid-Silurian disturbance of the deep Ordovician rocks, consistent with the observation that pore waters in the rock are seawater-derived brines likely derived from overlying Silurian evaporitic basins.

Calcite veins in Ordovician rocks outcropping at Picton, about 350 km to the east, give a simple age pattern with a single peak at 106 ± 5 Ma, while previous ID-TIMS data from a calcite vein about 150 km further east in the Ottawa area gave an age of 100 ± 1 Ma. Thus, the ca. 100 Ma event is regional in scale and its localization at surface may be related to fracturing following erosional unroofing. The nearest major event in time is the New England Hot Spot which passed to the east over the interval 130-110 Ma.

The deeper level Ordovician section shows no evidence of disturbance since Silurian time presumably because the confining minus pore fluid pressure was insufficient to allow fracturing. Fluid may also have been confined by overlying relatively impermeable Lower Silurian evaporite units. These results suggest that Ordovician carbonate rocks beneath the Bruce site provide a closed system with respect to fluid flow over geologic time scales despite significant geologic perturbations.

Developing the bedrock layer for Canada 3-D: The Precambrian-Phanerozoic boundary

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One of the most significant tectonostratigraphic features of the geology of Canada is the boundary separating 'cover' rocks of the Phanerozoic Eon and older 'basement' rocks; dominantly metamorphic and crystalline rocks of the Precambrian shield. In the context of the Canada-3D initiative to develop a 3D geological model of Canada from the surface to the Moho, we have begun to integrate data constraints for modelling this boundary, including geological map, drillhole and seismic data. The 3D surface development is being undertaken through the application of data (geostatistical, implicit modelling (GOCAD/SKUA and SURFE) and knowledge (SPARSE) driven methods. More accurate 3D delineation of this key boundary will help support applications such as the separation of bulk rock properties into cover and basement classes which could in turn be used for geophysical and mineral potential modelling. Coupled with heat flow and fracture density estimates; it could also contribute to future development of national-scale 3D favourability maps for geothermal energy and CO_2 sequestration potential. The project combines a large amount of data from various sources collected over the last 175 years since the initiation of geological mapping by the Geological Survey of Canada in 1842 by Sir William Logan.

The Precambrian-Phanerozoic boundary is dominantly an angular unconformity between the crystalline bedrock of the Canadian Shield and Phanerozoic sedimentary cover sequences, spanning a hiatus of several hundreds of millions to more than two billion years. In rare cases such as the Rapitan Group in the MacKenzie Mountains, it is a more conformable stratigraphic contact between Neoproterozoic and Cambrian formations. There are also many parts of Canada's subsurface which have no geologic record of the boundary where the crust is mainly composed of either younger Paleozoic and Mesozoic mobile belts (Central Newfoundland and British Columbia), or exposed basement of the Precambrian Shield. The geological data that constrain the Precambrian-Phanerozoic interval are spatially heterogeneous, and vary in quality from excellent observations from petroleum wells in the Western Canada and Williston Basins, to less reliable well logs in Southern Ontario, to interpretive map traces in the overburden covered Hudson Bay low lands. Seismic reflection and refraction data from Lithoprobe and industry surveys will support deeper interpretations of the boundary, and be integrated with constraints obtained by geological mapping in the more complex regions of the Canadian Cordillera and Appalachian orogens. Canada-3D is modelling other tectonostratigraphic features (crustal scale fault networks and major lithostratigraphic horizons) within the bedrock layer, above and below the Precambrian-Phanerozoic boundary, but by focusing early on this significant boundary we gain insight to the data distribution, the required methodology and processing gaps that exist tackling this problem at a national scale. As the project proceeds there will be a need for development of 3D tools to support uncertainty estimation, sparse data interpolation and extension, and interpretation workflows designed to cope with the many challenges presented by limited sampling of complex geologic terrains.

Keynote (40 min): The role of automated mineralogy in GeoMetallurgy

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Most deposits display a high degree of geological and mineralogical complexity and variability that can have serious consequences in metallurgical processing. Therefore, the proper characterization of the ore and gangue minerals requires a multi disciplinary approach combining geology, mineralogy, geochemistry and processing. However, mineralogy to a large extent informs the metallurgical process and SGS has integrated the application of automated mineralogy as a practical tool for this purpose, using QEMSCAN, along with other techniques (XRD, EMPA, LA – ICP MS, geochemistry, and other methods), throughout the mining chain from advanced exploration through to production. In this presentation we discuss key mineral types that impact processing, review some of the common technologies for their characterization as well showcasing actual case histories where automated mineralogy has been applied in a geometallurgical framework at a pre-feasibility to feasibility level. We will discuss examples from base metals (Cu-Pb-Zn-Ni) and rare metals (REE-Li-Nb-Ta) to illustrate how mineral quantification and improved understanding of inherent mineralogical parameters in relation to metallurgy reduce technical risk in both exploration and flowsheet development.

Till geochemistry and gold grain counts over the Amaruq property (Nunavut): Glacial dispersal of a gold deposit in permafrost terrain

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Understanding the nature of glacial dispersal processes affecting a mineral deposit is challenging, especially in polyphase glacial flow areas. It requires the mapping of glacial deposits in detail, the reconstruction of the ice-flow history and the mineral and chemical characterization of the mineralization. During the last Wisconsinan glaciation, the Laurentide Ice Sheet shaped the glacial landscape of the Amaruq deposit area (central mainland Nunavut) into ribbed and streamlined till landforms, indicating a predominant regional ice flow to the NNW. At the local scale, evidence for later ice flows to the NW and WNW was found on striated bedrock surfaces.

A detailed surface till geochemical survey (mesh 100×100m; n=2495) in 2015 over the Amaruq property provides a unique opportunity to characterize glacial dispersal from the gold deposit. A robust principal component analysis (PCA) was performed using the RobComposition R package on the till geochemical dataset (<63 µm, aqua regia digestion, ICP-AES&-MS). Results show a strong gold association with silver, arsenic, cobalt, chrome, nickel, copper, antimony and tungsten in the first component (45% of the variance). Kriging of sample scores for the first component shows three NNW trending anomalies, down-ice of known mineralization, interpreted as glacial dispersal along the main ice-flow path. In an area of thick till north of the Whale Tail zone, the deposit anomaly reaches the till surface approximately 1.5 km down-ice from the mineralization located beneath a lake. In 2016, 49 till samples were collected from frost boils along four NNW-trending transects over various till terrain types (~250 m sample spacing). Detailed surficial mapping shows different till types between Mammoth E (sandy/bouldery till) and Whale Tail (thin to thick fine-grained till) transects. Along the Mammoth E transect, gold grain counts increase to 1015 grains/10 kg 300 m down-ice (NNW) of known mineralized structure, decrease to 523 grains and then climb again up to 2433 grains 720 m further. In contrast, along the Whale Tail transect, only one major peak (1337 grains) is visible 1300 m from mineralization. Gold grain counts regional values (mean of 14 grains) are nearly reached at the end of the Mammoth E transect (36 grains) but not at Whale Tail (178 grains). The till geochemical study and gold grain counts strongly suggest that landform type and associated till thickness is an important factor when interpreting variations in till composition and glacial transport distances.

Relating Ediacaran fronds

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Ediacaran fronds are an important component of terminal-Proterozoic (Ediacaran – 579-541 Ma) ecosystems; they are amongst the most recognizable, widespread and common body forms amongst the Ediacara biota ranging across all major faunal localities and time slices postdating the Gaskiers Glaciation. The importance of the frond morphology is evident, evolving independently multiple times within metazoans and previous works have suggested that it evolved in no fewer than three distinct groups of Ediacaran organisms (i.e. the Arboreomorpha, Erniettomorpha and Rangeomorpha). Despite their ubiquity, questions still exist over issues of homology and functional morphology between, and within, purported "clades". Here we evaluate the evolutionary relationships among these taxa and test, among other factors, if major traits like elevating a feeding structure higher into the water column or growth dynamics have evolved independently. A we conducted the first multi clade cladistics analysis incorporating architectural, developmental, and structural characters to illuminate the evolutionary history of these groups. Through this study, it is possible to understand the pattern of evolution within, and between, these clades, including the identification of homoplasies, functional constraints, and ectomorphs for the first time. Ultimately, this study both validates previous studies of Ediacaran "clades", and accentuates instances where previous assumptions of their natural history is no longer warranted.

Three spatially and temporally associated porphyry deposits with distinct Cu:Au:Mo ratios, Woodjam district, central British Columbia

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The Woodjam district is part of the porphyry deposits of Late Triassic to Middle Jurassic age (216 – 183 Ma) and is located in the Quesnel terrane in central British Columbia. Porphyry centers include the Cu-Mo Southeast Zone deposit, hosted in the calc-alkalic Takomkane batholith, and the Cu-Au Deerhorn, Takom and Three Firs deposits and the Megabuck prospect. The latter are peripheral to the margin of the batholith and are associated with smaller monzonitic bodies that had intruded and mineralized the volcanic-sedimentary rocks of the Nicola Group. The Takomkane batholith intruded the Nicola Group and is host to the Southeast Zone that displays characteristics of a calc-alkalic Cu-Mo porphyry. The Deerhorn and Takom deposits are centered on narrow monzonite bodies with pencil-like geometries that intruded the Nicola Group volcanic sequence. Deerhorn displays characteristics of a high-K calc-alkalic deposit. The Southeast Zone, Deerhorn and Takom deposits have similar ages between each other, and their intrusive units share geochemical characteristics. Differences between alteration and mineralization of the deposits are attributed to the magmatic evolution of the system influenced by differences in the depth of emplacement. Cu-Au mineralization at Deerhorn is a more mafic and potentially shallower segment of the magmatic hydrothermal system. Cu-Mo mineralization in the Southeast Zone is the more felsic and potentially deeper parts of the hydrothermal system. Cu-Au mineralization in the Takom deposit is displayed as an intermediate member between the Southeast Zone and Deerhorn deposits. The porphyry deposits in the Woodjam district shows that various styles and assemblages of porphyry mineralization can form within a single district over less than one million years.

Reef response to sea-level and environmental changes during the end Ordovician deglaciation: Evidence from calcimicrobial-skeletal bioherms, Anticosti Island, Québec

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The end Ordovician (Hirnatian) reefs, superbly exposed in coastal and river outcrops on Anticosti Island, Québec, form isolated metre-sized bioherms to larger decametre-sized bioherm complexes overlying a regional disconformity. These paleotropical reefs and associated oncolitic calcirudites provide a unique opportunity to examine a far-field transgressive record immediately following the late Hirnantian glacial maxima. The reefal and associated oncolitic limestones represent a prominent regional marker unit known as the Laframboise Member of the Ellis Bay Formation and coincide with the main Hirnantian positive isotopic carbon excursion (up to 5‰). The Laframboise reefs were constructed by intergrown calcimicrobal and skeletal components (e.g. Wetheredella, Rothpletzella, Girvanella, bryozoans, tabulate corals, stromatoporoid sponges) to form a bindstone. Calcimicrobes are volumetrically more abundant than the metazoan skeletons. Internal geopetal micrite is largely filling the small internal cavities. Synsedimentary cements, microbes, and automicrite are present but of subsidiary importance. The stratigraphic architecture of the massive Laframboise reef cores display high- and low-frequency growth phases. An individual high-frequency growth phase (3-10 cm thick) is made of a dense basal calcimicrobial layer overgrown by numerous metazoan skeletons and capped by a thin layer of fine terrigenous sediment. Five low-frequency growth phases are made of alternating thin and thick packages of higher-frequency units within the bioherm core and laterally display contracted and expanded core margins. Associated with the overall late Hirnantian deglaciation, this study suggests that two smaller imbricated orders of climatic oscillations and/or sea level changes have regulated the amount of terrigenous material and nutrient delivered on the sea floor, which in turn controlled the carbonate production and accumulation as well as the development of the Laframboise bioherms.

The structure and chemistry of some lead-apatite minerals

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This study is based on some lead-apatite minerals, including pyromorphite, $Pb_5(PO_4)_3Cl$, mimetite, $Pb_5(AsO_4)_3Cl$, and vanadinite, $Pb_5(VO_4)_3Cl$. Emphasis is placed on their crystal structure and chemistry. The lead-apatite minerals belong to the hexagonal space group P63/m. In pyromorphite, mimetite, and vanadinite the XO_4 tetrahedra is occupied by P^{5+}, As^{5+}, and V^{5+} cations, respectively. Based on their general formula, $Pb_5(XO_4)_3Cl$, the variations in size of these cations result in different O-X-O angles and X-O bond distances in each mineral, thus influencing their unit-cell dimensions. Three samples of pyromorphite were studied, of which two are from China and one is from Ontario. Our mimetite sample is also from China and our vanadinite sample is from Morocco. To examine the structural trends among these samples, high-resolution powder X-ray diffraction (HRPXRD) results and electron-probe microanalysis (EPMA) analyses were used. Several structural trends were observed and explained in this study.

Carbonate clumped isotope thermometry of the Ordovician Red Head Rapids Formation: An evaluation of petroleum source rock development in the Hudson Bay Basin

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Carbonate clumped isotope thermometry is a recently developed geochemical technique that measures the abundance of the doubly-substituted isotopologue $^{13}C^{18}O^{16}O$ in carbonate material. A new clumped isotope facility has been developed in the Delta Lab of the Geological Survey of Canada, in order to evaluate the potential of clumped isotopes as thermometric indicators in various basins. The clumped isotope systematics are more laborious than the analysis of regular stable isotopes. Carbonate powders are reacted with phosphoric acid and the resulting CO_2 gas is cleaned using an offline, stainless steel, ultra-purification gas line under high vacuum. The CO_2 is sent through two water traps and a U-trap packed with porapak Q and silver wool to remove any hydrocarbons or other contaminants. The cleaned CO_2 is then analyzed on a Thermo Scientific MAT 253 isotope ratio mass spectrometer with modified cups, specifically designed for clumped isotope analysis. A key challenge in processing clumped isotope data is to obtain an internal reference frame taking into account the lab-specific isotopic behaviour during preparation and analysis, which is subsequently used to present the data in an absolute reference frame based on thermodynamic principles. The clumped isotope results obtained following this procedure will be presented for carbonate samples collected from an outcrop of the Upper Ordovician Red Head Rapids Formation in the Hudson Bay Basin on Southampton Island, Nunavut.

The Hudson Bay Basin is the largest intracratonic basin in North America, but it is the only one without any known petroleum resources. Nine exploration wells were drilled and 46,000 km of seismic line data were acquired from 1964 to 1985. At that time, exploration was halted because no hydrocarbon reservoirs were discovered, and the source rock was inferred to be thermally immature. Recent research, however, has discovered pockmarks and possible oil slicks in several localities across the Hudson Bay, suggesting that hydrocarbons are indeed present in the basin. The interest here is that the Red Head Rapids Formation directly overlies the potential source rock for the Hudson Bay Basin. Clumped isotopes may help unravel the thermal history and better understand hydrocarbon development in the basin.

Deep tunnelling geohazards: The critical role of engineering geology

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After the successes of the Swiss Gotthard and Loetchberg Base Tunnels, two twin tunnel projects totalling over 180km in length, deep tunnels are being planned, designed and constructed through some of the world's most challenging mountainous terrain. The most grandiose of these projects are the railway base tunnel projects with typically twin tunnels of 10m diameter, many tens of kilometers in length. Road tunnels with shorter length but similar diameters are also being constructed. Tunnels driven for hydroelectricity range in diameter from 4m to 10m and are of highly variable length and with challenging inclinations.

Long tunnels are typically driven with tunnel boring machines although a variety of other construction methods are in use. Construction costs can vary from several hundred million dollars for a small hydro-electric scheme to tens of billions for a base tunnel. Cost overruns and time delays can exceed 100% and many years. The primary reason for these delays is the challenges and risks associated with difficult ground conditions and unforeseen or underestimated ground stability problems. Inevitably such challenges arise during construction due to an incomplete, inaccurate or imprecise geological model at the early design and bidding stage. Due to the logistics posed by the challenging terrain, there is a low likelihood that geological hazards to tunnelling will be comprehensively detected, assessed or accurately located during site investigation. The likelihood of critical geohazards must be evaluated based on a detailed geological model, relying on sparse borehole investigation for local verification only. Strategically preparing for possible but unproven geohazards will increase the initial bid price of a tunnel. Modifying construction tactics in mid project to adapt to unanticipated geological challenges often costs much more. This is the choice facing the tunnel project owner and the contractors who bid on the project.

In Europe, the Brenner Base Tunnel and the Lyon-Torino Base Tunnel are under construction with depths up to 2km and ground conditions ranging from rockbursting in gneissic massifs to squeezing in tectonic melange, fault gouge and cataclasite zones to karstified nappes with high water inflow. In the Andes, the builders of long and deep tunnels for mine access, transport and water conveyance contend with deep seated zones of alteration, extreme rockbursting in brittle volcanics, complex hydrothermal stockwork, and folded sequences of sedimentary and volcaniclastic rock. In the western mountain ranges of Canada, strong residual tectonic stress fields and remnant deformation structures pose a hazard in otherwise competent rock, while in Sweden, complex tectonic history is reflected in complex ground conditions creating challenges for key tunnel projects.

Case histories in these regions will be used to highlight the importance of a comprehensive but focussed geological model to these critical engineering megaprojects and to illustrate the key role of the engineering geologist during design and construction. The role of the geological model in initial design, construction-phase decision making, contingency planning and monitoring strategy will be discussed.

Near field geomechanics: Excavation Damage Zone simulation and prediction from grain to excavation scale

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The Deep Geologic Repository (DGR) concept for the long-term (i.e., 1 Ma) safe management of radioactive waste is internationally accepted best practice. The concept incorporates a multi-barrier design including the waste form, the waste container, engineered clay based sealing systems, and the enclosing crystalline or sedimentary geosphere. Within the repository near-field, extending outwards from the excavated openings, perturbation occurring principally during repository construction and time-dependent alteration thereafter can influence rock mass integrity and repository performance. This zone is referred to as the Excavation Damage Zone (EDZ).

The EDZ is actually a gradational zone of decreasing damage and disturbance away from the excavation boundary. Moving outwards from the excavation boundary of an individual tunnel, shaft or cavern, there is an immediate EDZ system surrounding any individual tunnel, shaft or cavern comprised of visibly fractured, irreversibly damaged and mechanically disturbed or elastically influenced ground. There is also a repository scale zone of disturbance which evolves over the construction period, as well as the long term post-closure.

Research at Queen's University and in collaboration with other institutions has, for the past 10 years, focussed on the near-field and local EDZ, as well as on refining tools for larger scale analysis of the mechanical response of the near-field rockmass enclosing a repository. Damage processes at the grain scale and at the scale of internal heterogeneities such as the nodular texture of limestone (within one candidate host formation), and at the scale of block forming internal structure (joints and veins). The role of bedding structures on the larger scale rockmass response has also been investigated. These multi-scale elements of geo-structure and their role on EDZ development and behaviour have been investigated through laboratory experiments and numerical simulations including grain-based models, intra-block structural models and discrete fracture (inter-block) network integration with mechanical simulation. Hydro-mechanically coupled models at the grain and block scale have been used to improve predictive capacity with respect to the hydraulic changes in the rock and rockmass due to damage development.

This talk will provide an overview of developments aimed at ongoing improvements to the geological engineering toolbox for predicting, evaluating and comparing the EDZ character, mechanics and long term evolution and impact both at multiple scales and as a system, enhancing the capacity to manage and verify the EDZ in a variety of geological settings.

Characterization of the Temagami BIF hydrothermal system

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Neoarchean Algoma-type banded iron formations are considered to have formed at major volcanic centers, with Fe and Si sourced from proximal hydrothermal vents. Several models, both historical and more recent, have been developed to describe BIF formation in hydrothermally influenced marine environments. In particular, the physical and chemical conditions thought to be responsible for BIF deposition, including pH, redox, fluctuations in metal input, and biological controls, have been directly linked to the volcanic and hydrothermal activity.

A combined mineralogical, geochemical, sulfur isotope, and field study of the 2.72 Ga Temagami Algoma-type BIF has been carried out to test different models of the BIF genesis. Novel multiple sulfur isotope data (MIF-S) indicate that trace sulfur in the BIF is not sourced from direct input of sulfide particles from a hydrothermal plume. Rather the sulfur systematics of the host basin are entirely due to biological mineralization. The absence of hydrothermal sulfur implies little or no plume fallout from nearby "black smoker" style venting and also raises the possibility that Fe and Si were not sourced from proximal hydrothermal vents. It appears unlikely that chert and iron oxide deposition in the Temagami BIF was controlled by pH fluctuations caused by mixing of alkaline hydrothermal fluids with seawater as ultramafic lithologies required to generate the high-pH fluids are not present.

Some aspects of the chert-jasper-iron oxide layering preserved today, such as their low trace metal contents with the notable exceptions of relative Ge and Eu enrichments, suggest that Si and Fe were at least partly deposited from non-focused, diffuse venting of hydrothermal fluids high in Si and Fe, but low in other components. Characteristic mm-scale banding in the ores has been interpreted widely in terms of redox fluctuations in the host basin, but textural relationships between silica, hematite, and magnetite point to replacement processes within the bands. Textural and paragenetic relationships, together with trace element geochemistry of the iron-oxide layers, argue for development of the fine layering during diagenesis and volume loss during recrystallization. The fine layering has been suggested as evidence of deposition below storm-wave base, preserving banding that would otherwise have been distrubed. But a diagenetic origin allows for the possibility that BIF deposition occurred in relatively shallow water, with implications for the nature of the associated hydrothermal activity and biological controls (e.g., a direct role for phototrophic bacteria).

Contrasting styles of palladium mineralization in the Lac des Iles Complex, Ontario

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The Lac des Iles Complex (LDIC) in Ontario hosts two distinct styles of Pd-rich PGE-Cu-Ni sulfide mineralization: magmatic breccia and stratiform types. Magmatic breccia-type Pd mineralization is typical of the Roby and Offset deposits in the Mine Block Intrusion (MBI) of the mafic South LDIC, which have supported surface and underground mining operations at Lac des Iles for nearly 25 years. It is principally hosted by vertically-disposed varitextured noritic breccia bodies that commonly contain 0.5-2% disseminated Fe-Cu-Ni sulfide. It is characterized by high Pd tenors in sulfide (>1000 ppm in 100% sulfide), a lack of correlation between S/Se ratios and Pd concentrations, and an average Pd:Pt ratio of 10 that increases with the increasing Pd grade. Available geological observations suggest that magmatic breccia-type Pd mineralization formed as a result of multiple injections of metal- and volatile-rich noritic magmas into the proto MBI along a regional north-striking feeder structure (Shelby Lake fault).

Stratiform-type Pd mineralization occurs in the Sutcliffe Zone along the eastern flank of the cyclically-layered Northern Ultramafic Centre of the North LDIC. It is hosted by olivine websterite, websterite, gabbronorite and hybrid units that contain 0.5-2% disseminated Fe-Cu-Ni sulfide. It features moderate Pd tenors in sulfide (>1000 ppm) that decrease with increasing S/Se ratios and has Pd:Pt ratios of 0.9- 3.5 that remain constant with increasing Pd grades. Stratiform Pd mineralization at the Sutcliffe Zone is interpreted to have formed by a combination of fractional crystallization and dynamic recharge of two compositionally distinct ultramafic parental magmas: one silica-rich and the other silica-poor. Historical exploration results suggest that the Sutcliffe Zone lacks the grade, thickness and size to develop into an economic, near-surface Pd resource. Numerous other anomalous (i.e., >1 ppm Pd) Pd occurrences have been documented in the North LDIC. Some of these occurrences have a spatial association with the interpreted northern extension of the Shelby Lake feeder structure and could therefore represent a continuation of the magmatic breccia-type mineralization developed in the MBI. However, recent mineralogical and geochemical investigations of these occurrences indicate that they have more in common with the stratiform-type mineralization of the Sutcliffe Zone than the breccia-related deposits in the MBI.

Advancement of geoeducation and research via public response to the Ottawa-Gatineau Geoheritage Project

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During the fifteen years since the Ottawa-Gatineau Geoheritage Project was initiated, scientists trained in other disciplines have contributed substantial information of educational and scientific value. But so have many of those who have attended OGGP talks and field excursions. Here are some examples.

Metcalfe Geoheritage Park, an outdoor display of large rock specimens in Almonte, was one of the first major projects to which OGGP contributed. Since it was created in 2009, it has been significantly enhanced, culminating in re-opening of an upgraded display in 2016. Visitors to the original display provided suggestions that assisted in designing the new site, and revising explanatory information.

To counter the loss of insect and plant species that depend on open sandy areas for survival, Biodiversity Conservancy International initiated a project in 2011 to open a small area in the forest canopy over a sand-dune complex within Ottawa (The Pinhey Dunes). Members of OGGP became involved in this project soon after it started, and we continue to contribute in collaboration with biologists Peter Dang and Henri Goulet, thereby providing new opportunities to promote geoheritage. Sessions at the sand dunes with young students are especially rewarding, allowing innovative teaching methods to be applied involving sieves, magnets and marbles.

Lawyer Christopher Brett of Perth, Ontario, has never lost his scientific enthusiasm honed while earning his BSc. degree in Geology. When OGGP was helping to update geological collections in the Perth Museum, Chris was attempting to track down the discovery site for Climactichnites, the distinctive trace fossil brought to the attention of William Logan by James Wilson, the first physician in Perth. Since 2012, Chris has compiled an extensive geological archive via his blog (Fossils and Geology of Lanark County). He was present during the discovery of a new specimen of Climactichnites during a field excursion in 2016.

OGGP's efforts in geoeducation have been reciprocated by the provision of feedback about significant geosites, including notification of three new occurrences of megastromatolites. When a property owner observed that domal structures were the focus of interest during an OGGP excursion, he guided us to in-place strata on his land that contain evaporite molds in similar stromatolite-bearing strata. This has provided additional support for our proposal that stromatolites periodically flourished in the Early Paleozoic because of recurring hypersaline conditions inhospitable to browsing organisms – the same conditions that allow stromatolites to flourish today in Shark Bay, Australia.

The use of methane clumped isotopes as a new tool to understand the formation of natural gas reservoirs

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Natural gas is an increasingly important source of global energy production, and understanding of how natural gas forms and accumulates in reservoirs is important for identifying further resources and improving the efficiency of extraction. Methane stable isotope measurements (i.e. $^{2}H/^{1}H$ and $^{13}C/^{12}C$) have long been used to characterize natural gas reservoirs, but there are ambiguities that limit their ability to definitively identify methane formation processes. Recently the measurement of methane containing multiple rare isotopes (i.e. $^{13}CH_3D$ or $^{12}CH_2D_2$), or clumped isotopes, has emerged as a complementary tracer for methane in hydrocarbon systems. In many cases, where methane forms in isotopic equilibrium this measurement is directly related to either the temperature of methane production. Here we present a large body of methane clumped isotope data from a global set of natural gas samples, as well as complementary data from pyrolysis experiments. In general, these measurements indicate methane formation temperatures that are consistent with thermal maturity estimates. In some cases methane clumped isotope data provide temperatures that are higher than expected, with possible explanations including chemical kinetic effects during methane formation, the kinetic isotope effects of gas diffusion, or a contribution of methane from deep, high-temperature zones of sedimentary basins. Clumped isotope measurements of methane in natural gas reservoirs that are thought to be microbial in origin indicate lower temperatures, and this measurement has the potential to be a valuable tool in discriminating between microbial and thermogenic methane. We also present analyses of methane emitted from permafrost thaw lakes in Alaska, where clumped isotope data provide evidence for the release of gas from high-temperature reservoirs.

The Bissett Creek flake graphite deposit: Hydrothermal or metamorphic?

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As the importance of graphite continues to rise with the advent of many new green technologies and the increasing prominence of electric vehicles, the need to understand the factors controlling graphite mineralization has continued to grow. While graphite deposits are scattered across the Grenville Province in Ontario, the factors that allowed for their formation are currently debated. The Bissett Creek flake graphite deposit in the Ottawa River Gneiss Complex of the Grenville Province in Ontario represents a natural laboratory to evaluate and develop regional genetic graphite deposit models. In this study, the Bissett Creek flake graphite deposit is investigated to evaluate whether graphite mineralization is syngenetic (metamorphically derived) or epigenetic (hydrothermally emplaced) and to determine the source of the carbon responsible for mineralization. Graphite mineralization is hosted in biotite-rich quartzofeldspathic gneiss, garnet-diopside-tremolite-biotite gneiss and garnet-biotite-sillimanite gneiss. All of these units have undergone polyphase folding. Graphite mineralization is characterized by homogeneously distributed and disseminated graphite flakes (about 1 to 5 mm in size) that compose 2–10 vol.% of the gneisses. Graphite flakes are intergrown with metamorphic minerals, mostly biotite and garnet, and mineralization is stratabound. $\delta^{13}C$ values of graphite found on the property range from -14‰ to -31‰. Most of these values are consistent with a biogenic source for the carbon, but since there are values greater than -18‰, a hydrothermal contribution from sources with heavier isotopic signatures (e.g. devolatilization of carbonate minerals) cannot be ruled out. Considering the carbon isotope values, the disseminated and stratabound nature of graphite mineralization at Bissett Creek, and the intergrowth of graphite with metamorphic minerals, the deposit is interpreted to have formed as the result of high-temperature metamorphism of biogenic carbonaceous material likely in response to Grenvillian metamorphism.

The role of authigenic Mg-clays in calcrete-hosted uranium deposits at Lake Way, Western Australia

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The genesis of calcrete-hosted uranium (U) deposits has been studied for more than 50 years. Despite numerous formation models being proposed, their origin remains enigmatic. This study used an integrated, mineralogical, geochemical, and hydrological approach to compare barren and mineralized calcrete and related sediments to constrain the processes that facilitate the accumulation of U into calcrete-hosted U deposits around Lake Way, Western Australia. These deposits occur in Cenozoic groundwater calcrete, clay-rich fluvial paleochannel fill, and playa-lacustrine sediments on the margins of the Lake Way playa. Uranium is bound in the uranyl-mineral carnotite ($K_2(UO_2)_2(VO_4)\cdot 3H_2O$).

Drill hole conductivity data from the Centipede/Millipede ore body indicates the presence of a fresh hypopycnal groundwater lens that flows eastward into Lake Way, thinning toward the delta-playa transition. Calibrated down-hole gamma-ray data confirm that U mineralization occurs at 1 to 5m below surface and is concentrated along the base of the freshwater lens, with the highest-grade mineralization occurring at the brackish-water interface where inflowing fresh, low-density paleochannel groundwater interacts with the dense hypersaline groundwater of the playa. Further, detailed mineral analysis using XRD and environmental SEM/EDS techniques indicate a previously unobserved association between U mineralization, authigenic sepiolite ($Mg_4Si_6O_{15}(OH)$) and palygorskite ($Mg_{2.84}Al_{1.8}Si_8O_{20}(OH)_2\cdot 8(H_2O)$), together with synsedimentary dolomicrite. Sepiolite is common in groundwater calcrete, while palygorskite is more abundant in clay-rich playa sediments. Mineral stability plots constructed using previously published water chemistry data indicate that the pH, alkalinity, Mg/Ca ratio, Si saturation, and salinity of pore-water in this setting are ideal for the formation of sepiolite, palygorskite, and authigenic dolomite.

The significance of the sepiolite and palygorskite is that they possess high surface areas and negative surface charges over a wide pH range (pH 3.2-14), making the minerals particularly efficient at adsorbing positively charged aqueous metal species. The close association of dolomicrite with carnotite suggests that dolomite precipitation might encourage carnotite precipitation by removing bicarbonate from pore waters, thus allowing U to exist as $UO_2(OH)^+$. This change in the aqueous species of U would increase the potential for U to adsorb to negatively charged authigenic Mg-clays. Thus, the colloidal properties of sepiolite and palygorskite combined with modifying the activity of bicarbonate via dolomite precipitation at the brackish-water transition entering Lake Way facilitates a positive feedback mechanism creating favorable pore-water conditions, and providing abundant nucleation sites for carnotite precipitation.

Investigating the metamorphic history of the Bancroft Terrane (Ontario Grenville) using the new thermodynamic software approach Bingo-Antidote

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The Bancroft Terrane and the associated Central Metasedimentary Belt boundary thrust zone (CMBbtz) represent the northern part of the Central Metasedimentary Belt of the Canadian Grenville Province. Predominantly upper amphibolite-facies rocks of the Bancroft Terrane and the amphibolite to granulite-facies rocks of CMBbtz were thrust over amphibolitized granulite-facies rocks of the Central Gneiss Belt (CGB) in the north at <1080 Ma. Field studies point to an earlier amphibolite facies event in the Central Metasedimentary Belt at >1100 Ma. However, only few explicit pressure and temperature calculations exist, representing a lack of P-T data in the Bancroft Terrane. The study attempts to unravel the polymetamorphic history of the Bancroft Terrane, applying advanced thermodynamic approaches such as equilibrium assemblage diagrams.

First, pressures and temperatures (P-T) were computed with the Theriak-Domino software, which uses recently significantly updated thermodynamic data for the Berman-1992 database (including amphibole solid solution and melt). By now, thermobarometric data have been obtained for 8 samples that were collected during field work in the Bancroft Terrane and the southerly adjacent Belmont Domain in April 2017. It was possible to model the P-T conditions of a presumably early metamorphic event, which differs from the proposed upper amphibolite P-T conditions of the region. Samples showing a polymetamorphic history are characterized by zoned garnet with large variations in grossular content or different generations of amphibole.

Second, equilibrium assemblages were investigated on a microscale using the new thermodynamic software approach BINGO-ANTIDOTE. This new program combines the achievements of the two petrological software packages XMapTools and Theriak-Domino. XMapTools affords information about compositional zoning in mineral and local bulk composition of domains from electron microprobe mappings. Primarily BINGO-ANTIDOTE can be described as an inverse Theriak-Domino, because it uses the information provided by XMapTools to calculate the most probable P-T equilibrium conditions of metamorphic rocks, estimating the degree of agreement between the observed and calculated mineral assemblage.

Both approaches show a younger dominant event of 700±50°C and 7±1 kbar and an older less dominant event of 550±50°C and >7 kbar for at least 3 samples. We believe that our initial data suggest that the less dominant event represents the accretionary stage of the Bancroft Terrane which became overprinted by the later thrusting event at <1080 Ma. Future monazite dating on microprobe may give insights into the P-T-t history of the Bancroft Terrane.

Metamorphism of mafic metavolcanics at the Ore Chimney Mine, southwestern Grenville Province

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Mafic metavolcanics (amp-pl±qz±chl±bio±ep±cal±spl) associated with gold deposits (Ore Chimney Mine) along the southwestern limb of the Flinton Synclinorium in the southwestern Grenville Province preserve amphiboles and plagioclases that vary compositionally. Amphibole compositions vary from actinolite to magnesio-hornblende to tschermakite along the PL (NaM4SiCa-1AlIV), TK (AlVIAlIVMg-1Si-1), and ED (NaAAlIV□-1Si-1) substitution vectors. Coarse-grained amphibolite retains amphiboles with higher TK values (tschermakite) than fine- to medium-grained greenstone (magnesio-hornblende). Core to rim zoning from actinolite to magnesio-hornblende and from magnesio-hornblende to tschermakite is observed across individual grains in greenstone. TK and ED values of amphibole cores range from 0.26 to 1.05 and 0.0 to 0.15 apfu, respectively, whereas amphibole rims exhibit respective TK and ED values between 1.39 and 1.51 and 0.25 to 0.36. PL varies from 0.13 to 0.32 apfu between samples, with the most variability in PL observed in ED-depleted magnesio-hornblende cores. Plagioclase compositions vary from oligoclase to andesine, with oligoclase preserved as inclusions in amphibole and andesine preserved as grains in the matrix. Relict chlorite preserved locally in thin sections is interpreted to have formed during greenschist facies metamorphism that involved concomitant growth of actinolite and oligoclase. Prograde metamorphism from greenschist to amphibolite facies is marked by magnesio-hornblende and/or tschermakite overgrowths on actinolite and the formation of andesine. The prograde metamorphic path may be related to crustal thickening associated with a single regional metamorphic event, or potentially reflects polymetamorphism.

The Shawinigan and Ottawan orogenies in the northwestern Central Metasedimentary Belt, Ontario: Insights from the Mazinaw and Black Donald domains

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The Mazinaw and the Black Donald domains are part of the Elzevir terrane of the Central Metasedimentary Belt in the Grenville orogen. Detailed mapping in the northeastern part of Elzevir terrane indicates a complex structural relationship between the 2 domains. To the west and the south, the Black Donald domain tectonically overlies the Mazinaw domain. But in the northeast, the Mazinaw domain consists of northwest-directed tectonic slivers stacked upon the units of the Black Donald domain. South of Black Donald Lake, this northwest-directed vergence is reversed with Black Donald domain units overthrust to the southeast onto Mazinaw domain. This complex structural pattern was acquired during a protracted sequence of deformational events; of which a north-trending major regional shear zone, the Ross fault, played a central role. This succession of tectonic events is responsible for the fold-and-thrust belt and fan like geometry of the Black Donald domain characterised by northeast-trending megafolds separated by shear zones.

Structural analysis and U-Pb geochronology show that the Black Donald domain was affected by a multi-stage flat-lying tectonic event starting with thrusting and recumbent folding followed by belt-parallel top-to-the southwest shearing. This D_1 event was coeval with high pressure granulite facies metamorphism involving partial melting and calc-alkaline plutonism, both occurring at circa 1190 Ma. The Black Donald domain was thrust upon the Mazinaw domain sometime after 1190 Ma and likely before 1167 Ma. On the eastern side, thrusting of Mazinaw domain upon the Black Donald domain also occurred at this time. Despite the apparent absence of significant Shawinigan-age plutonism, the Mazinaw domain experienced Shawinigan metamorphism with numerous ages clustered at circa 1150 Ma. The D_2 event was characterised by a northwest-directed thrusting and folding to the west and a top-to-the southeast shearing to the southeast. The D_2 event was synchronous with felsic plutonism and took place circa 1135 Ma.

The Ottawan orogenic cycle was characterised by a D_3 west-southwest-directed out-of-sequence thrusting along the Ross fault on the eastern contact between the Mazinaw and Black Donald domains. This D_3 event is also contemporaneous with northeast trending upright folds in both the footwall and the hanging wall of the Ross fault. The D_3 Ross fault was subsequently folded by F_4 northeast trending upright folds. The last expression of Ottawan deformation is represented by conjugate sets of sinistral northeast trending shear zones coeval with northwest trending dextral faults. These strike-slip shear zones operated under middle to upper amphibolite conditions.

Calcite-graphite isotope thermometry in the western Central Metasedimentary Belt, Grenville Province, Ontario

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We have determined peak metamorphic temperatures in marble across the western Central Metasedimentary Belt (CMB) of the Ontario Grenville Province using calcite-graphite isotope thermometry. The prevalence of graphite-bearing marble allows application of this single thermometer across 5000 km^2. New data (N=130) combined with previous data reveal detailed thermal features across the region. Prior studies show the calcite-graphite system is especially able to retain peak T due to the extraordinarily limited diffusion of carbon in graphite. Based on previous comparative thermometry studies, we employ two calibrations of the thermometer, Kitchen & Valley (JMG 1996) above 600°, and Dunn & Valley (JMG 1992) below. Application below ~500°C requires excluding samples with anomalously low $\delta^{13}C$ values for material that may not be fully graphitized. Results for specific areas from the central Elzevir terrane to the western Bancroft terrane are as follows, ±1σ(N analyses): Tudor Twp 468°±26(18); N. Marmora 524°±33(9); Apsley 617°±55(10); Chandos Lake 624°±13(8); Faraday 617°±31(22); Coe Lake 621°±28(9); Paudash Lake 643°±22(7); Tory Hill 670°±34(12); Gooderham 627°±40(6); Salmon Lake-Catchacoma 658°±33(11); Galway Twp 712°±69(6); Glamor Lake 742°±22(3); Haliburton 724°±13(6); Carnarvon 714°±59(6); and Minden 731°±32(6). Regional isotherms form SW to NE lines, parallel to regional structures and without sinuous highs and lows E and N of Apsley, as previous interpretations have shown. The 700° isotherm runs from Galway to Tory Hill roughly along the eastern margin of the Glamorgan Complex. The Glamorgan is one of several crystalline thrust sheets W of the 700° isotherm that appear to represent a style of deformation distinct from the domes of the Harvey-Cardiff domain immediately to the east. The different structural styles may be attributable to the consistently warmer conditions to the west. The westward T increase appears entirely gradational within the precision of the thermometer, without breaks at terrane boundaries. Mezger et al.'s (CMP 1996) U-Pb ages for titanite in marble across the study area strongly suggest our temperature determinations pertain to the Ottawan orogeny (1070-1030 Ma). Marble with unusually large $\delta^{13}C$ values (>4‰) are found across the entire study area suggesting a common pre-orogenic affinity. This is distinct from the $\delta^{13}C$ of other Grenville marbles in adjacent terranes, and may support an isolated basin model for the pre-Ottawan history of the CMB.

An investigation of groundwater vulnerability in a karst aquifer near Plantagenet, eastern Ontario

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Karst landform features are well developed in Ordovician limestone in the Township of Alfred and Plantagenet, ON. Observations of petroleum hydrocarbon contamination discharging with groundwater into a limestone quarry prompted concern for groundwater vulnerability. The purpose of this study was to investigate vulnerability by characterizing bedrock fracture features and measuring recharge travel time to wells and to discharge points in the quarry. The investigation involved mapping of fracture patterns on areas of limestone pavement (alvar), time-series analysis of $\delta^{18}O$ in precipitation and groundwater collected from fracture-controlled discharge conduits at the base of the quarry, and time-series monitoring of hydraulic head (H) and specific conductance (SC) in domestic wells.

The ^{18}O analyses were conducted by CRDS and IRMS in the G.G. Hatch Stable Isotope Lab at the University of Ottawa. Hydraulic head and SC were monitored using Solinst LTC submersible dataloggers. All observed fractures are near vertical (± 6°) with four dominant orientations (011° ±5°; 030° ±7°; 049° ±3°; 109° ±6°) suggesting strong anisotropy in the flow system. Near-horizontal bedding-plane joints and fractures can be observed in the walls of the quarry but detailed observations and measurements were not possible. Seven domestic wells were monitored over a distance of approximately 2.2 km parallel to highway 17, just east of the South Nation River. Hydraulic head and SC measurements in the five western-most wells respond rapidly, with increases in H up to 7 m and simultaneous decreases in SC of 100 to 200 uS/cm within 24 hours of a 12.8 mm rainfall event. Two wells in the eastern portion of the study area displayed relatively small responses to the 12.8 mm rainfall event, with increases in H on the order of 0.5 m. The well monitoring data indicate significant spatial variability in groundwater recharge and storage, consistent with expectations for terrain with non-uniform karstification. Similar to the wells in the western portion of the study area, the time-series $\delta^{18}O$ data indicate that recharging rain and snowmelt water are rapidly transmitted to discharge points at the base of the quarry (less than 24 hours). The data demonstrate that the groundwater system in much of the study area is characterized by very rapid recharge rates – a feature of groundwater systems that corresponds with high vulnerability to contamination.

Experimental constraints on thermosolutal convection in the stratified Sudbury impact melt sheet

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The Sudbury Igneous Complex (SIC) is a differentiated impact melt sheet. Along its southern portion, above a xenolith-rich lower chilled margin, a basal norite orthocumulate grades upward through a transitional gabbroic layer into a thick layer of granophyre. Recent work has revealed the existence of a sharp compositional discontinuity in the granophyre, leading to the suggestion that the SIC formed as a pair of distinct magma bodies separated by a stable stratiform interface while both magmas were liquid. The lower body was quartz diorite and the upper body was granodioritic in composition. We have conducted experiments to determine the chemical diffusion coefficients in silicate melts chosen to represent our best guesses for the compositions of the magmas that coexisted on either side of the layer in the granophyre. Infinite couple diffusion experiments were conducted in the high pressure and temperature lab in the Earth Sciences Department at the University of Toronto. Natural samples of granophyre and quartz diorite as well as artificial approximations of granophyre were ignited to drive off volatile constituents, then fused in platinum crucibles before quenching to produce homogeneous, bubble-free glasses. The glasses were powdered and packed tightly into platinum capsules, separated by a planar interface, and brought to temperatures above their liquidus ranging from 1250°C to 1400°C at pressure of 1.0 GPa for periods of time ranging from a few seconds to several days. Other samples were hydrated with water by melting at high P and T conditions and used as material for experiments at similar conditions. After quenching of the experimental charges, they were sectioned and polished before being analyzed on an LA-ICPMS to measure chemical penetration profiles. The observed penetration profiles can be used to constrain diffusion coefficients and used as input parameters for a stability analysis of the interface in the context of multicomponent thermosolutal convection theory. Preliminary results show that melt of the upper granophyre composition would have been able to overlie the quartz diorite melt without undergoing multicomponent thermosolutal convection if they were both anhydrous and had reached the same temperature. While the H_2O concentration still needs to be measured in the hydrous experiments, measured diffusion profiles of the other components combined with a simplified simulation of H_2O diffusion suggest that melt of the upper granophyre composition would have been able to overlie the lower granophyre melt without destabilizing if it contained at least 1.7 wt% H_2O.

Metamorphic and tectonic history of Frontenac terrane revisited: Evidence for a high-pressure regime preserved in the hanging-wall of the Maberly shear zone, near Perth, Ontario

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Previous metamorphic studies in central and eastern Frontenac terrane in Ontario have suggested relatively uniform peak metamorphic conditions at circa 1168 Ma of 750-790°C, 4.5-5 kilobars (bathozone 4), with the highest conditions found north of Gananoque. However, preliminary evidence for much higher P-T conditions (bathozone 6) have been found in the hanging wall of the Maberly shear zone (MSZ) during 1:50 000 scale mapping, petrological and geochronological studies in the Perth area (NTS 31C16), as described below.

Almost all of the paragneiss units in the Perth area have undergone partial melting, indicating high temperatures. Primary muscovite is absent, suggesting metamorphic conditions above the muscovite-breakdown reaction. The common assemblage kyanite-garnet-biotite-rutile, indicates metamorphic conditions of >7 kilobars and >675°C, similar to those in the Wolf Grove structure in the footwall of the MSZ (7.2 kilobars, >718°C). In adjacent calc-silicate rocks and dolomite marbles, the common mineral assemblage diopside-plagioclase ± scapolite ± chondrodite suggests pressures and temperatures >8 kilobars and >670°C. Neither cordierite nor orthopyroxene have been found in gneisses in the Perth area; cordierite previously reported from hand specimens was likely bluish oligoclase.

Local evidence for even higher pressures include a paragneiss sample with the assemblage andesine-quartz-garnet-corundum-rutile and the rare zirconium-titanium silicate mineral srilankite, which could indicate metamorphic pressures as high as 11 to 14 kilobars and temperatures approaching 1000°C. Several paragneiss samples contain co-existing corundum-kyanite grains, as well as plagioclase-potassium feldspar coronas around kyanite. Such coronas, where previously reported from the Bohemian massif, have been interpreted as the result of a decompression reaction that occurs at ~8.5 kilobars, and would imply higher peak P-T conditions, consistent with the srilankite-bearing sample.

Bathozone 4 conditions exist near Lyndhurst, 20 km south of the Perth area, which would require significant structural displacement between the 2 areas. A possible candidate structure is the N-NE trending Chaffey's Lock fault. A difference of 2 kilobars between the Perth and Lyndhurst areas would involve a minimum vertical displacement of 7 km, which may have occurred in several stages from the Proterozoic to the Phanerozoic. The regional geological implications of such a major structure are still under investigation. Furthermore, these new results suggest a previously unknown complex high P-T regime metamorphic history related to the development and unroofing of the MSZ, but consistent with the MSZ being a major crustal boundary.

Metasomatism, syenite magmatism and rare earth element and related metallic mineralization in Bancroft and Frontenac terranes, Grenville Province, Ontario a preliminary deposit model

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Some of the earliest exploited and, at the time, nationally important, mineral deposits in Ontario are present in the Bancroft and Frontenac terranes of the Central Metasedimentary Belt of the Grenville Province. These deposits, herein referred to as “metasomatic deposits”, were sources of metallic and non-metallic minerals, such as apatite, mica, molybdenum and uranium. Most were small in size and associated with a complex series of host rocks including “calcite vein dikes”, coarse-grained pink calcite rocks, diopsidites, apatite veinlets, and mica pyroxenites. Although metasomatic deposits in Frontenac terrane were physically compared to those in Bancroft terrane, there was no prior indication that they might have formed at the same time, or by the same processes, in both terranes. New geochemical and geochronological data from mapping in the Brudenell (NTS 31 F/6), Cobden (NTS 31 C/10) and Perth (NTS 31 C/16) areas has provided further insights into the origin and time of emplacement of these metasomatic mineral deposits, including their potential to host rare earth element mineralization.

The metasomatic deposits appear to have formed at least twice; at circa 1160 Ma and circa 1060 Ma. At both times, the metasomatic deposits are associated with syenite intrusions emplaced during and after the peak of metamorphism and deformation into the overriding thrust sheet (hanging wall) of a major deformation zone (Maberly shear zone at circa 1160 Ma, Central Metasedimentary Belt boundary zone (CMBBZ) at circa 1160 and 1060 Ma). Although the syenite intrusions typically are not mineralized, they served as the heat source and the source of some of the metal-enriched solutions that led to deposit formation. The size and quality of mineralization decrease with increasing lateral and/or vertical distance from the deformation zone; even if the deposit is in the hanging wall and syenite intrusions are present. On-strike variations in metasomatic deposits along the CMBBZ may reflect compositional variations in the footwall, for example, uranium-rich deposits at Bancroft, aluminium-rich deposits at Craigmont, rare earth element mineralization near Brudenell, and abundant fluorite near Cobden. Such on-strike variations need to be recognized in any exploration program. The metasomatic deposits are probably not a stand-alone deposit type, but are likely part of a continuum of deposit types ranging from alkaline-porphyry copper ± molybdenum ± gold deposits, through iron oxide-apatite (Kiruna-type deposits) to manto deposits, with the different deposit types related to increasing distance from the magmatic source, as well as increasing amounts of hydrothermal activity.

Keynote (30 min): Dynamics of fault activation by hydraulic fracturing in overpressured shales

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Fluid-injection processes such as disposal of saltwater or hydraulic fracturing can induce earthquakes by increasing pore pressure and/or shear stress on faults. Natural processes, including transformation of organic material (kerogen) into hydrocarbon and cracking to produce gas, can similarly cause fluid overpressure. Here we document two examples from western Canada where earthquakes induced by hydraulic fracturing are strongly clustered within areas characterized by pore-pressure gradient in excess of 15 kPa/m. By contrast, despite extensive hydraulic-fracturing activity associated with resource development, induced earthquakes are virtually absent in the same formations elsewhere. Monte Carlo analysis indicates that there is negligible probability that this spatial correlation developed by chance. A detailed analysis was undertaken within a 400 square km region in Alberta, Canada where uniquely comprehensive data characterize dynamic interactions between well completions at 6 drilling pads. Seismicity is strongly clustered in space and time, exhibiting spatially varying persistence and activation threshold. The largest event (ML 4.4) can be reconciled with a previously postulated upper bound on magnitude, only if the cumulative effect of multiple treatment stages is considered. Induced seismicity from hydraulic fracturing reveals contrasting signatures of fault activation by stress effects and fluid diffusion. Patterns of seismicity indicate that stress changes during operations can activate fault slip to an offset distance of > 1 km, whereas pressurization by hydraulic fracturing into a fault yields episodic seismicity that can persist for months.

The global LIPs GIS database: Tool for exploration targeting

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The dramatic expansion in our understanding of Large Igneous Provinces (LIPs) since their initial recognition in the early 1990s, and particularly in the past decade, combined with the importance of a GIS framework for modern geoscience investigations means that it is timely to produce an updated GIS-based global LIPs dataset and assess its potential use in exploration targeting. Earlier LIPs databases focused on continental flood basalts and oceanic plateaus /ocean basin flood basalts and associated hotspot magmatism ranging in age back to 260 Ma. The current project expands the GIS dataset into pre-Mesozoic time back into the Proterozoic, where the flood basalt record has generally been removed by erosion, exposing the underlying plumbing system of dykes, sills and layered intrusions, and further back into the Archean, where a number of LIP candidates have been identified. Geophysical data can also reveal deeper structural aspects (e.g., aeromagnetic data for tracing units under sedimentary cover, gravity data for unexposed mafic-ultramafic intrusions within the crustal profile, and seismic data for the distribution of a magmatic underplate and any fossil plume head). The new GIS database also incorporates associated silicic magmatism, carbonatites, kimberlites and ore deposits as well as interpreted mantle plume centres, related structures (e.g. rifts), associated sedimentary basins (linked to LIP-related topography), and the spatial distribution of geochemical subgroups within individual LIPs. An industry consortium is currently providing support for this comprehensive Global LIPs GIS database that will be regularly updated and expanded. The database represents an advanced tool for multi-commodity, multi-scale exploration targeting by the resource community as well as a framework for research by the broader scientific community, in areas such as constraining global geodynamical evolution and quantifying the paleo-environmental impact of LIPs. From a resource perspective LIPs represent significant reservoirs of energy and metals that can either drive or contribute to a variety of metallogenic systems and also affect hydrocarbon and aquifer systems. LIPs can provide the energy, fluids, and/or metals for a variety of mineralising systems, including orthomagmatic Ni-Cu-PGE sulphides, native Cu, hydrothermal volcanogenic massive sulfide (VMS) and iron oxide-copper-gold (IOCG) deposits. The LIP GIS framework illuminates key relationships between LIP units and these and other resource types and will also more broadly assist in global plate reconstructions that can allow tracing of major metallogenic belts into greenfield areas on crustal blocks that were formerly attached.

Paleomagnetic testing of the Vaalbara supercraton joined to Superia

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Neoarchean cratons have traditionally been grouped into "clans" distinguished by their basement ages and volcano-sedimentary cover successions (Bleeker, 2003). Recent development of the LIP-barcode method of craton juxtaposition primarily by similarities in U-Pb ages (Bleeker and Ernst, 2006) has suggested the counterintuitive possibility of connections that bring together members of separate clans. One such reconstruction is presented in Bleeker et al. (2016) and Gumsley et al. (2017): the Vaalbara supercraton (de Kock et al., 2009) is presented immediately adjacent to the western part of Superior craton, along with Wyoming in its rotated reconstruction south of Superior (Kilian et al., 2016). If such a "SuperVaalbara" amalgamation existed in Paleoproterozoic time, it likely assembled during Neoarchean accretion. That model predicts a single apparent polar wander (APW) path for all constituent cratons, when all of the individual paleomagnetic poles are rotated quantitatively into the reconstruction, for the duration of their tectonic continuity. Our present contribution evaluates the rates and styles of APW implied by the SuperVaalbara model. While the model is consistent with a few published poles of broadly similar ages, relevant high-quality data are sparse. Some of the motions implied by the aggregate APW path are rapid relative to typical Mesozoic-Cenozoic rates, but not to the extreme. One challenge to the SuperVaalbara model is its post-breakup kinematic evolution, which requires Vaalbara to escape laterally while Wyoming rotates into position within the growing Laurentia assemblage as part of Nuna supercontinent. Migration of Hearne from the external margin of SuperVaalbara into the center of Laurentia is similarly challenging. Cratonic juxtapositions via the LIP-barcode method present intriguing hypotheses that demand quantitative evaluation in the continuous kinematic framework provided by visualizable software packages such as GPlates.

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The Oak Ridges Moraine was deposited between two fast-flowing ice streams

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Geomorphological mapping using high resolution (5 m) digital elevation datasets shows that the Greater Toronto Area and its immediate environs, Canada's largest urban area, is built across the former bed of two fast flowing ice streams (Ontario Ice Stream: OIS, and Ontario Lobe: OL) within the last Laurentide Ice Sheet (LIS), that are directly analogous to modern ice streams in Antarctica and Greenland. Their subglacial footprints consist of spectacular flow sets of highly elongated ridges (megascale glacial lineations: MSGLs) up to 5 km in length that converge on the Oak Ridges Moraine from the north and the south. MSGLs are distinguished from other co-related subglacial streamlined bedforms such as drumlins by having elongation ratios greater than 10:1; some as much as 40:1 and indicating ice velocities considerably in excess of 400 m yr^{-1} and possible as fast as 1 km yr^{-1}. The Oak Ridges Moraine (160 km long, 70 km^3) is southern Ontario's largest glacial landform and was deposited in an elongate glaciolacustrine depocenter between the two converging ice streams at c. 13,500 ybp. To date more than 100 ice streams have been recognized in the Laurentide Ice Sheet and the data presented here from the Greater Toronto Area adds significantly to that database in the eastern Great Lakes sector of the ice sheet. The ice stream paradigm provides a firm foundation for a comprehensive re-evaluation of much existing glacial geologic mapping and stratigraphy in Southern Ontario which hitherto has controversially and incorrectly emphasized the role of regional subglacial megafloods flowing below the Laurentide Ice Sheet.

Design, construction and use of an experimental vessel for the investigation of factors influencing soft-tissue decay and preservation with regards to clay mineralogy

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The processes underlying soft-tissue fossilization remain poorly understood. Softer tissues, such as hair or muscle, are less likely to be preserved, creating a bias toward the preservation of hard parts such as teeth, bones, and shells. Modern taphonomic research focuses on monitoring the geobiochemical changes that occur during tissue decay, as these processes are highly dependent on environmental conditions and microbial interactions that occur soon after death. The most significant parameters to monitor during decay leading to soft-tissue preservation include: 1) production of volatiles, such as carbon dioxide and hydrogen sulfide, 2) changes in aqueous pH and 3) changes in sediment mineralization. To this end, a gas and water tight vessel was constructed to allow for continuous monitoring of decay environments. The complement of sensors can be altered to monitor any aspect of decay product production, however for the purposes of this study, it was equipped with a CO_2 sensor, a pH meter, and three sediment core extraction implements. Data logging of all sensor responses was done continuously by use of a dedicated Arduino microcontroller. The sampling schedule for sediment core analysis can be set to any desired interval. In this study, the vessel was used to examine the influence of clay mineralogy on the decay of a model organism (Shrimp - Penaeus monodon). Over a three month period, the atmospheric CO_2 concentration and aqueous pH values were determined every hour. Sediment samples collected at one week, one month, and three months were analyzed for elemental and crystallographic changes by XRF, XRD, and scanning microscopy. Sediments were selected to target different mineralogies, including aluminum-rich clay, iron-rich clay, and clay of varying mineralogy. Preliminary results have shown that presence of clay alone influences the rate of CO_2 production and pH alternation compared to experiments done using silica sand, where clay allows for faster CO_2 release and earlier pH changes. This decay vessel has permitted for detailed analysis of fossilization processes under laboratory timescales. This in turn will help to elucidate preservational biases within the fossil record and provide clues as to why certain geologic periods, such as the Cambrian or Ediacaran, have higher instances of soft-tissue fossilization.

Magnetic fabric study of offset dyke emplacement and sulfide mineralization in the North Range of the Sudbury Impact Structure, Ontario, Canada

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The Sudbury Impact Structure contains abundant world-class nickel, copper and PGE sulfide ores, with mining at numerous localities having been underway for over a century. Ongoing mineral exploration at Sudbury focuses on the magmatic and hydrothermal systems that were generated by the 1.85 Ga meteorite impact event as a melt sheet (Sudbury Igneous Complex) and associated radial and concentric `offset' dykes of bulk quartz diorite composition were emplaced within fractures in the target rocks. In this study, we have taken multiple oriented core samples from 13 sites in offset dykes of the less deformed North Range of the Sudbury Impact Structure. We use the Anisotropy of Magnetic Susceptibility (AMS) method on >6 samples per site to define anisotropy ellipsoids which can act as a proxy for bulk mineral fabric in a rock, therefore helping to interpret the passage and possible emplacement of sulfide ore deposits associated with the injection of impact melts. Preliminary results show that three major fabric orientations exist in the North Range Foy and Hess offset dykes: 1) planar fabric oriented parallel to the dyke margins; 2) planar fabric oriented nearly perpendicular to the dyke margins at two localities in Foy near its intersection with the Hess dyke; and , 3) weakly to strongly anisotropic fabric showing a subvertical maximum susceptibility orientation near local large sulfide pods in the outcrop. The AMS fabrics studied so far imply that dyke flow may possibly be used to establish the relative timing and geometry of the sub-impact melt sheet plumbing system while the emplacement of sulfides may be traceable at a local and perhaps larger scale using AMS lineation fabrics that could act as an exploration `vector' to the Ni-Cu PGE mineralization.

Siliciclastic units of the Proterozoic Vazante Group, Minas Gerais, Brazil: Evidence for arc provenance

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The Proterozoic, sedimentary Vazante Group, Minas Gerais, Brazil is a mixed, carbonate - siliciclastic sequence that is encountered within the Southern segment of the Brasilia Fold Belt. The age, provenance, and tectonic setting during deposition of the Vazante Group remain controversial due to complex folding and thrusting in the region. Twenty-five exploration drill-holes located from the North and South of the district were logged and sampled. Three hundred samples were selected for further studies, which cover the length of the Vazante Belt exposure and extending up to 915 m in depth. They comprise major siliciclastic units contained within the Vazante Group, including the Serra do Garrote and Serra do Poço Verde formations. Textural and mineralogical investigation was followed up by lithogeochemical studies, which results are summarized below.

The Serra do Garrote Formation, the thickest siliciclastic unit at the base of the Vazante Group, is characterized by variably-organic, muscovite + chlorite + quartz-bearing pyhllites. The pelites of the Serra do Poço Verde Formation, which are interlayered with dolomites in the middle of the Vazante Group, are characterized by muscovite + biotite + K-feldspar + quartz-bearing phyllites. The detrital minerals suggest a felsic or continental source.

Three subunits G1, G2 and G3 were identified in the Serra do Garrote based on their Al_2O_3/TiO_2 ratios, as Al and Ti are immobile in this system. Tectonic discrimination diagrams of other immobile elements (Zr/Sc versus Th/Sc, Hf versus La/Th, La-Th-Sc, Th-Sc-Zr/10) indicate that both the Serra Garrote and Serra do Poço Verde formations were derived from sources with a magmatic arc signature, with varying degrees of contribution from old continental sources. The old continental crust signature is more prominent during the sedimentation of the pelitic rocks of the Poço Verde Formation. Significantly, the pelitic units derived mainly from arc-related sources have anomalous zinc contents (up to 0.46% Zn).

Previous studies concluded that the Vazante Group was deposited on a passive continental margin. However, our results indicate the presence of magmatic arcs in the vicinity of the São Francisco Craton during deposition of the Vazante Group, raising the question of possible back-arc basin setting.

The origin of Late Devonian (Frasnian) stratiform and stratabound mudstone-hosted barite in the Selwyn Basin, Northwest Territories, Canada

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Multiple occurrences of bedded barite ($BaSO_4$) are preserved in mudstones of the upper-most Canol Formation (Frasnian) of the Selwyn Basin (Canada). Samples of barite were collected from eight sites (seven measured sections), and examined using petrographic and isotopic techniques ($^{87}Sr/^{86}Sr$, $\delta^{34}S$ and $\delta^{18}O$ values) to determine whether the barite has a diagenetic or hydrothermal origin.

Barite at all locations occurs in two morphologies: (1) laminated barite, and (2) nodular barite consisting of barite, hyalophane, cymrite (hydrous Ba-silicate) and minor pyrite. At the Cowan occurrence, one sample has a mineral assemblage comprising barite and nodular barium carbonates (witherite, norsethite).

The $\delta^{34}S$ and $\delta^{18}O$ values of the laminated barite co-vary, and range between +24.1 to +35.3‰ and +14.8 to +18.3‰ respectively. The laminated samples have an average $^{87}Sr/^{86}Sr$ of 0.7085 (n = 8), which is consistent with Frasnian seawater (0.7081) that has undergone some minor water sediment interaction during early diagenesis.

The nodular barite has highly variable $\delta^{34}S$ (+4.8 to +56.5‰) and $\delta^{18}O$ (+9.2 to +19.3‰) values, which developed from more evolved diagenetic pore fluids with limited sulphate re-supply (i.e. as a relatively closed system). In these conditions sulphate reduction likely occurred at a slower rate, and the sulphate in the barite records both kinetic ($\delta^{34}S_{SO4}$) and equilibrium ($\delta^{18}O_{SO4}$) isotope effects. One sample of nodular barite has a $^{87}Sr/^{86}Sr$ ratio of 0.7086.

Our data supports the interpretation that the barite horizon is a stratigraphic marker throughout the Canol Formation. Laminated and nodular barite formed as a result of diagenetic processes, which recycled Ba from organic matter in the sediment below, and reprecipitated it above, the sulphate methane transition zone in the sediments. We suggest that the combination of high biological productivity and low seawater sulphate at this time contributed to the efficient cycling of Ba from seawater into the sediments on the continental margin.

Spot the difference: Investigating in situ lead isotope variations by LA-ICP-MS in plagioclase and clinopyroxene from the Kiglapait layered intrusion

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The isotopic geochemistry of layered intrusions (e.g., Skaergaard, Duluth, Muskox, Bushveld) associated with large igneous provinces (LIPs) is a very powerful tool for constraining magmatic processes during crystallization and for identifying mantle source components and quantifying extents of crustal assimilation. The ca. 1307 Ma Kiglapait intrusion is the largest troctolitic intrusion of the ~20,000 km^2 Nain Plutonic Suite (Labrador, Canada), a "large plutonic province" that was emplaced incrementally over ~75 million years (1365-1290 Ma). Kiglapait is one of the most influential layered intrusions in petrology. Solution analyses by multiple collector-inductively coupled plasma-mass spectrometry (MC-ICP-MS) document puzzling Pb isotopic differences between coexisting plagioclase and mafic minerals in the Kiglapait intrusion. By in situ analysis, we aim to identify the mineral(s) and processes responsible for this isotopic heterogeneity. In situ Pb isotopic ratios were determined in plagioclase and clinopyroxene directly on thin section by laser ablation ICP-MS (LA-ICP-MS) at the Pacific Centre for Isotopic and Geochemical Research. Due to low Pb concentrations in Kiglapait plagioclase (0.3-3.26 ppm) and clinopyroxene (0.03-1.12 ppm), Pb isotope ratio measurements were carried out on a Nu Instrument AttoM single collector high-resolution sector-field ICP-MS; for plagioclase and clinopyroxene, internal precision on $^{208}Pb/^{206}Pb$ was 1% and 2% (2RSE), respectively. Age-corrected in situ Pb isotopic ratios of plagioclase ($^{208}Pb/^{206}Pb_i$ = 2.40 ± 0.05, 2SD, n = 361) overlap with those of the leached plagioclase measured by solution MC-ICP-MS ($^{208}Pb/^{206}Pb_i$ = 2.40 ± 0.03, n = 10). Notably, there is no difference in composition between plagioclase cores and rims, whereas solution analyses of unleached plagioclase ($^{208}Pb/^{206}Pb_i$ = 2.08-2.37) and leached plagioclase yield distinct compositions. Surprisingly, in situ Pb isotopic ratios of clinopyroxene cores and rims ($^{208}Pb/^{206}Pb_i$ = 2.41 ± 0.13, n = 56) overlap with those of plagioclase and not with the measured ratios in bulk mafic and clinopyroxene separates ($^{208}Pb/^{206}Pb_i$ = 2.05-2.38). The results indicate that the plagioclase and clinopyroxene have a restricted range of Pb isotopic compositions and that the radiogenic Pb, documented by solution analyses, must be carried by a mafic phase other than clinopyroxene in the Kiglapait intrusion. A potential candidate is interstitial sulfide, which is the target of on-going in situ work. The application of in situ Pb isotopic analyses by LA-ICP-MS to layered intrusions has the potential to yield significant breakthroughs in our understanding of their petrogenesis and links to contemporaneous flood basalts and mafic dike swarms as part of LIPs throughout geologic time.

The influence of spatial and temporal resolution when simulating groundwater – surface water interactions with a fully integrated model

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Increasingly, groundwater - surface water (GW-SW) interactions are being recognized for their significant influence on the hydrologic characteristics of Southern Ontario. The behavior of the hydrologic system in turn has a strong influence on contaminant fate and transport, which then ultimately affects water quality within the Laurentian Great Lakes. Because of climate and topographic variability, as well as heterogeneities in soil and subsurface lithology, quantifying GW-SW interactions at a scale meaningful to the Great Lakes requires the use of advanced modelling tools. However, in hydrologic modelling there is always a trade-off between spatial scale and process resolution, and as of yet a comprehensive understanding of how model resolution influences simulated GW-SW interactions does not exist. To address this outstanding question, we are conducting a detailed modelling-based study of GW-SW interactions within the Grand River Watershed, using the HydroGeoSphere fully-integrated GW-SW modeling platform. As part of the work, we are employing two watershed scale (7000 km^2) models built at contrasting resolutions (low: 625K nodes; high: 3.5M nodes) and an ultra-high resolution 2D cross-sectional model to simulate GW-SW exchanges. Using transient climate/weather data at temporal resolutions ranging from monthly to daily as forcing data, simulations are being conducted for a range of different hydrologic conditions that span the drought to flood spectrum. Output from the simulations will be used to provide insight on how model spatial and temporal resolution can influence the interpretation of GW-SW interactions within a heterogeneous and highly dynamic hydrologic environment. Results from this work are intended to guide future modelling initiatives that require realistic multi-dimensional and highly transient representation of the fully-coupled GW-SW flow system.

Platinum group element residence sites in Ni-Mo-Zn-PGE mineralized black shales, Yukon

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Polymetallic metalliferous shales are an important global resource for Zn, Ni, Cu, Mo, Se, U, V, ± Cr, Co, Ag, Au, platinum group elements (PGE) and rare earth elements (REE). The deposits are typically thin (<10 cm) and laterally widespread, covering thousands of km^2. Yukon hosts some of the best examples in the world and the Nick Ni-Zn-Mo-PGE deposit is the best-known example in Canada. However, many basic questions remain unresolved regarding the formation of these deposits, including the host mineral(s) for the PGE. Our research aims to determine the residence and mineralogical associations of PGE and other elements in the Nick deposit and several other localities with similar mineralization.

Mineralization is constrained to a thin (<10 cm) layer that is located at the contact between the Cambrian to Middle Devonian Road River Group and the Middle to Upper Devonian Canol Formation. Within this layer, the maximum metal abundances are as follows: Ni (7.0 wt.%), Mo (0.33 wt.%), Zn (2.3 wt.%), Pt (511 ppb), Pd (202 ppb), Ir (10.9 ppb), Ru (12 ppb), Re (25.8 ppm), Se (0.57 wt.%) and As (1.1 wt.%). The semi-massive sulfides consist predominantly of vaesite (NiS_2), pyrite and sphalerite, with lesser millerite (NiS) and gersdorffite (NiAsS). Gangue minerals are primarily quartz, barite, apatite and trace to minor K-(Ba) feldspar and pyrobitumen.

Vaesite shares mutual boundaries with pyrite, and typically forms 0.1 to 0.2 mm-thick encrustations on pyrite or occurs as minute grains within pyrite nodules. Less commonly, vaesite occurs as discrete, anhedral grains. Preliminary laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) trace element concentration maps indicate that vaesite is the principle PGE host mineral; these data show the highest abundances of Ru (up to 1 ppm), Pd (up to 10 ppm), Os (up to 2 ppm) and Pt (up to 5 ppm) in vaesite, which suggest that PGE- and Ni-bearing sulphides were deposited coevally. Although Ir is present in relatively high abundances in the lithogeochemical data, our preliminary LA-ICP-MS data do not identify its host mineral, and the residence site(s) for Ir currently remain unresolved. Ongoing research will continue to investigate the nature and residence of PGE at the Nick deposit and other, similar types of deposits in Yukon. Our salient goal is to develop an internally consistent model that describes the striking metal enrichment within this regionally significant layer.

Surficial stratigraphy, past ice flows and their implications for drift prospecting in the Hudson Bay Lowlands, Canada

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The Hudson Bay Lowlands, with their major part located in Ontario, are an extensive region underlain by Paleozoic carbonate bedrock along the western coast of the Hudson and James bays. Despite their location near the centre of the Pleistocene Laurentide Ice Sheet, thick Quaternary deposits up to 100 m thick occur, which include till, sub-till non-glacial deposits and Holocene lacustrine, marine and peat materials. The Pleistocene sequence consists of multiple till units and an underlying non-glacial deposit which contains sand, mud and organic materials of lacustrine, fluvial and marine origins formed under temperate conditions similar to those of the present day. This sub-till non-glacial deposit, underlain by till locally, is commonly correlated across the lowlands to the Missinaibi Formation of the Last Interglacial (Sangamonian) defined in the Moose River basin southwest of James Bay. Radiometric dating of this deposit, e.g., radiocarbon, U-series and OSL, has produced inconsistent results ranging from Middle Wisconsinan, Last Interglacial (MIS 5) to the previous interglacial stage (MIS 7). The age of the deposit thus still remains to be determined. The overlying till sequence consists of several, typically 2, major (thick) till units overlain by the lateglacial tills usually as veneers. The major till units can be correlated, in a descending order, to the Late Wisconsinan and older glacial stages depending on the dating results of the sub-till non-glacial deposit. Regardless of their ages, the ice flow directions these tills are associated with are consistent across the lowlands, orienting toward the southwest, west-southwest or west. This has strong implications for drift prospecting in this region. In Ontario, significant mineral deposits have been found in recent years along the margin of the lowlands to the west, e.g., the world-class chromite and large nickel-copper-PGE deposits in the McFaulds Lake area known as the Ring of Fire area. Recent surficial mapping and till sampling by Ontario Geological Survey has recovered significantly anomalous amounts of detrital chromite grains from the Late Wisconsinan till along the upper Attawapiskat River. Because of the southwestward ice flow direction of this till, these anomalous chromite grains are very likely derived from an unknown source(s) rather than the known chromite deposits (e.g., Black Thor, Big Daddy and Blackbird) located about 40 km to the north-northwest, indicating good potential for finding additional such deposits in this area.

LA-ICP-MS determination of Pb isotopes and trace elements in galena from the Caribou VMS deposit, New Brunswick, Canada: Implications for the source of metals and fluids

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The Caribou volcanogenic massive sulphide deposit is in northern part of the Bathurst Mining Camp, New Brunswick. The deposit is currently in production and contains 7.23 Mt of measured and indicated resources with average grades of 6.99 % Zn, 2.93 % Pb, 0.43 % Cu, 84.4 g/t Ag, and 0.89 g/t Au. The deposit is hosted at the base of the volcano-sedimentary Spruce Lake Formation. The immediate footwall and host of the stringer sulphide mineralization is dominantly shale with minor altered volcanic rocks, while the hanging wall consists dominantly of felsic volcanic with minor related sedimentary rocks. Massive sulphide mineralization forms six lenses along a horizon within the Caribou Synform. Each lens is internally zoned with Cu-rich vent proximal facies mineralization at the base, and Pb-Zn-rich bedded sulphide facies at the top. Nine polished thin section samples from different depths within five of the six lenses were selected for analysis, and 25 grains of galena larger than 100 µm were found in each polished thin section (n=225). Laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) analysis was done using the Resonetics S-155-LR 193nm Excimer laser ablation system coupled to an Agilent 7700x quadrupole ICP-MS at the University of New Brunswick. Ablation conditions were 60 µm beam diameter, 3 Hz, 0.35 J/cm^2 fluence, and 20 s ablation duration and data was standardized using Broken Hill galena and MASS-1 reference material, as well as in-house reproducibility standards. ^{204}Pb, ^{206}Pb, ^{207}Pb, and ^{208}Pb were simultaneously determined with Ag, Cd, In, Sn, Sb, Te, Hg, Tl, and Bi. Resulting ^{206}Pb/^{204}Pb and ^{207}Pb/^{204}Pb values were relatively homogeneous and overlapped within error, but ^{208}Pb/^{204}Pb values show a clear spectrum of values typical of a mixed source. In 4 of the 5 lenses, the sample from the base of the lens contains higher ^{208}Pb/^{204}Pb than the top. This indicates a change in fluid source during the formation of this deposit from a crustal A-type magmatic affinity (Th rich) to a normal upper crustal affinity. Variations in ^{208}Pb/^{204}Pb shows statistically significant negative correlations with Bi, Tl, Te, Cd, and Ag. This may simply be due to the greater abundance of trace elements at the top of the lenses, and the resulting increase in coupled substitutions into the galena structure. This study confirms that LA-ICP-MS analysis of galena can be a relatively rapid and inexpensive method for studying Pb isotopes, metal sources, and examining trace-element distribution in Pb-bearing base-metal deposits.

Crustal-scale tectonism of the Yukon Tanana Terrane, northern Canadian Cordillera: Constraints from zircon and apatite thermochronology

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Despite the relatively high elevation of the northern Canadian Cordillera, the lithosphere is more than 100 km thinner than the adjacent craton, reflecting the contrast in thermal regime and crustal exhumation history between the craton and mountainous Cordilleran region. The models commonly used to explain the present-day lithospheric structure of the cordillera are down-welling and delamination of the lower lithosphere. To better resolve the model for the northern Canadian Cordillera, the exhumation history and thermal structure within the Yukon Tanana Terrane will be elucidated, from which lithospheric strength profiles may be evaluated. The first phase of this study is determining the timing and rate of exhumation of different crustal blocks within this area of the cordillera using low-temperature (U-Th)/He thermochronology. Five crustal blocks spanning between 40 and 150 km wide have been defined using magnetic anomaly data and previously published structural and geochronological data. Numerical modeling of the zircon and apatite thermochronology data indicates that the Reid Lakes complex of the Yukon Tanana Terrane reached surface temperatures by 50 Ma after a protracted cooling history in the upper crust. However, most crustal blocks exhumed rapidly (~10 °C/m.y.) to the surface by 80 Ma following orogenic collapse, and preceding the exhumation to shallow depths of the mid-Cretaceous metamorphic core complex in western Yukon. These results mark an older exhumation history compared to the Alaskan and southern Canadian Cordillera, which define a dominant Eocene signature. Understanding the different processes governing orogenic plateau formation in the northern and southern Canadian Cordillera is significant for understanding the evolution of craton margins.

Ductile deformation and shear zone development in the South Range of the Sudbury impact structure

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The Sudbury impact structure represents a deformed impact crater that formed when a bolide collided with the southern margin of the Superior craton at 1850 Ma. The southern rim (South Range) of the Sudbury impact structure has been affected by several orogenic events, but the amount of ductile deformation that can be attributed to post-impact versus pre-impact events is still a matter of debate. Most orogenic events that affected the South Range have the same structural trends (shortening to the northwest), making it difficult to differentiate between events. Some structural features predate the impact and could be attributed either to the Blezardian (2450-2200 Ma) or Early Penokean (1890-1875 Ma) orogenies, but the extent and timing of pre-impact deformation are not well known. The South Range was brecciated during the impact and was thermally metamorphosed during cooling of the fractionated impact melt sheet, likely overprinting earlier structural features. The South Range was modified after the impact by the formation of major shear systems, such as the South Range Shear Zone (SRSZ). The older literature attributes the post-impact ductile deformation to the Late Penokean Orogeny (1850-1830 Ma). Although Penokean ages were obtained in a recent geochronological study of the SRSZ, other studies suggest that at least some of the deformation corresponds to the 1770-1600 Ma Mazatzal-Yavapai orogenies, and a circa 1450 Ma event. The different ages for deformation along the SRSZ could indicate that the shear zones formed through several deformation events, but the geometry of these post-impact structures could also be explained by a single, progressive dextral transpression event. In the southwest Sudbury impact structure, two main orientations of major shear zones overprint regional folding: 1) northeast-trending shear zones, which displace the SIC and are on strike with with the SRSZ to the northeast, and 2) an east-trending mylonite zone, which possibly correlates with the Creighton fault and displays dextral shear sense indicators. A strong, steeply dipping stretching lineation is present in the shear zones and within all rock types in the study area. The dextral displacement and the stretching lineation in the east-trending mylonite zone could have formed by dextral transpression, or during two separate deformation events. Using a combination of field mapping and microstructural analysis, the development of shear zones in the southwest Sudbury impact structure will be investigated to resolve this question and further our understanding of the structural evolution at the southern margin of the Superior craton.

Application of a hydrogeological conceptual model, south-central Ontario

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Often political and public perception is that we don't know enough about our groundwater flow systems to make effective decisions. Scientists also express frustration with the lack of readily available data and information. Perhaps the problem is simply that we as scientists have not done an adequate job of disseminating the wealth of hydrogeologic knowledge in a readily digestible format. This is illustrated through water resource management decisions and infrastructure installation problems that proceed seemingly unaware of the historical lessons learned regarding the hydraulic function of the flow system setting.

A regional three-dimensional geologic and hydrogeological understanding of subsurface conditions can be a very powerful tool to apply not only to regional initiatives such as water resources management but also to more local site specific investigations. A regional understanding of the hydrogeologic architecture (i.e. the conceptual model) should ideally draw upon subsurface information (e.g. borehole geology, hydraulic properties, water levels and chemistry) generated from historical projects. To effectively draw upon a wide pool of available information and to synthesize the information into a defensible conceptual model, a management and analysis system is necessary.

The philosophy for developing a regional conceptual model is that information and knowledge gained from previous projects can benefit future projects. This information allows specific sites under investigation to be placed into context within the regional flow system, and also to perhaps benefit from the knowledge gained from other similar hydraulic settings. For example, is the site in an area with high groundwater pressures? How extensive is the aquifer that occurs beneath the site? Such information has ramifications to the construction methods proposed and also to the types of investigative methods that will need to be employed.

This presentation discusses the development and current state of the study area hydrogeological conceptual model, and how it can assist us in our future endeavours. Specifically discussed is the status of 'groundwater problem area' mapping that seeks to disseminate hydrogeologic knowledge in a format useful to public works, planning and scientific practitioners. A key feature of the conceptual model is that it is continuously subject to refinement as new data and information becomes available.

Along-strike comparison of orogenesis and orogenic collapse within the Canadian Cordillera: Consequences of long-lived oblique convergence

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The long-lived oblique convergence along the western margin of the North American craton has resulted in a highly variable geodynamic setting through time that has produced one of the world's most complex orogens, the North American Cordillera, which is characterized by a seemingly chaotic collage of accreted terranes. An along-strike comparison of the variability of orogenesis and orogenic collapse within the Canadian Cordillera will be made, which can be attributed to the change in the obliquity of convergence through time from one of sinistral transpression to orthogonal to dextral transpression to dextral transtension.

Development of high-grade metamorphism and penetrative fabrics within the Canadian Cordilleran hinterland is strongly diachronous along the length of the orogen. An older and longer history of tectonism seems best preserved in the northern Canadian Cordillera that includes Permian to Late Cretaceous events, whereas its southern counterpart mainly preserves Early Jurassic to Late Cretaceous events. Regardless, a significant phase of orogenesis along the entire length of the Canadian Cordilleran orogen appears to coincide with Early Jurassic to mid-Cretaceous obduction of allochthonous terranes over the North American continental margin, which together with the imbrication of parautochthonous rocks, formed a foreland-propagating orogenic wedge.

Cordilleran orogenesis culminated in a Cretaceous plateau system that may have extended along most of the length and width of the Canadian Cordilleran hinterland. The plateau system likely achieved a maximum crustal thickness of at least 55-65 km, akin to that of the Altiplano and Tibetan plateaux, and was underpinned by plutonism, penetrative ductile deformation and high-grade metamorphism.

From north to south, the timing and modes of collapse of the plateau system and attendant exhumation of the deep crust appear to be quite different. In the north, the metamorphic hinterland changed from orogen-perpendicular wedge dynamics to orogen-parallel extension in the mid-Cretaceous. Rocks situated in the deep crust in the Middle Jurassic to Early Cretaceous were exhumed in the mid-Cretaceous along southeast-directed orogen-parallel extensional faults from beneath a supracrustal lid. Like the Himalayan orogen and eastern Alps, orogen-parallel extension in the northern Cordillera developed in an orthogonal plate convergent setting, simultaneous with, and bounded by, orogen-parallel strike-slip faulting that facilitated northwestward lateral escape of rocks normal to the direction of convergence. Conversely, collapse of the plateau system in the south was facilitated by Paleogene orogen-normal extensional faulting that coincided with a transition to a dextral transtensional plate convergence setting between oceanic lithosphere and the North American plate.

Gold deportment: Insights from exploration techniques

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Gold has numerous distinctive characters which makes evaluating its deportment in mill difficult. Gold grains are rare, distribution is uneven, and thus statistical representativeness is difficult to reach. Therefore establishing where it stands and how it behaves in a mill can be challenging. Gold is present as part per million in the ore, and parts per billion in the tails. Conventional techniques are of no match with statistics, and intense preconcentration is required to obtain a sufficient abundance of gold grains to be meaningful.

Preconcentration of gold grains for counting is routine technique in glacial drift exploration. Insight from the latest technologies enabling recovery of very fine grains can be used for assessing gold deportment in metallurgical processes. Conventional shaking table faces a recovery collapse for grains smaller than 50 µm. Compilation of hundreds of ore petrography studies indicates that gold grains smaller than 50 µm account for 43% of the metallurgical balance, although they represent 88% of the grains. A significant increase in recovery is achieved with fluidized beds (ARTGoldMD proprietary technology) and automated SEM grain counting, down to a grain size of 20 µm and 90% of mass recovery. Grains smaller than 20 µm are concentrated by centrifuging the sample in proprietary salt-based heavy liquids at a density up to 4.0 g/cm^3 or higher while grains are counted with automated SEM at high magnification. Non-liberated gold grains, hosted in particle larger than 20 µm, are concentrated with heavy liquids at a density up to 6.0 g/ml. Mineral proportion and attachment are evaluated with MLA type SEM routine. These preconcentration processes enable sufficient statistical representativeness even at the ppb gold level. Gold substituted in sulphide lattice can be evaluated by counting sulphides with MLA routine, plus spot checks of grade with LA-ICP-MS technique. Finally, gold is also present as remnant of cyanide leach liquor left as moisture, which can be evaluated by laboratory leaching. Combining these methods enables to document gold deportment accurately, locates recovery issues and allows adjusting the process accordingly. Tests are currently being conducted in a few mines from Abitibi.

The "Lift-Index": A method for the recognition of complex and heterogeneous signal in soil geochemistry

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Complexity of soil geochemistry and the metal enrichment processes is typically underestimated by exploration geochemists. This difficulty is traditionally circumvented by using simple statistical interpretation, assuming that the presence of a metal source in bedrock will contaminate its environment in a distinctive manner. Detailed surveys and test indicated that metal content in soil is dictated by its chemical micro-environment that controls fixation of metal from the mineralized occurrence. Consequently, metal content varies on a scale which is much smaller than its source, and the footprint of such mineralized occurrence is multifold. Most of the metallic signal is controlled by parameters such as pH, δpH, Eh, TDS, LOI, CEC plus a few controlling or buffering metals such as calcium and iron. The interplays of these parameters can be factored in using deterministic approaches, and a residual signal is obtained. This residual signal indicates that cations compete for adsorption site in a complex manner leaving entangled signatures which can hardly be deciphered with the use of statistics. The method is time consuming. However, the signal can be processed with the use of a binary classificator (artificial intelligence), which computes the rate of association of a specific signal (metal content) with a designated event (a known mineral occurrence).

Among the estimator use by binary classificator, the "simple lift" represents the rate of over-representation of a specific phenomenon (such as Fe between 500 and 5000 ppm) within a target population $L = (N_{tp}/(N_{tp}+N_{fn}))/(N_p/N_{total})$. This estimator is computed for each quartile (bin) of each variable, and its value is attributed to each variable of an entry (each analysis of each sample). Then, the "lift index" is calculated, which is the sum of the "simple lift" of the various elements for each sample. Results of the "lift index" are plotted on a map. The method has been extremely powerful at recognizing complex and heterogeneous signatures over a learning target (mineralized zone) and detecting similar although partial signature in the remaining population. Example will be given where geochemical signal in peat developed over 50 metres of overburden in the Abitibi Clay Belt efficiently responded to buried mineralization.

Charaterization of the metamorphic gradient across the New Quebec Orogen and relationships to tectonics

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The South-Eastern Churchill Province, accreted and deformed in a transpressional regime during the Paleoproterozoic Trans-Hudson Orogeny, is among the best exposed examples of possibly transitional tectonics between Archean and modern dynamics. Determining its past thermal state is key to the understanding of secular evolution of collision zones. The New Quebec Orogen (NQO) (1,82-1,77 Ga) is located on the west part of the province and results from the oblique collision between the Superior craton and the Core Zone (CZ). The NQO is subdivided in two main lithotectonic groups: the Labrador Trough (LT) and the Rachel-Laporte Zone (RLZ). The volcano-sedimentary sequences of the LT are interpreted as the low-grade westward-thrusted passive margin of the Superior craton and the RLZ the distal section of the margin involved in the metamorphic wedge. We present the preliminary results of the metamorphic quantification in the central segment of the orogen along a 50 km-long section, investigated by petrography, thermobarometry and geochronology. The described samples are garnet ± micas ± staurolite ± Al_2SiO_5 metapelites and garnet-bearing amphibolites. Pseudosection modelling is performed on both chemical systems. The peak conditions vary from upper-greenschist facies conditions in the LT (5.9-7.4 kbar/521-660°C, with uncertainties ranging from 0.7 to 2.5kbar for the pressure and 40 to 172°C for the temperature, AvgPT tool, THERMOCALC) to upper-amphibolite and locally granulite conditions in the East (7.0-8.3 kbar/725-823°C). These estimates are concordant with the observation of migmatites, locally in the RLZ and systematically in the CZ and yield a 40°C/km metamorphic gradient. These observations point to a common metamorphic evolution of RLZ and CZ during NQ orogeny supporting the hypothesis that the paraderived RLZ and basement-dominated western CZ may constitute a coherent tectonic unit. However, metamorphic peak conditions in the Torngat Orogen and the eastern CZ are older than the acknowledged age for the NQO collision phase, implying a possible tectonic boundary within the CZ that could coincide with the Lac Tudor shear zone (LTSZ). Lu-Hf dating on garnet, coupled with U-Pb on zircon and monazite are in progress to constrain prograde and retrograde metamorphism timing, and confirm the inferred polymetamorphic evolution of the CZ. Preliminary results highlight significant burial of supracrustal sequences along a Barrovian gradient during the NQ orogeny, which is hardly compatible with the dominantly strike-slip movement of all major shear zones in the South-Eastern Churchill Province.

Influence of inherited Indian basement faults on the evolution of the Himalayan Orogen

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The Himalaya is the result of on-going convergence and collision of India and Asia. The configuration of the Indian plate prior to collision with Asia is often overlooked, despite its importance in controlling the subsequent evolution of the orogen. Three fault-bounded orogen-perpendicular paleotopographic ridges of Precambrian Indian basement underlie the Ganga Basin south of the Himalaya. Analysis of spectrally filtered Bouguer gravity data and edges in its horizontal gradient at different source depths suggests that the bounding basement faults extend as deep as the base of the Indian lithosphere, and as far north as the northern extent of the underplated Indian lithosphere beneath the Asia crust. The location of these faults coincide with along-strike changes in the steepness of the underplating Indian lower crust and tearing of the subducting Indian continental lithosphere.

In the eastern Himalaya, the Yadong-Gulu rift is an active orogen-perpendicular graben developed in the upper plate (Asia), extending southward toward the north slope of the Himalayan range. The graben aligns with an earthquake-generating strike-slip fault in the high Himalaya, and with the Kishangang basement fault exposed in the lower plate farther south in peninsular India. It is argued that the graben results from the development of a crustal necking zone due to the reactivation of the underplated basement fault. In the central Himalaya, along-strike diachronous deformation and metamorphism within the Himalayan metamorphic core, as well as lateral ramps in the foreland thrust belt, spatially correspond to the Lucknow and Pokhara faults bounding the subsurface Faizabad ridge in the Indian basement.

Analogue centrifuge modeling confirms that offset along such deep-seated basement faults can affect the location, orientation, and type of structures developed in the mid- and upper crust at various stages of orogenesis. Our models suggest that (1) deep-seated, reactivated basement faults can localize structures in the upper crust during different stages of orogen evolution, and (2) it is mechanically feasible for strain to propagate through a melt-weakened mid-crust.

We suggest that these major orogenic cross-strike structures have affected the ramp-flat geometry of the basal Main Himalayan thrust, partition the Himalayan range into distinct zones, and ultimately contribute to lateral variability in tectonic evolution along the orogen's strike. Our interpretation also suggests that south Tibet graben are spatially related to deep-seated lithospheric-scale faults rooted in the underplated Indian crust.

Testing the veracity of a key paleomagnetic pole from the initial assembly of the North American continent

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A quantitative kinematic model for the initial assembly of the North American continent has been developed in recent years based on rapid growth of paleomagnetic and geochronologic data. But problematic data remains which is hard for current model to reconcile. Previous paleomagnetic poles from the Slave craton at 1.96-1.87 Ga define a ~110° arc near the equator, known as the Coronation loop. If all poles on the Coronation loop are robust, the assemblage history of the North American continent is more complex than currently envisaged. In particular, the paleomagnetic pole from the 1.96 Ga Rifle Formation lies substantially east of the rest Coronation poles and is difficult to explain in terms of the modern plate tectonics. Alternatively, this discordance is argued to be produced by local vertical-axis rotation, true polar wander, or anomalous geomagnetic field. Despite large uncertainties, the Rifle pole has been incorporated in various reconstruction studies, pointing to the significance of testing the veracity of this key pole. We collected five oriented block samples from one horizon of the Rifle Formation (redbeds) in the Kilohigok basin, eastern Slave craton, NW Canada. Detailed thermal demagnetization was conducted up to 700 °C. The characteristic remanent magnetization (ChRM) was isolated at high unblocking temperature (640-680 °C), indicating the hematite is the carrier of the ChRM. The mean ChRM shows a SE down and shallow direction after tilt correction, which yields a corresponding paleomagnetic pole considerably different from the previous Rifle pole but is in agreement with the rest poles on the Coronation loop. Stratigraphic correlation suggests that our new samples underlie the previous samples and are more close to the dated ash layer (1.96 Ga). The new Rifle pole is consistent with the current assembly model of the North American continent. However, because of the lack of rigorous field tests and insufficient sampling, it is important to conduct a systematic and continuous paleomagnetic study of the Rifle Formation in future work to evaluate the robustness of the Rifle poles and to help better constrain the initial assembly of the North American continent.

Early mafic magmatism in the Coldwell Alkaline Complex in comparison to MCR volcanism

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The earliest magmatic event in the Coldwell Alkaline Complex is represented by three distinct units of pyroxene hornfels grade metabasalt that together make up about 1/3 of the volume of the Eastern Gabbro Suite. Timing for emplacement of the metabasalt, previously referred to as fine grained gabbro, correlates with early stage formation of the Midcontinent rift including the lower units of the Mamainse Point Volcanic Group. Contact metamorphism occurred during intrusion of the Layered Series and the later Marathon Series which is associated with Cu-PGE mineralization.

The metavolcanic rocks consist of fresh plagioclase, clinopyroxene, orthopyroxene, and olivine and are classified as gabbronorite to melagabbronorite. The dominant texture is granoblastic with equigranular crystals having scalloped contacts and 120 degree triple points. Grain size in the lower and upper units is less than about 100 microns, whereas crystals in the middle unit are up to 1.5 mm. Poikiloblastic olivine and clinopyroxene crystals up to 2 mm in size, occur in the lower and middle units. It is likely that some middle unit samples represent shallow level intrusions.

The basal and middle units exhibit highly variable Al_2O_3 (5-16%), Ni (100-1325 ppm) and MgO (6-24%) contents similar to group 1 volcanic rocks at Mamainse Point, whereas the upper unit is relatively homogeneous with Al_2O_3, Ni and MgO abundances of 14-16.4%, 66-162 ppm and 6.1-9.4%, respectively. The basal unit is distinguished from the upper two units by high TiO_2 (1.3-1.86%), low La/Zr PM (<2.3) and low La/Nb PM (<2.0). The upper unit is distinguished from the lower two units by low Gd/Yb PM (<1.6). All three metabasalt units exhibit distinctive patterns on a PM normalized spider diagram with depleted Rb, K, Th, Zr and Hf and enriched Sr relative to Mamainse Point volcanic groups 1 and 2. In addition, Zr/Hf in metabasalt is lower than for MPVG groups 1 and 2, whereas Th/Yb and Nb/Th from each area are similar.

These observations suggest negligible crustal contamination of magma that formed the metavolcanic rocks. The basal and middle units are similar in some respects to Group II volcanism of the MCR, but with depleted LILE and HFSE suggesting the source mantle region for the early Coldwell magmas was different than that which generated Mamainse Point magma; perhaps due to the presence of residual amphibole in the mantle. The relatively low Sm/Yb PM in the upper unit suggests partial melting occurred a shallower depth than the other units.

Stratigraphy, structure and magmatism at the Superior—Southern province boundary, southwestern corner of the Sudbury Igneous Complex, Ontario

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Paleoproterozoic Huronian Supergroup (HSG) supracrustal rocks were deposited in a continental rift basin along the southern margin of the Superior Province during breakup of the Superior craton. The Ni-Cu-PGE endowed Sudbury Igneous Complex (SIC) is located within this rifted margin straddling the boundary between the Superior Province to the north and the Southern Province to the south. This area, last mapped over 50 years ago by the OGS, has been subjected to multiple episodes of deformation which has implications for control and modification of SIC-related mineralization. The extent and character of the Archean and Proterozoic rocks in the southwestern portion of the Sudbury Structure have recently been refined through new bedrock mapping, geochemistry and geochronology with the goal to improve the subdivision of the HSG stratigraphy and intrusive rocks, and to use this information in the interpretation of the structural history of the area.

Based on lithological, stratigraphic and geochemical characteristics, the sedimentary rocks have been divided into the Matinenda, McKim, Ramsay Lake, Pecors and Mississagi formations. All belong to the lower HSG and were deposited during the early rifting phase. The HSG and Archean basement were subsequently intruded by numerous mafic and felsic suites. In addition to the previously identified Matachewan and Sudbury dike swarms, Drury Township intrusion, and Nipissing intrusive suite, recent mapping has identified 1) early, NE-trending plagioclase-phyric dikes that cross-cut the Drury Township intrusion but pre-date the HSG, and 2) late, EW-trending hornblende gabbro sills and NE-trending felsic dikes, which cross-cut the HSG and Nipissing intrusive suite.

Structural elements are divided into pre- and post-SIC. Pre-SIC deformation resulted in early thrust faults near the base of the HSG and large-scale anticlinal and synclinal folding. Post-SIC deformation includes South Range Shear Zone related NE-trending faults, which offset the SIC and HSG, and an EW-trending mylonite zone, up to 500 m wide, that straddles the Superior-HSG unconformity. The majority of previously identified HSG volcanic rocks occur within this mylonite zone which is a major structural feature in Drury Township and may represent the westernmost expression of the Creighton fault.

Results from this study highlight: 1) pre-SIC deformation in the Sudbury area is more complicated than initially interpreted, 2) possible westward extension of the Creighton fault, which is known to displace mineralized offset dikes, 3) the exposure of HSG volcanic rocks is thinner westward than previously mapped, and 4) there are intrusive events that require further research to unravel.

Large-scale landscape and lithospheric flexure responses to the Pliocene-Pleistocene climate transition, Arctic Canada

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In the Canadian Arctic the magnitude of landscape responses to the Pliocene-Pleistocene climate change is greater than any other in the late Cenozoic globally, in part owing to a steepening of the latitudinal thermal gradient since the Pliocene. The White Channel Gravel (WCG) in Yukon, Beaufort Formation throughout the Archipelago, and correlative deposits formed an extensive cover of dominantly fluvial and alluvial deposits. Here, in tectonically quiescent regions, we demonstrate that the landscape experienced a binge-purge response to the climate transition. ^{10}Be-derived paleo-erosion rates on King Solomon Dome were slow (mean 3 cm/ka) during the deposition of the lower WCG from 3.80.3 to 3.50.5 Ma (1-σ error on ^{26}Al/^{10}Be isochron burial ages) while thick saprolites developed (binge-phase). At 3.5 Ma erosion rates quadrupled (purge phase) as climate began to cool (as evidenced by cooler paleovegetation, first appearance of ice wedge casts, and globally a significant glaciation 3.5 to 3.3 Ma). The upper WCG (3.50.5 Ma to 2.80.2 Ma) records a gradual slowing of erosion (mean 2 cm/ka) following the purge phase as the system became weathering limited. Mineral liberation analysis on the lower and upper WCG reveals a diagnostic inverse stratigraphy with respect to sediment maturity. The lower WCG has mature quartz-dominated sediment, whereas the upper WCG is increasingly less weathered toward the top. This is also reflected in the decreasing concentration of placer gold from lower to upper WCG. We propose this response was even greater poleward. Between 3.8 and 2.8 Ma on the western Archipelago, the forested, quartz-sand dominated Beaufort Fm coastal plain thickened westward to form a clastic wedge reaching over 2.5 km thick offshore (Iperk Fm). Surface processes that contributed to this binge-purge mechanism include intense weathering and permafrost thawing (e.g. of the Eureka Sound Group) until 3.5 Ma, followed by intense frost-cracking and greater precipitation after 3.5 Ma. Striated clasts in a cobble gravel within the Beaufort Fm on northern Banks Island may have been deposited during the MM glaciation. We show that lithospheric flexure induced by clastic wedge loading and Northwest Passages incision explains large-scale elements of topography and the remnant distribution of the Beaufort Fm, and requires more than 100 m of Beaufort Fm erosion on some islands.

Stratigraphy, chemostratigraphy and paleoenvironmental analysis of a ~1.0 Ga carbonate shelf succession: The Brock Inlier, Northwest Territories, Canada

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The Brock Inlier is an uplifted region east of Darnley Bay, Northwest Territories, composed of mainly carbonate and siliciclastic sedimentary rocks of the early Neoproterozoic (~1000-720Ma) Shaler Supergroup. Strata were deposited in a large embayment (Amundsen Basin), an epeiric sea within the supercontinent Rodinia. Strata in the Brock Inlier correlate with other inliers of the Shaler Supergroup to the northeast on Victoria and Banks islands, and with the Mackenzie Mountains Supergroup, to the southwest. The ~900Ma Boot Inlet Formation, occurs stratigraphically in the middle of the Shaler Supergroup and is interpreted to represent deposition along a storm-dominated carbonate ramp. Ooidic grainstone characteristic of the basal Boot Inlet Formation is interpreted to represent inner-ramp shoals that indicate gradual shallowing from hummocky-cross bedded quartz arenites interbedded with laminated dolosiltites and dololutites representing mid-ramp deposits of the conformably underlying Grassy Bay Formation. Upsection, a transition to intraclast rudstone interbedded with molar tooth lime-mudstone represent intermittent storm activity and net deepening to mid-ramp facies. Overlying strata are not exposed in this part of the study area, but to the northwest, are inferred to be represented by stromatolitic bioherms that capture another shallowing event to inner-ramp deposits. These rocks are succeeded by mid-ramp and then outer-ramp facies comprising laminated dololutites with interbedded green clay-bearing shales, which represent rapid basin deepening. Mid-inner ramp facies comprising cross bedded dolosiltites present evidence of a final shallowing event that is capped by a distinctive ~90m thick, regionally extensive, stromatolite biostrome. Multiple shallowing/deepening events are therefore preserved in approximately 300m of section. The upper Boot Inlet Formation is not preserved in the study area as it has been precluded by sub-Cambrian erosion.

Stable isotope analysis of 131 carbonate rock samples from the Boot Inlet Formation yield $\delta^{13}C$ values ranging from -0.2 to 7.6‰ trending positively upsection. $\delta^{18}O$ values range from -4.1 to -9.5‰ with no apparent stratigraphic trend. No covariation between $\delta^{13}C$ and $\delta^{18}O$ values is observed, suggesting that diagenesis did not significantly modify the primary signal. $\delta^{13}C$ and $\delta^{18}O$ data coupled with lithostratigraphy and a preliminary sequence stratigraphic framework support and strengthen correlation between the lower Boot Inlet Formation on Victoria Island (~400km to the northeast) and the lower part of the Little Dal Group in the Mackenzie Mountains (~600km to the southwest). This establishes the broad (>1200km wide) regional distribution of a carbonate platform that extended from the Amundsen Basin, to a contemporary platform in the Mackenzie Basin.

Contrasting Archean and Proterozoic subcontinental lithospheric mantle: Constraints from the geochemistry of LIP continental flood basalts

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Approximately 3700 basalts from 10 Continental Flood Basalt provinces (CFB) representing 9 Large Igneous Provinces (LIPs) are used to compare Archean and Proterozoic subcontinental lithospheric mantle (SLM). Mantle source compositions are assessed using Similarly Incompatible Element Ratios (SIER; e.g. Nb/Pb, Rb/Ba) which are minimally impacted by differentiation and melting percentages. We also use Fe, Mn, Sc, V, Cr, Ni, Cu and Zn Transition Metal (TM) concentrations in 109 primitive CFB (Mg# = 0.69-0.72) as proxies for mantle geochemistry. Relative SIER behavior in the data set is consistent with CFB, regardless of emplacement age, but transecting Archean lithosphere, having higher SLM source concentrations of Rb, K and Pb. Phosphorus, Ti, Nb and Ta appear elevated in Proterozoic and younger SLM sources. Archean SLM may have been enriched in alkali metals and Pb in association with melting of subducted ocean floor to form Archean tonalite-trondhjemite-granodiorite suites. Niobium, Ti, and Ta were not efficiently transferred to the SLM suggesting stabilization of oxide phases in down-going Archean slabs. Archean SLM has EM1-like SIER but the ratios are more extreme than in oceanic island basalts (OIB) supporting an Archean SLM origin for OIB EM1 (Enriched Mantle 1). Transfer of Archean SLM to the convecting mantle may be from Phanerozoic subduction-related delamination or local SLM fragmentation during rifting. In contrast, OIB HIMU (high U/Pb) sources appear to have more extreme SIER than in all CFB but are closest to CFB from Proterozoic SLM. A SLM source for OIB HIMU provides long-term isolation (no homogenization in the convecting oceanic mantle) for incubation of subducted ocean floor to yield the extreme Pb isotopic compositions of HIMU. There is a tendency for lower Sc, Cr, Ni and Cu, and higher Zn, in Archean-cutting CFB and EM1 OIB, than in Proterozoic-cutting CFB and HIMU OIB. All CFB have SiO_2 (pressure proxy) – Nb/Y (percent melting proxy) relationships supporting low pressures and high percentages of melting that resemble OIB tholeiites, but TM concentrations do not correlate with percent melting. Various works have suggested that TM-fertile LIP layered mafic intrusions tend to occur in association with rifted Archean terranes. However, it does not appear that their economic viability is related to higher metal concentrations or higher percentages of melting in Archean SLM. Other characteristics of these Archean-cutting LIP magmas (e.g. S or O fugacity) may lead to element scavenging/concentration during differentiation to form ore deposits.

Understanding the response of arsenic in sub-Arctic lakes to Holocene climate variability

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Climate variability has a profound impact on the bio-physico-chemical environment in high-northern latitudes by altering lake hydrology, seasonality, and permafrost development, in addition to other mechanisms. These changes, in turn, influence chemical loading, cycling, and stability in northern lakes. Characterization of the impact of these and other drivers of chemical change are thus critical for sustainable development of natural resources and environmental assessment. This is particularly true of hydrothermal gold deposits in the Slave Geological Province (SGP), Northwest Territories (NWT), associated with abundant arsenopyrite that can transform to more toxic forms of arsenic (As) through weathering and ore processing. For example, the Giant Mine near the Yellowknife released substantial quantities of As to the environment during ~65 years of gold ore processing. In the NWT, where aforementioned gold mining activity pre-dates long-term monitoring data, paleoecological studies of lake sediments permit reconstruction of natural variation in As associated with climate change. To define past and current impacts from resource development, and to understand the impact of climate change on As concentrations in lacustrine systems, sediment cores were recovered from Milner Lake, a site adjacent to a prospective gold mine within heavily mineralized shear zones in the SGP ~15 km North of Yellowknife.

Sediment cores were collected using freeze coring, a method that permits the high-resolution sampling required in slow-sedimentation, high-latitude lakes, where <1 cm of sediment deposition may represent >100 years. Sediment cores were analyzed using Itrax core-scanning x-ray fluorescence (Itrax-XRF). Itrax-XRF provides sub-mm geochemical data for a fraction of the cost and time required for ICP-MS analysis. This high-resolution approach is necessary to identify climate cycles (e.g. Pacific Decadal Oscillation) and hypothesized associated chemical trends occurring on a timescale relevant for land-use planning. Sediment cores were sub-sectioned into 12 × 3 cm slabs and transported to the McMaster University Itrax core-scanning facility for analysis. On site, sub-sectioned material was placed into custom-designed sample holders used for analyzing frozen sediment. Remaining core material was sub-sampled for particle size analysis, Rock Eval pyrolysis and micropaleontological analyses to provide insight into the processes potentially involved in geochemical change and to quantify ecological responses to climate and chemical change. Bulk organic matter samples were selected at regular intervals along the core length for radiocarbon analysis. Here we present preliminary results from geochemical analysis of a core and comment on the observed geochemical response to major climate events, such as the Little Ice Age.

Keynote (30 min): Self-consistent shear zone formation with applications to thermochronological dataset interpretation

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Crustal-scale shear zones are generated by strain localization, which in turn has several controlling mechanisms. We perform two-dimensional numerical simulations of shortening a viscoelastoplastic lithosphere to investigate the strain localization due to thermal softening.

Our modelling results demonstrate that orogenic wedges develop spontaneously in response lithospheric shortening in a basic thermo-mechanical framework. The modelled orogenic wedges are characterised by the presence of (i) a first order deeply rooted shear zone, and (ii) a sequence of second-order shear zones in the upper crust. All shear zones are caused by thermal softening and result from local temperature increase due to shear heating and the temperature-dependence of viscosity. Continental underthrusting takes place along a first-order shear zone that initiates spontaneously. Whereas a sequence of second-order shear zones dissects the upper crust in a series of tectonic nappes altogether forming an orogenic wedge. The depth of the upper/lower crust boundary controls the lateral spacing of upper crustal shear zones. In the models, the second order shear zones are typically active for a duration between ~1 and ~4 My, while the first-order shear zone is active during the entire simulation (10 to 20 My).

The changes in rate of exhumation cause the underlying temperature field to change; the shear zones strongly deflect the isotherms by heat advection during the orogenic event and the rapid thermal relaxation towards a conductive geotherm that follows. The high temporal resolution of our experiments demonstrates that such shear zones are transient in time so that the resulting shear heating is also transient. These thermal processes have an effect on the techniques used to determine exhumation rates in the upper crust and consequently on the techniques used to determine the age of the faults and shear zones. To include the effect of a transient temperature field requires solving the heat equation numerically. Examples of natural temperature histories will be discussed in the terms shear zone histories by comparing false interpretations using traditional techniques and their reinterpretation based on numerical predictions.

Use of anisotropy of magnetic susceptibility (AMS) to analyze magmatic petrofabrics in Cu and PGE bearing gabbroic units of the Marathon Cu-PGE deposit, Ontario

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Petrofabric assessment of Cu and PGE bearing gabbroic units has been conducted on oriented drill core samples obtained from the Main Zone of the Marathon Cu-PGE deposit. Samples taken from three oriented drill cores representing mineralized and non-mineralized zones were analyzed using Anisotropy of Magnetic Susceptibility (AMS). These magmatic Cu-PGE sulphide deposits are proposed to have formed by intrusion of a crystal mush within a magma conduit setting. Magnetic anisotropy is influenced by the preferred orientation of the long axes of grains of magnetite, which is similar to the overall petrofabric of the samples defining the flow direction of the crystal-bearing magma. Susceptibility ellipsoids constructed from analysis of AMS measurements were plotted on a Flinn diagram to investigate the dominant petro fabric textures, indicating the presence of a well-defined planar fabric. Samples that gave results of the highest degree of planar fabrics were from the Two Duck Lake Gabbro lithology; the lithological host of most of the Marathon deposit. Stereonet projection of the directional distribution of the susceptibility ellipsoid maximum and intermediate vector directions gives a well-defined planar fabric orientation of strike 177 and dip 25° to the west, in excellent agreement with proposed flow direction based on 3D modeling of footwall troughs containing the higher grade mineralization. A fabric lineation has also been detected for drill cores obtained from the Main Zone with an average trend of 295 and a plunge of 29° reflecting the likely direction of origin for the magma. Samples obtained from W-horizon area of the Marathon deposit also indicate strong planer fabric foliations. The AMS fabric orientation is a potentially useful tool to independently quantify flow structures in magmatic systems.

Community organization of equatorial reef-dwelling brachiopods from the early Silurian (late Telychian) Attawapiskat Formation, Hudson Bay, Canada

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The well-known benthic assemblage (BA) concept developed in the 1970s has facilitated understanding the community structures of early–middle Paleozoic level-bottom environments, through the study of rich and diverse invertebrate faunas. The concept, however, is difficult to apply to reef settings due to increased substrate heterogeneity and the common mixing of generally discrete level-bottom benthic communities. In this study, Shannon and Simpson diversity indices were calculated for reef-dwelling brachiopod faunas from several North American, and one European, localities. Reef-dwelling brachiopod diversity collapsed at the end of the Ordovician and did not recover for several million years until the mid-Aeronian when modestly diverse reef faunas appear in the high-latitudinal tropics of Laurentia. Reef-dwelling brachiopods did not achieve high diversity levels until the Telychian when reefs colonized the paleoequatorial located Hudson Bay and Moose River basins. The middle–late Telychian Attawapiskat Formation contains the earliest known coral-stromatoporoid reef complex which is associated with a highly diverse (53 species) brachiopod-dominated benthic fauna. Large collections (>9000 specimens) of brachiopods from this formation were collected from 30 sites on Akimiski Island, James Bay, Nunavut in the early 2000s. Cluster and principal components analyses separated the reef-dwelling fauna into 10 community associations based on taxonomic composition. These associations were further grouped into a level-bottom-like and cryptic group based on dominant brachiopod taxa, diversity levels, average shell size, substrate type, and the area of the reef they inhabited. The level-bottom-like group consisted of low-diversity associations dominated by large shells which prefer flat inter-reef areas while the cryptic group is composed of high diversity assemblages dominated by small shells which aggregated within reef cores surrounded by corals and stromatoporoids. Brachiopod community zone mixing within the Attawapiskat Formation is explained by water temperature and storm frequency. It has been shown that the equatorial seas were too warm during the Telychian to be invaded by the cool-water Stricklandia. The presence of deep-water species Clorinda and Gypidula in the shallow water Attawapiskat reefs is due to the lack of hurricane-grade storms in the equatorial region. In higher latitudes these storms restrict these species below storm wave base as their small shells would be easily smothered by storm deposited mud.

One billion years of fluid-flow through giant carbonate mounds, Mesoproterozoic Nanisivik zinc district, Nunavut

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The Mesoproterozoic (1.1 Ga) Borden basin (Nunavut) contains extremely large deep-water dolostone seep-mounds (Ikpiarjuk Formation) associated with syndepositional faults. Primary voids in the Ikpiarjuk Formation's microbial framework contain multiple generations of synsedimentary and late cement. The mounds' post-seafloor diagenetic history, as recorded by late cements, was studied using in situ analytical methods, including petrography, SEM analysis, fluid inclusion microthermometry and evaporate mound analysis, LA-ICP-MS analysis, and SIMS analysis of O isotopes. Six void-filling late cements include, in paragenetic order: inclusion-rich euhedral dolomite (ED), finely crystalline clear dolomite (FCD), hematite-bearing dolomite (HD), coarsely crystalline clear dolomite (CCD), quartz (Q), replacive calcite (RC) and late calcite (LC). Average homogenisation temperatures of fluid inclusion assemblages in FCD, HD, CCD, and Q are 110°C, 84°C, 117°C, and 154°C, respectively. Combined eutectic and ice melting (Tm(ice)) temperatures of FCD, HD, and CCD inclusions indicate Ca-rich, saline fluids (20 to 37 wt. % equiv. NaCl). In contrast, the Tm(ice) for quartz-hosted inclusions indicates a lower-salinity NaCl fluid (14 wt.% equiv. NaCl) than preceding phases. Average $\delta^{18}O$ values of dolostone, ED, FCD, CCD, Q, RC and LC are +26.3‰, +34.3‰, +35.4‰, +24.5‰, +26.6‰, +15.2‰ and +9.5‰, respectively. Dolostone, ED, and FCD have shale-normalised REE+Y patterns, with LREE<HREE, no La or Gd anomalies, and positive Y anomalies. Hematite-bearing dolomite has abundant hematite inclusions and rare pyrite, sphalerite, and galena inclusions. Coarsely crystalline clear dolomite has significant LREE depletion and MREE>HREE. Calcite displays LREE<HREE and a strongly negative Ce anomaly. In paragenetic order, the cements record the following history: (1) ED precipitation by autocementation during shallow burial (fluid 1); (2) progressive mixing of Ca-rich hydrothermal fluid with seawater-derived pore water, resulting in precipitation of FCD followed by HD (fluid 2); (3) continued hydrothermal dolomite precipitation (CCD) from a mixture of high-Ca and K-bearing fluids (fluid 3); (4) hydrothermal Q precipitation (fluid 4), and (5) RC and LC precipitation by meteoric water (fluid 5) in or since the Mesozoic. Sulphide inclusions in HD provide a possible link to the Nanisivik Pb-Zn mineralising event (ca. 1.1 Ga). Fluids associated with FCD, HD, and CCD may have been mobilised during deposition of the upper Bylot Supergroup; this interval was the most tectonically active time in the region's Mesoproterozoic to Recent history. The entire history of episodic fluid migration and cement precipitation spans over 1 billion years.

Late Ordovician chemostratigraphy of the Hudson Bay and Moose River basins

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The Paleozoic epicratonic Hudson Platform contains several sub-basins segregated by basement arches. The Moose River Basin (MRB) (northern Ontario), and the Hudson Bay Basin (HBB) (northern Ontario, northern Manitoba, and southern Nunavut) contain approximately similar stratigraphic successions that differ substantially in thickness. To investigate the thickness differences of the two basins during the Late Ordovician, stable $\delta^{13}C$ isotope chemostratigraphy was undertaken on core samples. Ten isotopic stages are identified in Upper Ordovician strata of the HBB. These stages are correlatable across much of the subsurface stratigraphy and into the type-section outcrop belt near Churchill, Manitoba. These isotope stages are best developed in basinward sections, whereas sections closer to the paleo-basin margin display heterogeneity due to paleoenvironmental differences. When combined with published biostratigraphic data, several of the positive isotope excursions in the HBB isotope curve are linked to established North American isotope excursions, including the end-Ordovician Hirnantian Isotope Carbon Excursion (HICE), and possibly the Elkhorn, Whitewater, and Waynesville excursions. Stable isotope stages are more difficult to distinguish in the MRB, where biostratigraphic data are limited; five distinct isotope stages are present. The stable isotope profiles in the MRB seem to have been variably affected by extensive dolomitisation, and interpretation is further complicated by substantial lateral changes in lithofacies and possible exposure intervals. Based on interpreted position of the Ordovician-Silurian boundary, the HICE is also identified in the MRB, but poor biostratigraphic control makes linking of other MRB isotopic excursions to the HBB and the global curves tenuous. Chemostratigraphic correlation confirms that Late Ordovician (Katian through Hirnantian) sediment accumulation rates were markedly different in the HBB (200 m) and MRB (50-75 m). Despite the thickness variation, the C isotope curve, lithofacies, and the interpreted paleoenvironment through the Portage Chute Formation in both basins are very similar. The C isotope curve through the Surprise Creek Formation differs markedly between both basins, in spite of displaying a similar thickness through both basins and broadly similar paleoenvironments. The Caution Creek and Chasm Creek formations are entirely absent in the MRB yet there is no evidence for a lengthy depositional hiatus, and the lowermost Red Head Rapids Formation of the MRB may represent a lateral facies equivalent of missing strata. The uppermost Red Head Rapids Formation was a subaqueous evaporitic basin in the HBB, but a subaerial mudflat in the MRB, and despite the vast difference in lithofacies and paleoenvironment the C isotope curves are similar.

New U-Pb ages on Neoproterozoic dykes in Yukon and Tasmania: Further evidence for a Laurentia-Tasmania liaison in Rodinia?

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We report new high-precision U-Pb baddeleyite ID-TIMS ages on Neoproterozoic dyke swarms in Yukon and Tasmania. The small, arcuate, N-NE trending Tatonduk dyke swarm straddles the Alaska-Yukon border in the Proterozoic Tatonduk inlier at the western extremity of Laurentia, where it intrudes late Mesoproterozoic–Tonian strata of the Pinguicula and Fifteenmile groups. These mafic dykes are assumed to be equivalent to the Pleasant Creek Volcanics, a sequence of massive and pillowed basalts lying unconformably above Tonian strata and conformably below Rapitan-aged glacial deposits. Concordant U-Pb data on baddeyites from a single Tatonduk dyke yield a weighted-mean $^{206}Pb/^{238}U$ age of 713.7 ± 0.9 Ma (2σ, MSWD = 0.13, n=4). The Tayatea dyke swarm comprises a series of mainly tholeiitic dykes that intrude the Mesoproterozoic Rocky Cape Group in and near the Smithton Synclinorium in northwestern Tasmania. The Tayatea dykes have been subdivided into three groups based on their geochemistry and orientation. Baddeleyite crystals separated from two of these groups yielded weighted-mean $^{206}Pb/^{238}U$ ages of 711.5 ± 2.5 Ma (2σ, MSWD = 0.22, n=7) and 690.3 ± 2.3 Ma (2σ, MSWD = 0.83, n=8). The new date on the Tatonduk dykes and stratigraphic relationships imply that the Pleasant Creek Volcanics were emplaced during the early Cryogenian (Sturtian) glaciation. It also provides a maximum age on deposition of overlying iron formation that is strikingly similar to a detrital zircon U-Pb maximum age on the Sayunei iron formation in the Rapitan Group on the Yukon-Northwest Territories border. Both dates are close to the older Tayatea dyke age and similar to SHRIMP U-Pb ages on the Sturtian Scout Mountain Member of the Sturtian Pocatello Formation in southern Idaho. The younger Tayatea age is similar to SHRIMP ages obtained on the upper Pocatello Formation, the equivalent Edwardsburg Formation in central Idaho, and the Gataga Volcanics in northern British Columbia. Together, these new radiometric ages support a Proterozoic link between Tasmania and the Cordilleran margin of Laurentia, which has been proposed based on the parallels between the Rocky Cape Group and the ca. 1.45 Ga Belt Supergroup and their respective detrital zircon spectra. These ages also add to a growing list of intermediate to mafic magmatic events along the northern and western margin of Laurentia that overlap with ages from the Franklin large igneous province (LIP) and collectively define a spectrum from plume- to rift-related magmatism associated with the break-up of Rodinia and onset of Cryogenian glaciation.

Matachewan dyke swarm: New high-resolution U-Pb studies refine the emplacement chronology of the Matachewan LIP

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The Matachewan large igneous province (LIP) comprises one of Earth's most extensive and voluminous radiating mafic dyke swarms, infolded remnants of flood basalts, gabbroic to anorthositic layered intrusions and, locally, granitic plutons and rhyolites. Yet despite its enormous size and relevance to plate reconstructions involving the Superior craton and now dispersed members of its predecessor craton Superia, the detailed age structure of the Matachewan LIP has remained to be resolved. The Fe-rich, qz-tholeiitic Matachewan diabase dykes, striking mostly N-S to NW, outcrop over 300,000 km^2 and appear to radiate from a magmatic focal point south of Sudbury along the southern Superior margin. The widely-cited, pioneering U-Pb study by Heaman (1997) established constraints from four Matachewan dyke localities, revealing ages at 2445 Ma and 2473 Ma, and a possible minimum span of magmatism of ~30 Myr. Coupled with ages for a number of lavas, plutons and mafic layered complexes (some of which host Ni-Cu-Cr(V) and PGE mineralization) near the cratonic margin, the potential interval of magmatism reaches ~45 Myr.

We present new U-Pb baddeleyite geochronological data for 11 Matachewan dykes, collected from a wide geographic area, in order to provide accurate and precise limits on the emplacement chronology of this giant radiating swarm, to test the pulsed or continuous nature of the magmatism, and to test age relationships between intrusive and extrusive members of this LIP. With one exception, we find that all Matachewan dykes studied appear to have been emplaced in a continuous fashion within a narrow time interval between 2462 Ma and 2450 Ma. A single, roughly N-S trending dyke from Rouyn-Noranda yields a much older age of 2479 Ma, but lacks characteristic plagioclase phenocrysts/megacrysts and has anomalously high La/Yb relative to typical Matachewan dykes. This dyke may represent a component of a distinct, unrelated swarm, intermediate temporally between Matachewan dykes and the ca. 2505-2515 Ma Mistassini dyke swarm, focused further northeast along the southern Superior margin. Ongoing efforts are being made to improve the accuracy and precision of ages for other components of the LIP (e.g. East Bull Lake intrusions, see Clough & Hamilton, this meeting). Paleomagnetic studies of precisely-dated dyke samples suggest they capture at least one polarity reversal during this interval. Precise correlations are now more reliably testable with mafic magmatism in Wyoming and Karelia-Kola cratons, which have been suggested as complementary components of a rifted supercontinent formerly involving Superior craton.

U-Pb dating of Payne River and Tasiataq diabase dykes of the NE Superior craton: Implications for the 2.17 Ga Biscotasing magmatic event and rifting along the eastern cratonic margin

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Early U-Pb dating of two NNW trending Payne River dykes in northern Ungava indicated an imprecise age estimate of ca. 2170-2160 Ma. Further study of these two dykes has been carried out to refine their ages. A paleomagnetic study of the NW trending Tasiataq dyke, ~200 km south of the Payne River dykes, suggested that it was part of the 1998 Ma Minto dyke swarm. However, more recent work indicated that this dyke might not belong to the Minto swarm based on differences in geochemistry, paleomagnetic polarity, and dyke orientation (ie. an orientation inconsistent with the overall geometry of the newly-identified Minto-Lac Shpogan giant radiating swarm). Therefore, U-Pb dating of the Tasiataq dyke has been carried out to clarify its age. The pair of Payne River dykes yield concordant, overlapping CA-ID-TIMS U-Pb zircon ages of 2169.9 ± 1.5 Ma and 2169.2 ± 1.5 Ma. The Tasiataq dyke yields a U-Pb baddeleyite age of 2169.5 ± 2.1 Ma. Therefore, the ages of the Tasiataq dyke and Payne River dykes are indistinguishable. Taken together, these dykes suggest a radiating pattern focused near the coeval Cramolet Lake gabbro sills of the New Quebec Orogen. These three units are also coeval with the extensive Biscotasing dyke swarm and the Otish gabbro sills of the Otish sedimentary basin in the southern Superior craton. The Biscotasing swarm trends SW and may form part of an overall radiating pattern with the Payne River and Tasiataq dykes, although the Biscotasing dykes have yet to be traced close to the New Quebec Orogen. If so, then the overall, short-lived, voluminous 2.17 Ga mafic magmatic episode – termed the Biscotasing event – would appear to be centred along the Superior craton's eastern rifted margin. Elements of this magmatic event may be found on whichever cratonic block rifted away from the eastern Superior. The three subswarms are dominantly Fe-enriched, quartz-normative tholeiites with coherent incompatible trace element compositions. Paleomagnetic data from Tasiataq, Payne River and Biscotasing dykes are broadly consistent, and record at least one magnetic field reversal. The Biscotasing paleopole and the Tasiataq virtual geomagnetic pole (VGP) are known to date from the time of dyke emplacement, whereas the Payne River VGP has not been demonstrated primary. The difference between the Tasiataq VGP (from a single dyke) and the Biscotasing paleopole may reflect secular variation, although a small amount of block rotation between the northeastern and southeastern Superior craton cannot be ruled out.

An experimental and innovative approach to peer learning in the field

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The use of active learning and collaborative strategies is widely gaining momentum at the university level and can be applied in class and field instructional settings. Peer learning, when students learn with and from each other, is based on the principle that students learn in a more profound way by explaining their ideas to others and by participating in activities in which they can learn from their peers. The Multidisciplinary Applied Geochemistry Network (MAGNET), an NSERC Collaborative Research and Training Experience (CREATE) initiative, recently experimented with this approach during our 4th annual workshop. In August 2016, we took a group of 25 geochemistry graduate students from across Canada to explore three remarkable field sites in Montana and Wyoming spanning 4 billion years of Earth history: the Stillwater Complex, the Beartooth Mountains and Yellowstone National Park. Rather than developing a rigorous teaching curriculum led by faculty, groups of students were tasked with designing and delivering half-day teaching modules that included field activities at each of the locations. Over the course of two months and with feedback from mentors, the students transformed their ideas into formal lesson plans, complete with learning goals, a schedule of teaching activities, equipment lists, and plans for safety, environmental mitigation and archiving of samples and data. This shift, from teacher-centered to learner-centered education, requires students to take greater initiative and responsibility for their own learning and development. We highlight the goals, structure and implementation of the workshop, as well as some of the successes and challenges. We also present the results of participant feedback taken immediately after each lesson and both pre- and post-trip surveys. This self-reflection and peer assessment provides valuable insight into student learning and perceptions of what worked and what could be improved. The outdoor classroom and hands-on activities enhanced understanding of concepts introduced earlier in the year and gave students a sense of scale, context and perspective. The trainee-led format facilitated peer knowledge transfer and the development of skills in three key areas: (1) project and time management, (2) teamwork and communication, and (3) critical thinking and problem-solving. Time constraints and unforeseen field circumstances were the most difficult aspects that the student instructors had to overcome. The MAGNET experience with peer learning offers the opportunity to learn from an established Canadian training program and represents a model that can be adapted for future field courses and workshops.

High-energy subglacial to proglacial erosion produced eskers, canyons and "scabland-like" river courses draining into the Pasfield Lake Impact Structure, northeastern Saskatchewan

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WITHDRAWN

During the retreat of the last continental ice sheet across northern Saskatchewan, the Pasfield Lake Impact Structure provided a deep crater lake basin, up to 300 m deep, into which voluminous sand and gravel were deposited from eskers and associated, subglacially-scoured, river channels and canyons. Pasfield Lake, an oval-shaped lake 27 km long by 13 km wide and up to 120 m deep, is located in the eastern part of the Athabasca Basin. It is surrounded by sandstones of the Manitou Falls Formation of the Proterozoic Athabasca Group. These rocks were locally swept clean of 10-15 m of till, and also channelized into scabland-like sections of bedrock up to 2 km long and up to 1 km wide. Large meanders developed initially until the bedrock surface was exposed. Locally this surface displays flutes attesting to the high-energy flow regime. Subsequent down-cutting along radial faults, related to the impact, produced steep-walled canyons up to 3[illegible] m deep and 200 m wide and several kilometres long. These were commonly joined by tributary canyon streams along more concentrically oriented faults. The canyons end somewhat abruptly about 2.5 to 3 km from the shore of Pasfield Lake, and are believed to mark the location of the crater wall. Beyond the canyon mouths, the river valleys widen, flatten and become broad sweeping meanders floored by boulder pavement or outwash and delta sands. The river courses and canyons are best developed along the east side of Pasfield Lake. They are mainly dry or have very under-fit, spring-fed streams. Th[illegible] there are dry rapids and dry waterfalls up to 20 m high, some of the latter are horse-shoe shaped, and some had plunge pools. Proglacial erosion appears to have continued the process and may have been related to sudden draining of higher levels of Pasfield Lake as indicated by raised beaches, eroded delta terraces at and above the mouths of the canyons, and erosion of previously deposited sandstone fragment deposits in the lower, shoreward sections. The position of the crater wall indicates a crater of about 19 km diameter into which post-impact sedimentation could occur. Uranium exploration diamond drilling, between 2006 and 2009 by Triex Minerals Corporation, intersected up to 200 m of mudstone, sand and gravel partially filling the crater. The volume of sediment contributed by subglacial erosion into the crater is estimated to be 54 to 72 km^3.

A new geological map and map database for Canada north of 60

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Two and a half years in the making, staff of the Geological Survey of Canada (in cooperation with the Yukon Geological Survey, the Northwest Territories Geological Survey and the Canada-Nunavut Geoscience Office) have been constructing a new regional-scale geoscience map and map database for Canada north of 60. The purpose of this presentation is to provide an overview of the map and related database components and capabilities for access and retrieval of a wide range of geoscience information as might be used for land use evaluation, and mineral and energy exploration across the region.

Types of data include polygon and line spatial objects covering Yukon, Northwest Territories, Nunavut and the offshore. Linear features include faults of various types. Primary polygon attributes include: lithologic units (assigned from a list of 164 terms) and compiled at the "super assemblage" level; plutonic and volcanic settings and environments of sedimentary deposition; protolith age range (based on the latest ICS International Chronostratigraphic Chart); terrane and craton name; and map label. Example captured tectonic features include cratons (Slave, Superior, Rae, Hearne) and terranes (Hottah, Narsajuaq, Meta Incognita, Pearya, Cassiar, Cache Creek, Wrangell and others). Secondary polygon attributes accessed through the database include map and data source references, source unit name, source unit descriptions as provided by source map legends, tectonic settings, grain-size, particle type and bedding features of stratified units to compositional and metamorphic mineral assemblages. All attributes are documented using a best-practice, internally-consistent science language and hierarchical schema developed by the project team.

Recently released source maps compiled for the present publication include Yukon (scale 1:1,000,000, western Northwest Territories (1:250,000), Arctic Islands (1:1,000,000), northern and southwestern Rae Craton (1:500,000) and parts of southern Baffin Island (1:100,000). Release of the new geological map and map database for Canada north of 60 is planned for later in 2017 (1:4,000,000).

The life of a LIP plume tail: Hawaiian-Emperor chain over ~85 Myr

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Large igneous provinces (LIPs) are voluminous outpourings of basaltic magma that occur over geologically short timescales. LIPs that erupt in oceanic settings provide the opportunity to study the deep mantle source removed from continental sources of contamination and, for long-lived systems, their evolution of with time. In the case of the Hawaiian-Emperor (HE) chain, the sourcing of magmatic material by a long-lived, deeply-sourced mantle plume allows for insight into plume dynamics, deep mantle geochemistry, and variations in magmatic flux.

This study completes the geochemical record of the entire HE chain by filling in a significant data gap along the Northwest Hawaiian Ridge (NWHR), which is composed of 51 volcanoes spanning ~42 Myr between the bend in the HE chain and the Hawaiian Islands. The NWHR is where geochemistry of the Hawaiian plume changed drastically: only Kea geochemical compositions are observed on Emperor seamounts (>50 Ma), whereas the Hawaiian Islands (<5 Ma) have both Kea and Loa type lavas. We have analyzed 23 samples of shield stage tholeiitic rocks from 13 NWHR volcanoes for Hf, Nd, Pb, and Sr isotopic compositions to test for the presence of the Loa composition along the NWHR.

We have also compiled a database of ~700 Hawaiian Island shield basalts Pb-Hf-Nd-Sr isotopic compositions to construct a logistic regression model of Loa or Kea affinity. Logistic regression creates a unique discriminator model to sort data into a dichotomous category and reveals the relationship between independent variables. We use the model to predict whether newly analyzed NWHR samples are Loa or Kea type based on their isotopic compositions. The logistical regression model is significantly better at prediciting Loa or Kea affinity than the constant only model ($\chi2=117.3$, df=4, $p<0.0001$), with Pb and Sr isotopes providing the most predicitive power of whether sample is Loa-type. Daikakuji, West Nihoa, Nihoa, and Mokumanamana erupt Loa-type lavas, suggesting that the Loa source is sampled ephemerally along the NWHR and increases in presence and volume towards the younger NWHR (younger than Midway ~20-25 Ma). These results complete the picture of how the Hawaiian mantle plume has behaved geochemically and geodynamically for ~85 Myr, and show that the Hawaiian mantle plume has transitioned from a dominantely Kea source during the Emperor seamounts and older NWHR to an increasingly enriched Loa source from the mid NWHR to Hawaiian Islands. We propose this is due to Hawaiian mantle plume drift through different lower mantle geochemical domains.

Integration of high-resolution datasets for hydrogeologic characterization of contaminated glacial sediments in south central Wisconsin

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Understanding the spatial scale of heterogeneity in unconsolidated sediments is fundamental to appreciating hydrogeologic variability that influences recharge, discharge, and groundwater flow pathways and rates. At contaminated sites, characterization of subsurface sediments is also essential to understand influences on non-aqueous liquid flow, solute transport rates, contaminant attenuation, and feasibility of remediating these sites. The heterogeneous nature of glacial sediments, especially near ice margins affected by multiple advances and retreats, makes it difficult to determine the vertical and lateral continuity of sediments from surface physiographic elements and sparse data. Furthermore, geologic information alone does not predict hydrogeologic character. Hence, this study involved the collection and integration of 1D high-resolution vertical profiles of multiple data types to create golden-spike holes with well-informed associations of sedimentary characteristics, hydraulic head, contaminant concentrations, and moisture content conditions within each hole. Continuous cores with high-resolution vertical logging and sampling was the foundational dataset, with multiple cores drilled in 3 distinct surface physiographic elements: glaciofluvial, glaciolacustrine, and drumlinized till plain. These data were used to design high-resolution depth-discrete multilevel monitoring systems that would allow measurement of head profiles. These datasets provide exceptional vertical detail about sediment contacts, scale of sediment heterogeneity, and location of vertical hydraulic gradients, which can be used to hydraulically calibrate geologic data. Location of these golden-spike holes along 2D geophysical surveys was essential for extending 1D vertical profiles laterally across the site. Integration of datasets was used to develop a robust Site Conceptual Model (SCM) in the highly variable glacial deposits. Eight stratigraphic units were identified recording multiple ice advances and retreats, with unit boundaries only subtly affecting groundwater flow, likely due to the large sand fraction within all sediments. Where found, subtle hydraulic contrasts are associated with top of rock, sand-diamict contact, interbedded diamict, and mud beds. At the site, small scale geologic heterogeneity, not necessarily predicted by the stratigraphy, impacts contaminant distribution. This explains why a mixed organic contaminant plume is still present after 50 years despite remediation efforts and some of the challenges associated with targeted monitoring for in situ remediation and evaluation of natural attenuation. The new SCM will help inform a 3D surface water recharge and shallow groundwater flow model. Integrated datasets, such as collected here, can significantly enhance the predictive power of SCMs and numerical models, which in turn can improve selection and implementation of targeted remediation technology.

Characterizing gold remobilization

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Recognizing remobilization of Au is critical to understanding what controls high-grade ore zones in Au deposits. Determining if Au has been remobilized is, however, difficult, and most studies fail to produce conclusive evidence. If evidence for remobilization can be shown, then primary versus secondary processes can be separated, which is paramount to understanding the evolution of Au deposits. The Jerome deposit in the Archean Swayze greenstone belt (SGB) of northern Ontario is hosted by altered and deformed monzonites that intruded Timiskaming-like conglomerates dated at <2680 ±2 Ma. Gold mineralization is present in two generations of arsenian pyrite (Py1, Py2). Py1 is inclusion-poor and oscillatory-zoned with invisible Au in As-rich zones. Py2 overprints Py1 and contains native Au and sulfide inclusions (e.g., chalcopyrite, gersdorffite, tetrahedrite, molybdenite, galena); it is also characterized by relict oscillatory zoning, a porous texture, and has irregular grain boundaries with Py1. Evidence in support of Au remobilization from Py1 includes: (1) relict zoning in Py2 that extends across grain boundaries from Py1; (2) the porous texture in Py2, which is commonly associated with dissolution-reprecipitation processes (DRP); (3) all elements in Py2 and its inclusions being present in Py1 zones; and (4) inclusions in Py2 are commonly multi-phase. Analysis (SEM-EDS and EMPA) of Py1 shows that zoning and Au incorporation are predominantly controlled by S availability. That S and As have a near-perfect, negative correlation across oscillatory zones suggests that, as S became depleted during Py1 growth, As substituted in S sites. This As substitution created distortions in the cubic structure of pyrite, which allowed more Au to be incorporated. Py2 is the result of DRP in Py1 with elements being redistributed and decoupled from their original associations. Documenting such decoupling is critical because it allows the distinction of primary versus and secondary geochemical signatures. The DRP textures and evidence of Au remobilization from sulfides are not exclusive to this deposit. The Kenty and Rundle Au deposits, also in the SGB, both show evidence for Au remobilization. Future work will focus on the detailed investigation of Au transport mechanisms responsible for the upgrading of ore to form high-grade Au deposits.

The Neoproterozoic and Triassic convergence records of metasedimentary rocks in the accretionary Nam Co complex, Song Ma Suture Zone, NW Vietnam

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The P–T conditions, depositional and metamorphic ages, and provenance of metasedimentary rocks from the Nam Co complex, Song Ma Suture Zone, northwestern Vietnam, were constrained in order to reveal the convergent history between the Indochina and South China cratons. The complex is structurally characterized by an antiformal metamorphic core complex of two distinct metamorphic zones: the biotite and garnet zones towards its core. The representative mineral assemblage of metapelites in the former zone consists of biotite + chlorite + plagioclase + muscovite + quartz whereas that in the latter zone of garnet + chlorite + plagioclase + muscovite + quartz. The peak metamorphic conditions estimated from two garnet-zone schists are in the range of 450–480°C and 9–14 kbar, and are subject to the epidote amphibolite- to blueschist-facies conditions. The U–Pb isotopic compositions of detrital zircon from a semi-pelite and two metasandstone samples were measured, using a SHRIMP ion microprobe. The U–Pb ages of analyzed zircon crystals from the samples showed major populations (greater than 50%) around ~850 Ma with minor populations scattered between 1.2 to 3.0 Ga. In particular, structurally uppermost sample SM09 in the biotite zone had nearly unimodal Neoproterozoic age spectra. The age patterns of detrital zircon are representative for magmatic activity at the convergent plate margin. The U–Th–Pb isotopic compositions of monazite from a garnet-zone schist were measured directly in pieces of thin section, using a SHRIMP ion microprobe, and defined a common Pb mixing line with the lower intercept age of 234 ± 10 Ma (2σ) reflecting the Indosinian metamorphism. The age distribution pattern of detrital zircon in the Nam Co complex is compatible with that of South China craton rather than those of Indochina craton. Therefore, the sedimentary protoliths of Nam Co complex had been deposited in convergent-related basins along the southwestern margin of South China craton during the Neoproterozoic, and then was amalgamated to the Indochina craton during the Indosinian orogeny.

Ferromanganese concretions record lake history over the past >7000 years.

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Ferromanganese concretions, crusts and nodules, composed primarily of alternating micro-laminae of iron and manganese oxides, have been recovered from post-glacial shallow seas and temperate lakes as well as from the deep oceans. Intense scavenging of other metals and trace elements by the concretions over thousands of years has been shown to enable the determination of their ages and accretion rates as well as providing important information about their geochemistry and growth histories, patterns and processes. Here we show that freshwater ferromanganese concretions can be dated at mm resolution using carbon-14 and uranium series isotopes.

Concretion ML2014 was recovered during a scuba dive in Magaguadavic Lake in New Brunswick, Canada. Samples collected at measured intervals from the outer edge toward the central nucleus of ML2014 were analysed for ^{14}C ($T½ = 5730$ yr) and ^{226}Ra ($T½ = 1600$ yr). Measurement of the ^{14}C:^{12}C ratios were made by accelerator mass spectrometer at the University of Ottawa. The maximum age at the nucleus is 7220 ± 68 years and ages systematically decrease toward the rim suggesting an average accretion rate of 0.003 mm per year. These ages were subsequently confirmed by measurement of ^{210}Po activity (assuming secular equilibrium with ^{226}Ra and minimal loss of ^{222}Rn) using alpha spectrometry. Future work will focus on analysis of the mineralogy and geochemistry of the ferromanganese concretions in an effort to find correlations with the environmental conditions affecting the lake during the Holocene.

Challenges in subdividing the Quaternary System: From the Anthropocene to formal subseries for the Cenozoic

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The Quaternary System is presently defined by three global boundary stratotype sections and points (GSSPs): the base of the Quaternary itself (and that of the Gelasian Stage, lower Lower Pleistocene, Monte San Nicola, Sicily, estimated at 2.58 Ma), the base of the Calabrian Stage, upper Lower Pleistocene Subseries (Vrica, Calabria, Italy, 1.80 Ma), and the base of the Holocene Series (Greenland NorthGRIP2 ice core, 11,700 years b2k). The Middle Pleistocene Subseries GSSP has not yet been defined, but proposals representing three candidate sections, the Valle di Manche and Montalbano Jonico sections, both in Italy, and Chiba section in Japan, are expected later this year. The Matuyama–Brunhes reversal (770–773 ka) will serve as the primary guide. The Upper Pleistocene Subseries has yet to be defined but historically is taken to coincide with the onset of the Last Interglacial (~130 ka). Two potential GSSP locations have recently been suggested: the Fronte Section, Taranto, southern Italy, and an ice core in Antarctica. Proposals for the Middle Holocene (Greenland NorthGRIP1 ice core, 8326 years b2k) and Upper Holocene (Mawmluh Cave speleothem, Meghalaya, India, 4200 yr before 1950) subseries GSSPs were recommended by the International Commission on Stratigraphy's (ICS) Subcommission on Quaternary Stratigraphy in 2016, but have been set aside by the ICS pending resolution of whether Cenozoic subseries should have formal rank in the International Chronostratigraphic Chart (which provides the framework for the International Geological Time Scale). In 2016, the SQS voted decisively in favour of formalizing subseries (e.g. Middle Pleistocene, Lower Holocene) following long tradition. The Anthropocene Working Group (under the SQS) is working towards submitting a proposal for the formalization of the Anthropocene, and is presently focused on finding the best sections to host a GSSP. The current view is that the Anthropocene should be defined at the rank of series/epoch, with a mid-20th century age (the "great acceleration") best able to meet the requirements for chronostratigraphic definition. However, the Anthropocene is presently undefined, and beyond stratigraphic circles this has led to confusion regarding its timing and nature. Defining the Anthropocene as a geological term should resolve this confusion.

Provenance and sedimentary environments of the Labrador Trough, Canada: Contributions from petrography, geochemistry and Nd systematics of metaconglomerates and matrix-rich metasediments

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The New Quebec Orogen (NQO) consists of a supracrustal belt that underwent reworking when the Superior craton collided with the Core Zone terrane during the Paleoproterozoic Trans-Hudson Orogeny. Within the NQO, the Labrador Trough regroups the Kaniapiskau Supergroup (KS) with greenschist-facies sedimentary and volcanic sequences, and the Laporte Group (LG) composed of similar successions but metamorphosed to higher grades. Competing models support that the LG is either a deeper higher-grade exposure of the KS, or an exotic terrane.

Studies of matrix-rich sediments benefit from the use of a combination of provenance tools because high-textural maturity sediments do not reveal the presence of sources with low zircon contents, which are usually easily weathered at the source, and deposited as fine-grained sediments.

A petrographic classification divides the KS in to four terrigenous lithotypes; One group with greater compositional and textural sedimentary maturity classified as meta-quartzarenites and meta-subarkoses, and another group with low textural maturity classified as meta-feldspathic wackes and meta-mudstones. These associations are typical of craton interior and transitional continental paleo-environments.

The LG include more homogeneous lithotypes represented by meta-feldspathic and meta-lithic wackes with varied matrix contents. The presence of plagioclase and alkali-feldspar in similar proportions indicates that the main sources are granitic, in accordance with the dominant clast population in metaconglomerates (varying from leuco-granodiorites to leuco alkali-feldspar granites). Additional sources are indicated by the presence of clasts of hematite-bearing iron formation.

Rocks from the KS have a large variation of SiO_2 and Al_2O_3 contents (SiO_2/Al_2O_3 =3.7-51) relative to rocks from the LG that have a restrict range (SiO_2/Al_2O_3 =4.4-6.8). Within LG two main formations are recognized, Grand Rosoy (basal), which includes polymictic metaconglomerates, and Deborah an upward unit. In general, the geochemical variations of both formations can be explained by the main varieties of clasts, however, the increase of TiO_2, P_2O_5, MgO, Co, Ni and Cr contents, including high Th/U and Rb/Sr ratios in the Deborah Formation, requires the presence of additional sources.

Our results combined with U-Pb detrital zircon provenance provide strong evidence that the KS was deposited in an extensional environment as a passive margin with exclusive recycled (εNd(1.87Ga) -12) Paleoarchean sources (TDM 3.2 Ga). In contrast, the LG marks a transition between a continental forearc (Grand Rosoy Fm.) with typical juvenile source, including highly evolved granitic clasts (εNd(1.83Ga) -0.1 to +3.1) to a collisional pro-foreland basin (Deborah Fm.) with mixing of old crustal components (εNd(1.83Ga) -4.4 to -9.1).

Evidence for ~ 40 Ma transition from a continental forearc to a wedge-top basin in eastern part of Labrador Trough

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The New Quebec Orogen (NQO) is the best preserved supracrustal belt of the deeply eroded Paleoproterozoic Trans-Hudson Orogen, and thus constitutes an exceptional window to investigate one of the most ancient Wilson cycle sedimentary records within the Manikewan paleo-ocean. It consists in a Paleoproterozoic supracrustal belt that underwent reworking when the Superior craton collided with the Core Zone terrane, during the Trans-Hudson Orogeny. Within the NQO, the Labrador Trough comprises greenschist-facies sedimentary and volcanic sequences (Kaniapiskau Supergroup) inferred to represent the rifted margin of the Superior craton, whereas the Laporte Group composed of similar successions but metamorphosed to higher grades, remains of unclear origin. Competing models purport that the Laporte Group is either a deeper, higher-grade exposure of the Kaniapiskau Supergroup, or an exotic terrane.

Large-scale sampling, petrography and SHRIMP U-Pb detrital zircon geochronology combined with geochemistry and Nd systematics of metaconglomerates and matrix-rich metasediments, provide insights to elucidate the sedimentary provenance and depositional environments for both zones.

The Kaniapiskau Supergroup detrital zircons yield ages older than 2.5 Ga (2570.3 ±3.7 Ma, maximum depositional age), showing a signature typical of the Archean Superior craton with a main peak at ~ 2.72 Ga. There is more than a 150 Ma gap between detrital zircon ages and the interpreted depositional age, suggesting a divergent environment like a rifted and passive margin.

In contrast, detrital zircons from the Laporte Group yield ages as young as 1834 ± 2.4 Ma and a dominant age peak at 1.84 Ma. The presence of age peaks at 2.2- 2.4 Ga suggests that the Core Zone exotic terrain is the main source area and the metamorphic monazite ages previously dated at 1793 ± 2 Ma, points to a relative short depositional time.

The presence of the De Pas Batholith Andean-type magmatic arc supports the interpretation of an eastward subduction at 1860-1830 Ma. Furthermore, a lag time between crystallization and deposition ages within the Laporte Group points to convergent and collisional settings with transition between continental forearc (cycle I) to collisional pro-foreland basin (cycle II), around 40 Ma, which marks the consolidation of the Columbia Supercontinent in the northeastern of Laurentia.

The 175 Objects Project: Canada@150, GSC@175: 1842-2017

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As Canada celebrates its 150^{th} anniversary, the Geological Survey of Canada (GSC) achieves its 175^{th} year of service to the country and to science. Ambitious projects to suitably mark this special time were proposed over 3 years ago by GSC retirees and members of their History Committee, with minimal response. This Committee has been preserving GSC's development since 1970, the end-date of the comprehensive history of GSC, Reading the Rocks by Morris Zaslow.

A proposal was then made, in 2015, by A. G. Plant of the History Committee, to present the History of the Geological Survey of Canada through 175 Objects. The object descriptions and their images were intended to illustrate the contribution of the GSC to the exploration and development of Canada. The GSC@175 Steering Committee endorsed the proposal and the Chair, Andrée Bolduc, sent an email to all GSC staff on November 18, 2015, summarizing the project and inviting staff to submit object descriptions. The first of these were received in a matter of hours.

The project has had the enthusiastic participation and collaboration of over 100 contributors, both past and present employees, and with objects proposed from across Canada. For each "object" (letters, publications, samples, maps, technologies, datasets, compilations, events, advances, milestones, discoveries etc.) there is a short expert description, relevant illustrations, geographic location, and references. An example is the role GSC played in the development of the National Museums.

The project is intended for the interested general public. A website presentation at Science.gc.ca has been developed, using the objects and their descriptions to inform and educate Canadians about the GSC and its contribution to the "Story of Canada" in this the 150^{th} year since Confederation.

Iodine-129 age and porewater residence time constraints within Upper Ordovician clastic and carbonate sediments of the Michigan Basin

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Preserved rock core samples were obtained for an 840 m thick Paleozoic sedimentary sequence on the eastern flank of the Michigan Basin beneath the Bruce nuclear site, near Kincardine, Ontario. Previous studies have indicated that the porewaters contained within the Upper Ordovician low permeability sediments that comprise the lowermost 400 m of the sedimentary sequence were ancient, hypersaline with evidence pointing to residence times of up to 300 My [Clark et al., 2013]. To provide additional age constraints, iodine-129 (half-life: 15.7 million years) produced in-situ by the spontaneous fission of uranium is used to further examine porewater residence times. The concentration of ^{129}I at secular equilibrium was calculated using uranium concentrations in crushed core samples and compared to the porewater ^{129}I concentration measured in water leachates by AMS. The upper section of the Ordovician sequence comprised of the 70-m thick Queenston shale formation has ^{129}I concentrations at secular equilibrium, suggesting porewater residence times of equal to or greater than 5 half-lives or 80 million years. Thus, porewater and ^{129}I have remained in situ within this shale aquiclude (K~10-14 m/sec). However, in the Ordovician limestone of the Black River Group, there is a ^{129}I enrichment over secular equilibrium, suggesting an additional source of radiogenic ^{129}I, such as fluids migrating up in to the Black River limestones from the underlying Precambrian gneisses or mineralogical controls. Most ^{129}I was produced in the clay mineral phase of the limestones and shales due to their higher uranium concentration. This presentation describes the methodology used in determining ^{129}I age constraints for the porewater of these Ordovician sediments with low porosities and water contents (<7%).

Soft-sediment deformation structures and associated microbial mat structures in the Paleoproterozoic Gordon Lake Formation, Huronian Supergroup

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Large, well preserved soft-sediment deformation structures (SSDS) were recognized in the 2.45-2.2 Ga Paleoproterozoic Gordon Lake Formation, Huronian Supergroup in the Bruce Mines area, Ontario. One outcrop exposure, 235 m long and 37 m thick, is composed of mudstone to medium-grained sandstone that contains 3 to 106 cm size load casts, 1 to 51 cm high flame structures, convolute bedding, and 2 to 120 cm size ball and pillow structures. One 6 m thick section of the outcrop contains in situ microbial mat structures and mat chips up to 100 cm long. The association of microbial structures with a number of SSDS suggests that ancient biofilms formed impenetrable barriers that caused heterogeneous fluid escape through the sediment, which led to overpressuring and subsequent soft-sediment deformation. A combination of driving forces and trigger mechanisms, including inverse density gradients, overpressuring, loading by storm waves and tidal shear, are interpreted to have led to the formation of the SSDS. Preservation of microbial mats and SSDS, the presence of desiccation cracks and lenticular bedding, and the gradational contact with the overlying tidal inlet-sand shoal deposits of the Bar River Formation, support deposition of the Gordon Lake Formation sediments in shallow water and on a tidal flat. Outcrops of the Gordon Lake Formation in the Baie Fine, Flack Lake, and Cobalt plains areas contain neither the same quantity, nor size of SSDS as seen in the Bruce Mines area. This is significant because it suggests that the western portion of the basin may have been affected by different sedimentary processes or local tectonic events.

Structural analysis and paragenesis of the Arrow uranium deposit, Athabasca Basin, Saskatchewan

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The Athabasca Basin in northern Saskatchewan hosts the world's highest-grade uranium deposits, which are commonly spatially associated with structural zones that have undergone multiple episodes of brittle reactivation. Although the evolution of these zones is complex, unraveling the relationship between structure, alteration, and mineralization is vital in understanding the controls on uranium mineralization. This study examines the relationships between the ductile framework and brittle reactivation of structures, mineral paragenesis, and uranium mineralization at the Arrow deposit, the largest undeveloped uranium resource in the Athabasca Basin. Approximately 400 samples from 18 representative drillholes that intersect the deposit have been collected. These include unaltered, altered, and mineralized rocks, and a combination of hand sample examination, thin section microscopy, and electron microprobe analyses has been used to generate a detailed paragenesis. The rocks hosting the deposit are variably silicified and overprinted by early ubiquitous fine-grained white mica alteration and multiple generations of chlorite alteration. Overprinting earlier alteration, is relatively late argillic (kaolinite-illite) and hematite-limonite alteration, multi-generational sulphides, and hydrothermal graphite, as well as quartz-, carbonate-, and dravite-lined brittle structures and veins. At least four phases of uranium mineralization have been identified, including early euhedral and brecciated uraninite, remobilized uraninite, and late uranophane and coffinite. Semi-massive to massive, fracture- and foliation-controlled uraninite is spatially associated with hematite-limonite alteration, chlorite alteration and late carbonate veins, whereas disseminated uraninite is present in clay/chlorite/muscovite-rich zones. Sulphides and graphite are pre-, syn-, and post-mineralization, whereas dravitic structures are dominantly syn- or post-mineralization. Paragenesis has been integrated with detailed structural analysis and will be used as the framework for the ongoing determinations of the ages of mineralizing events. The Arrow system developed along sub-vertical, northeast-trending chloritic-graphitic shear zones (A1, A2, A3, A4 and A5 Shears). These shear zones appear to have developed along the limb of a regional-scale fold and have subsequently reactivated, creating various small-scale brittle fault linkages oblique to, and connecting the main fault zone. Detailed analysis suggests a predominantly sinistral Riedel-type system, where multiple brittle reactivations of primary shear fractures have occurred, allowing for migration of hydrothermal fluids, alteration of host rocks, and precipitation of uranium. The Arrow deposit is interpreted as a structurally-controlled uranium deposit hosted within competent basement rocks below a thin veneer of Athabasca Group sandstone. Continued studies surrounding these controls will aid in developing a structural template for exploration of new target areas within the recently established southwestern Athabasca Basin uranium camp.

Modelling infrastructure for national scale 3D geological models

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National geological models are increasingly being developed to help address a variety of continental and global issues such as those related to climate, water, or hazards. However, their nascent development is highlighting many scientific and technological challenges, primarily related to the construction and maintenance of very large 3D models. These are manifest technologically as gaps in modeling methods, related to sparse data and regional interpretation, as well as infrastructure gaps related to the handling of massive data volumes that overwhelm present commercial modeling systems. To overcome this infrastructure gap, new approaches are taken here for the storage, management, viewing and dissemination of a national geological 3D model for Canada, ranging from the surface to the deep subsurface (~46km). The infrastructure is comprised of several components: geometry data model, hierarchical data structure, geospatial database, visualization software, and an upcoming web portal. To represent the wide variety of possible geometries for 3D geological models (points, curves, surface meshes, structured and unstructured 3D grids) the open source VTK (Visualization Tool Kit) data model is adopted. Interactive visualization of a massive 3D model is accomplished by 3D tiling, in which 3D model components are inserted into an octree-based hierarchical data structure that partitions the data into blocks with different resolutions and sizes, limiting viewing to relevant data. The evolving national 3D geology model is stored in an open source database, PostgreSQL, which contrasts with prevalent file-based modeling systems. It is visualized directly from this database using customizations of the Paraview and ParaviewWeb software, for both desktop and forthcoming web-based environments. Ongoing tests on desktop system have shown this environment to scale effectively for the expected data volumes, indicating this approach is promising as a national 3D geological modeling infrastructure.

Timing and influence of major faults in the evolution of the Devonian-Permian Maritimes Basin complex, New Brunswick and adjacent offshore, eastern Canada

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Carboniferous rocks in New Brunswick and the adjacent offshore area are part of the Devonian-Permian Maritimes Basin complex centred under the Gulf of St. Lawrence: a successor basin to the Silurian-early Devonian Appalachian orogenic collage. The evolution of this basin has been controlled by major orogen-parallel strike-slip faults. The current model for the evolution of this basin consists of fault-controlled subbasins formed through the Tournaisian and Viséan, followed by a more general subsidence during the Pennsylvanian. This model is critically assessed using recently acquired and reprocessed industry seismic reflection profiles. These profiles permit an improved three-dimensional resolution of basin architecture and Carboniferous stratigraphy, and especially timing of individual fault movements.

This study concentrates on two large strike-slip faults: the Belleisle and Kennebecasis faults and the related North River and Clover Hill faults. The Belleisle Fault has the longest history of movement, originating in the Devonian, and exerts influence on Tournaisian deposition into New Brunswick, but late Viséan units (Windsor Group) overlie the fault. The estimated 120 km of right-lateral displacement on this fault are pre-Viséan. A similar pre-Viséan history, involving around 60 km of right-lateral strike-slip displacement can be inferred for the North River Fault. Major movement shifts SE-ward to the Kennebecasis Fault during the late Tournaisian, and major movements along this fault continue into Serpukhovian time, with some 30 km right-lateral displacement occurring. A similar history can be inferred for the Clover Hill Fault with 7 km right-lateral displacement. Some fault reactivation during the Pennsylvanian is evident on the Kennebecasis Fault, some of which is associated with salt movement, but the major Pennsylvanian displacements occur to the SE along the Wood Creek-Shepody Fault between the Sackville and Cumberland basins.

Using timing relationships and estimated displacements from this and earlier studies, a palinspastic reconstruction is attempted for the hydrocarbon-bearing early Tournaisian Horton Group subbasins, successively restoring faults from the southeast to the northwest ending with the Belleisle Fault movement. This reconstruction shows the onshore Moncton and Cocagne and offshore Cascumpec subbasins to have originated from a single basin. Strike-slip faults exercised an influence on basin development into the Pennsylvanian, but from late Tournaisian to late Pennsylvanian this influence progressively shifted to the southeast.

The Kaskattama highland: Till composition and indications of a new Precambrian inlier in the Hudson Bay Lowland?

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The Kaskattama highland in northeast Manitoba is a prominent topographic high that rises 130 m above the flat-lying Hudson Bay Lowland. The region is thought to consist of thick (an inferred 223 m) Quaternary sediment cover, as observed in a single drillhole on the northwest side of the highland. This region was targeted during the 2016 field season as part of an ongoing study of the Hudson Bay Lowland Quaternary stratigraphy in northeast Manitoba. Natural exposures of Quaternary sediments were logged and till samples were collected at a reconnaissance-scale over the region. A suite of till samples collected contain a high proportion of dark grey metasedimentary and metavolcanic rocks (interpreted greenstone), relative to the regional calcareous surface till. Greenstone concentrations within till from the highland region are as high as 55 ct. %, whereas the calcareous surface till west of the highland contains 10-12 ct. % greenstone clasts. Till-matrix geochemistry is consistent with the clast lithology counts. In particular, four samples have elevated concentrations of Fe and Ni. We use K-means cluster analysis and principal component analysis to aid in till-composition analysis and provenance interpretations. The closest known outcrops of greenstone bedrock occur 60 km southwest of the highland, and form part of the Paleoproterozoic Fox River Belt; however, using geophysics, the Fox River Belt has been delineated under the highlands, albeit under presumed Paleozoic cover. The Kaskattama highland region is streamlined by two different flowsets: a southwest-trending flowset west of the highland and a northwest-southeast oriented flowset of unknown ice flow direction on top of the highland. Northeastward transport of detritus from known outcrops is unlikely based on realistic glacial reconstructions. Elevated surficial greenstone-enriched till samples are located in the vicinity of the extension of the Fox River belt and with no known sources to explain the observed till composition, these initial results suggest a local bedrock source. In northern Ontario, the Sutton ridge and associated outcropping Paleoproterozoic Sutton inlier is a possible analog, as it is a similarly enigmatic positive relief feature in the typically flat Hudson Bay Lowland. These results present a potential new source of Precambrian detritus which significantly alters glacial dispersal reconstructions in the Hudson Bay Lowland. Additionally, exposed basement would present a favourable exploration target for Ni-Cu-PGE associated with the ultramafic units of the Fox River belt, along with broad potential for gold and diamond deposits.

Revisiting the Belcher Group: High-resolution carbon isotope chemostratigraphy reveals carbon cycle fluctuations at ~2.0 Ga

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The Belcher Group is an ~10 km thick succession deposited 2.0-1.8 Ga along the margin of the Superior Craton. Despite containing a rich sedimentary record of this time interval, the Belcher Group has been hardly studied since the 1980s, and its geochemistry remains unconstrained. Here, we present stratigraphic sections measured through the entirety of the Belcher Group, along with a high-resolution carbon isotope curve. The Belcher Group comprised six depositional stages; the lowermost stage, the Kasegalik Formation, is a shallow subtidal-intertidal transgressive carbonate platform. This is followed by the flood basalt phase of the overlying the Eskimo Formation. A second transgressive carbonate platform buildup is composed of the Fairweather, McLeary, Tukarak, Costello, and Laddie formations. The McLeary Formation is notable for its wide variety of extremely well-preserved stromatolite morphologies and microfossils. The next depositional stage records further progradation in the intertidal, mixed carbonate-clastic Rowatt Formation and mature sandstones of the Mukpollo Formation. This regressive stage ultimately resulted in the development of a restricted basin, as suggested by deposition of the Kipalu granular iron formation. This phase is punctuated by the Flaherty Formation, a thick, submarine basalt unit that covers much of the Belcher Islands. The final stage in the Belcher Group records a turbidite flysch and overlying distal molasse, the Omarullok and Loaf formations, respectively. The carbon isotope record from Belcher Group carbonates spans a range from -2 to +3‰ and exhibits multiple systematic shifts of up to 4‰ that are correlatable across tens of kilometers (without palinspastic restoration). The absence of extremely positive $\delta^{13}C$ values suggests that the Belcher Group post-dates the Lomagundi-Jatuli excursion, and hence is younger than ca. 2.06 Ga. The magnitude and style of the carbon isotope oscillations recorded during Belcher Group deposition seem to record a transition between the highly enriched values of the preceding Lomagundi-Jatuli Excursion and the extreme $\delta^{13}C$ stasis near 0‰ characteristic of the middle Proterozoic.

A long-lived Neoproterozoic carbonate platform and its Cryogenian glacial record: Stratigraphic development of the Otavi Group in the easily accessible southern Kunene Region, Namibia

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The carbonate-dominated Otavi Group covers the southwestern promontory of the Congo craton and is exposed in 400-km-long fold belts bordering orthogonal branches of the geon-5 (500-599 Ma) Pan-African orogenic system. The present southern margin of the carbonate platform and its distally-tapered foreslope lay in the tropics of the southern hemisphere and faced the late Tonian paleoequator. Subsidence resulted from N-S crustal stretching (770-650 Ma), followed by thermal contraction (650-590 Ma), and abortive subduction (590-540 Ma) beneath the Swakop and Dom Feliciano magmatic arcs. During crustal stretching, normal faults on the future platform were antithetic to a N-dipping crustal-scale detachment. Erosional denudation of uplifted footwalls shed cannibalized clastics into a peritidal carbonate depositional regime. Carbonate production was interrupted by the Sturtian (717-659 Ma) and Marinoan (ca 645-635 Ma) panglacial epochs, which struck during the stretching and thermal subsidence stages respectively. Polymictic Sturtian glacial deposits form moraines and fill bedrock troughs and half grabens. Its cap-carbonate sequence is dominated by unusual sublittoral microbialites hosting diverse assemblages of eukaryotic microfossils. Platform-foreslope zonation was first established at the end of the stretching stage, after which the platform aggraded differentially by 1.5 km. Marinoan glacial deposits include lodgment tillite on the inner platform and a grounding-zone wedge on the mid-foreslope, accompanied by giant moraines. A falling-stand wedge preceded glaciation on the foreslope, and an Fe-rich drape rife with ice-rafted debris records the glacial termination in submerged areas off the platform. Marinoan glacial debris is derived from directly underlying carbonate strata, eroded preferentially from the inner platform and the upper foreslope. The syndeglacial cap dolostone is thickest on the raised outer platform, where glacial deposits are absent. Up to 200 m of tubestone stromatolite and overlying former-aragonite sea-floor cement formed a rim, from which the cap-carbonate sequence prograded landward. After 45 Myr of post-Marinoan carbonate accumulation, the platform was destroyed by abortive subduction, accompanied by coherent, map-scale, submarine landslides on trench outer slopes, karst-landscape development over the forebulge, and terrigenous, orogen-derived, marine and terrestrial sedimentation. The carbonate C-isotope record includes two positive anomalies, bounded by negative excursions, in each of the late Tonian, Cryogenian and early Ediacaran intervals. Our reconstruction of platform development relies on over 8000 C- and O-isotope pairs, and around 580 closely-spaced measured sections concentrated in ten, well-exposed, structurally-coherent transects. Opportunities abound for additional research in this easily-accessible field area of friendly inhabitants and relatively unaltered natural beauty.

Depocenters on Snowball Earth: A tunnel valley, subglacial rift-valley lake, giant moraine and erratic blocks in the Sturtian Chuos Formation of NW Namibia

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The median thickness and accumulation rate of Sturtian glacial deposits at 88 sites in NW Namibia are 48.2 m and under 10^{-6} m/yr, respectively, an order of magnitude less than for Phanerozoic (polar) glaciations of comparable (58 Myr) duration. These data are consistent with the weak hydrologic cycle of a Snowball Earth. Locally, however, the Sturtian deposits thicken up to 1.7 km, 35× their median value. What accounts for local thickening of glacial deposits on a putative Snowball Earth? We investigated three local depocenters by measuring closely-spaced columnar sections. We measured the nonglacial bounding strata in order to distinguish paleovalleys and morainal buildups. At Omutirapo springs (19.122°S, 13.936°E), a round-shouldered U-shaped paleovalley, 0.45 km deep by 3.0 km wide, is incised into Tonian carbonate strata. The bedrock trough is 10% overfilled by massive polymictic diamictite. Discontinuous bodies of sorted siltstone and sandstone are localized within the trough, which we tentatively infer to have been a tunnel valley. On Toekoms farm (20.370°S, 14.430°E), a distally-tapered wedge of conglomerate, glacial diamictite and ferruginous subglacial lake(?) deposits abut against granitoid basement rock uplifted along a border fault. Fault movement ceased before the Sturtian cap-carbonate was deposited. The locus of maximum deposition shifted over time, from proximal to distal wrt the border fault, similar to Mesozoic half grabens developed above listric detachments imaged seismically on North Atlantic margins. At Vrede domes (20.407°S, 14.148°E), a wedge of glacial diamictite, 220 m thick by 2.0 km wide, overlies a disconformity that is demonstrably not incised into underlying preglacial strata. The wedge is draped by a postglacial cap-carbonate and argillaceous strata, and was erosionally truncated at its apex by thin Marinoan glacial deposits and their basal Ediacaran cap dolostone. On Fransfontein Ridge (20.2056°S, 15.1463°E), a 40×140 m granitoid erratic, resting upon Sturtian glacial diamictite, was progessively onlapped and buried by marine postglacial strata. Other erratics of similar dimensions occur elsewhere in the Chuos Formation. Our investigation confirms what others have found, that Cryogenian glacial deposits are lithologically unremarkable. While their average accumulation rate and paleolatitudinal range are distinct, lithofacies analysis is ineffective in discriminating between regional and global-scale glaciation, however vital it may be for reconstructing local paleogeography.

Expanded freshwater oligotrophy on Snowball Earth and the origin of modern marine planktonic cyanobacteria

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Molecular clock data suggest that the last common ancestors of major clades of modern marine planktonic cyanobacteria were Cryogenian (roughly-speaking) and some of these diverged from freshwater forms. These clades include unicellular nitrogen fixers and super-abundant picocyanobacteria. They apparently evolved from benthic filamentous forms through adaptations that favoured unicellularity and small cell size. These same clades are predominant also in modern polar freshwater ecosystems, including supraglacial cryoconite holes and ponds, glacial meltwater streams, and meromictic ice-capped lakes. The highest-known concentrations of the picocyanobacterium Synechococcus, up to 8 billion cells/L, are found in the summer mixolimnion of some Antarctic saline lakes, and they are the dominant photosynthetic cell type in High Arctic coastal lakes. In contrast, these clades are notably rare or absent in the polar oceans. This suggests that their success in polar freshwater habitats is not due to cold-tolerance but to tolerance of oligotrophy (nutrient starvation). During the Cryogenian Snowball Earth episodes, the total area of oligotrophic freshwater habitats expanded. Cryoconite holes and ponds dotted the trans-equatorial sublimation zone of the global sea glacier, encompassing 12% of global surface area. Climate modeling suggests that bare land covered roughly 6-24% of global surface area, where dry valleys were occupied by salinity-stratified (meromictic) ice-capped lakes. The first Cryogenian (Sturtian) Snowball Earth gave cyanobacteria 58 million years to press their advantage. When it ended, the former sea-glacier dwellers along with coastal lacustrine populations, dispersed by the postglacial marine inundation, found themselves in the meltwater lid of the global ocean. Surface waters warmed rapidly, to their benefit, and salinification (to which they were not intrinsically sensitive) was gradual over tens of kyrs, because whole-ocean mixing was retarded by the stable density stratification. The evolving planktonic cyanobacterial clades were soon pushed away from nutrient-rich coastal waters, but found permanent homes for which they were preadapted in the oligotrophic ocean gyres.

Call for further research on the architecture and evolution of the crust during continental arc magmatism: Coast Mountains batholith, British Columbia

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This presentation is a call to widen the scope of research on the outstanding unresolved problem in the Coast Mountains of British Columbia, which is the origin of the batholith - the largest calcalkaline plutonic complex on earth. We propose a Geological Society of America Thompson Field Forum across the Coast Mountains at the latitude of Prince Rupert, to be held summer of 2018. This transect provides a window into the architecture of the batholith and its country rock, which preserves a record of batholith formation and emplacement during terrane accretion, crustal contraction and thickening, and extensional collapse.

Extant geologic maps, and petrological, structural, geochronological, and geophysical data provide a framework on which to base new research. The knowledge base includes results from very high quality seismic profiling, with precise location of the present Moho and lithologies through the crust based on Vp/Vs data, and a wealth of metamorphic P-T-time data.

The proposed Forum hopes to inspire research that would lead to development of a geodynamic model for the evolution of the batholith. Particularly relevant would be studies that (1) utilize new dating techniques to refine timing of stages of development of the batholith; (2) integrate new structural data with the metamorphic results to track orogenic development through the wide range of crustal conditions recorded in the batholith; and 3) investigate the kinematic and dynamic evolution of crustal scale shear zones through the batholith. Specific questions include: How did crustal thickness change during formation of the batholith? What were the roles of crustal thickening and crustal thinning processes in the evolution of the complex? What were the relative contributions of mantle versus crust derived melts? What was the role of sedimentary basins/accretionary wedges to the generation of melts, either as source or from devolatilization of sediments? What was the crustal deformational response to the formation and intrusion of melts? What is the role of faults and translation to batholith construction? What were the roles of assimilation and contamination in forming the melt compositions? Did lithosphere delamination occur? Was there ridge subduction? Existing age data for the plutons require high magma flux events; what triggered these? What caused segmentation and along strike variation in the batholith? The Forum will illuminate the research path forward for the innovations and insights of present and future generations of earth scientists.

Mg isotope tracing of fluid migration during dolomitization

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Dolomite is abundant below the Devonian Prairie Evaporite Formation in the Williston Basin (Canada-USA), but relatively uncommon above this formation. For this and other reasons, brine-reflux factors prominently in models of dolomitization in the Williston Basin. However, radiogenic signatures of Sr-isotopes in dolomite, first reported in the partially dolomitized Ordovician carbonates of the Red River Formation (which is interlayered with bedded anhydrite), and later in the Winnipegosis Formation directly underlying the Prairie Evaporite, are incompatible with dolomite formed from evaporatively concentrated seawater sinking into underlying carbonate units from above. Here we explore the possibility that Mg isotopes may also trace the direction of fluid-flow during dolomitization. Dolomite takes up light Mg-isotopes, thus enriching dolomitizing fluids in heavy isotopes. Dolomite δ^{26}Mg values should therefore increase in the direction of paleo-fluid flow. We tested this hypothesis on dolomitized (Thalassinoides) burrows in the lower 'C member' carbonate of the Red River using core samples collected from wells spatially distributed across the Williston Basin. In all the cores examined, the burrows are pervasively dolomitized and the matrix is limestone. If evaporatively concentrated seawater descended through burrows and dolomitized them, then burrow-dolomite δ^{26}Mg values should increase toward the center of the basin in the direction of the paleo-dip of the 'C-member' carbonate beds. What we find instead is burrow-dolomite δ^{26}Mg values increasing away from the center of the basin in all directions (–1.9‰DSM3 to –1.3‰DSM3), indicating that the dolomitizing fluids ascended rather than descended through the burrows. This is evidence that the dolomitizing fluids were connate waters that originated in the deepest part of the Williston basin. Burrow-dolomite ^{87}Sr/^{86}Sr ratios decrease away from the basin-center supporting this interpretation. Acquired through water-rock interaction with Precambrian basement rocks, the radiogenic signature of the dolomitizing fluid will become progressively less radiogenic due to mixing with Sr released from carbonate rocks along the flow path during the process of dolomitization. We conclude that dolomitization of the Red River burrows is unrelated to downward migrating brines associated with evaporite deposition in the Williston Basin, but possibly linked to the thermal history of the basin. We speculate that a late Paleozoic heating event triggered Mg-bearing connate waters to ascend through burrows of the 'C member' carbonate, and possibly other permeable units in the Williston Basin as well, dolomitizing them at higher than burial temperatures.

Mineralogical and chemical complexity in alteration in the Nechalacho rare-earth element deposit, NWT

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The Nechalacho rare-metal (REE, Y, Nb, Ta, Zr) deposit, is hosted by a sequence of altered, layered nepheline syenites. Three distinct whole-rock geochemical signatures are evident. Two of these signatures have high P, of which, one has high heavy REE (HREE) (type 1) and one has low HREE, but high light REE (LREE) (type 2). The third signature has low P and high HREE, LREE and Zr (type 3). Type 1 and 2 signatures represent abundant xenotime ((Y, HREE)PO_4) and monazite ($LREEPO_4$), respectively. Type 3 represents zircon and a variety of non-phosphate REE minerals, such as allanite, fergusonite ((Y, REE)NbO_4), or bastnäsite ($REECO_3F$). The results support the hypothesis that the ore mineralogy can largely be predicted from whole rock geochemistry. Phosphates are an important reservoir for the LREE at the Nechalacho deposit. Two main textural types of monazite have been recognized: columnar and equant. These can be distinguished geochemically based on U and Th concentrations. The columnar monazite is associated with biotite-quartz alteration, whereas the equant monazite is associated with chlorite-ankerite alteration. Xenotime also occurs in various habits, such as rods and anhedral patches. The deposit is divided into upper and basal zones, the Basal Zone having a higher HREE/LREE ratio than the Upper Zone. It has been previously proposed that the LREE were transported from magmatic eudialyte in the Basal Zone to the Upper Zone by hydrothermal fluids and precipitated there as LREE minerals. A recent geochemical model predicted that a series of pulses of aqueous fluid transporting REE and P, passing through a nepheline syenite would precipitate monazite crystals that were progressively more depleted in HREE (relative to the starting fluid) with increasing distance from the source (height in the system). The REE chemistry of monazite from Nechalacho, obtained using LA-ICP-MS, does not support this model for the origin of the Upper Zone because the concentrations of HREE in monazite show no consistent decrease upwards in the intrusive body, which suggests, along with the textural variability of the phosphates and their association with different assemblages, that the genesis of the LREE mineralization was caused by multi-stage alteration and is more complex than the proposed models imply. Fluid inclusion microthermometry on primary fluid inclusions in quartz and xenotime indicate that the alteration fluids had salinities of ~8 to 13 wt.% NaCl equivalent, and temperatures of 330 to 480 °C.

Late Mesozoic volcanism in the middle and lower Yangtze River reaches, China

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The late Mesozoic volcanism in the middle and lower Yangtze River reaches were restricted within eight volcanic basins, which expanded roughly along the Yangtze River, make up a discrete volcanic basin belt. The late Mesozoic volcanic rocks in this area are dominant medium to intermediate-felsic rocks, rhyolitic rocks only exposed in Jinniu Basin, Fanchang Basin and Liyang Basin, margin of the volcanic basin belt. These volcanic rocks show obvious characteristics of alkali enrichment, and can be divided into two types according K_2O contents, one is shoshonitic series volcanic basins, including Ningwu Basin, Lishui Basin, Luzong Basin and Huaining Basin, locates inside of the volcanic basin belt. Another is high-K calc alkaline series volcanic basin, including Jinniu Basin, Fanchang Basin, Chuzhou Basin and Liyang Basin, locates margin of the volcanic basin belt.

Geochemically, the shoshonite series volcanic rocks enriched in strong incompatible elements such as Rb, Th, U and K as well as light rare earth elements (LREE), depleted in high-field-strong-elements (HFSE) such as Nb and Ta. Their Nd and Sr isotope compositions are roughly similar with the enriched subcontinental lithospheric mantle of the Yangtze craton, imply that their parental magma were mainly come from partial melting of the enriched subcontinental lithospheric mantle. But the tectonic setting of the basins are also play an obvious role on the magma characteristics, indicating the existing of crustal contamination.

Compare with those shoshonite series volcanic rocks, the high-K calc alkaline series volcanic rocks show relative great differences in geochemistry, indicate inhomogeneity of magma source and complicacy of magmatic processes. In general, contribution of crustal material for the high-K calc alkaline series volcanic rocks was much more than the shoshonitic series volcanic rocks.

The shoshonotic series volcanic rocks formed in a very short period from 128 to 134 Ma, with a peak about 130 Ma. Whereas the high-K calc alkaline series volcanic rocks formed in a relatively long period, from about 140 Ma to about 122 Ma, with three different altitude peaks, about 133 Ma, 128 Ma and 124 Ma respectively. The volcanism in the Middle-lower Yangtze volcanic belt show migrating current northwestward with time, and migrating from center area of the volcanic belt outward subtilly. The bidirectional migration of the volcanism may be the result of relative movement of the Pacific plate and the Asia continental plate and late Mosozoic lithospheric thinning happened in the Middle-lower Yangtze region.

Keynote (40 min): The stratigraphic expression of slope channel processes

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The sedimentary processes that form and maintain submarine channels are difficult to constrain due to the inaccessibility of the deep-sea, as well as the destructive nature and infrequency of formative gravity flows. Fluvial channels have been used as analogues to submarine channels due to similarity in their sinuous planforms. However, outcrop characteristics from deep-water Cretaceous strata of the Magallanes Basin (Chile) and Nanaimo Basin (BC), as well as fluvial deposits of the Alberta Basin suggest distinct formative processes. Meandering fluvial systems are represented by inclined strata that reflect genetically linked point bar accretion and cut-bank bank erosion. In contrast, the deposits of single-thread deep-sea channels are commonly characterized by sandstone-dominated channel form bodies composed of turbidites that bi-directionally lap onto channel edges. Outcrop observations indicate that accommodation generation in submarine systems, presumably via deep incision, coarse-grained sediment bypass, and aggradation of levees, is largely detached from the processes that result in accumulation of thick sands in the channel. Through careful analysis of slope channel fill deposits, however, formative flow dynamics can be deduced and linked to key paleoenvironmental interpretations, such as channel sinuosity development, and turbidity current frequency and magnitude.

Slope channels are sculpted as a result of protracted erosion and sediment bypass. Inherently, evidence for these processes is not recorded by a substantial depositional record. Sandstone-dominated slope channel fill biases the stratigraphic record towards evidence for channel-filling processes at the expense of the record of sediment bypass. Outcrop evidence for sediment bypass includes: (1) nested scours, which indicate a multi-phase history of erosion and infill; (2) mudstone drapes that mantle erosion surfaces, attributed to suspension sedimentation from the dilute tails of turbidity currents that largely bypassed the channel setting; (3) thick successions of thin-bedded turbidites at the edges of channel fills that record a particularly complete record of channel processes; and (4) remnants of sandstone characterized by up-slope dipping cross-stratification attributed to cyclic steps or antidunes. The expression of these sedimentary characteristics within slope channel fills is often subtle, yet their recognition is critical for understanding formative processes and deducing the history of protracted sediment transfer across deep-water slopes.

Keynote (40 min): Transport, fate and impact of metallic and metalloid elements in mining-affected river systems

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Present-day and historic mining activities have released large quantities of metallic (e.g., cadmium, lead, zinc) and metalloid (e.g. arsenic, antimony) contaminants into fluvial environments, via discharges of mine or processing wastes, tailings dam failures, mine drainage and remobilization of mining-contaminated alluvium. The contaminants pose a significant environmental threat to microorganisms, plants and animals (including humans) which inhabit the river systems, as the elements can be ingested from water, soil and vegetation, or inhaled from dusts. Several decades of research to help manage and protect river systems from the effects of mining-related contaminants has focused on answering the question: What are the geochemical-mineralogical-geomorphological controls on, and rates of, the mobilization and deposition of contaminants? Such controls are varied and include Eh, pH, temperature, precipitation, organic matter content, bacterial activity, nanoparticle formation, catchment morphology and sediment grain size. This presentation will give an overview of developments in our understanding of the transport, fate and impact of contaminants in mining-impacted river systems, using examples from field studies from around the world and complementary laboratory experiments.

Overall approach for conducting a postclosure safety assessment for a deep geological repository for used nuclear fuel

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The Nuclear Waste Management Organization (NWMO) is responsible for the implementation of Adaptive Phased Management (APM), the federally-approved plan for the safe long-term management of Canada's used nuclear fuel. Under this plan, used nuclear fuel will be placed in a deep geological repository in a willing and informed host community.

The safety of the repository depends on the combined effects of the geology, the engineered design, and the fabrication and operating methods during construction. The ability of the repository to safely contain and isolate used nuclear fuel in the long-term is achieved by multiple barriers, these being the ceramic used fuel pellet, the fuel sheath, the robust long-lived container, a series of clay-based seals and backfill material, and the rock formation within which the repository will be located.

This paper will discuss the overall approach to creating a postclosure safety assessment. Topics addressed include safety acceptance criteria, radionuclide screening, scenario identification and sensitivity studies, the use of geoscientific data, the critical group, computer modelling, treatment of uncertainties, and confidence building through the use of natural analogues. As s specific site has not been identified, hypothetical sites and conceptual repository designs are used to illustrate how this approach would be applied.

A structural investigation of the Thelon and Judge Sissons faults, northeast Thelon Basin, central Rae Domain, Nunavut

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The Thelon and Judge Sissons faults provide a unique opportunity to study a long-lived, post-orogenic Paleoproterozoic fault zone that preserves ductile to brittle structures, as well as an important hydrothermal fluid system. These faults are located along the southern margin of the northeast Thelon Basin in the central Rae domain and were investigated through detailed structural mapping and examination of drill core. The Thelon and Judge Sissons faults are ENE-trending and can be traced upwards of 100 km or more along strike. Individual fault strands have well-developed damage and core zones, which vary from < 1 to 15 m in width, and are characterized by multiple generations of quartz veins and breccias. The veins host a variety of primary growth (chalcedonic, comb, zoned, cockade), recrystallization (moss), and replacement (bladed) textures. The two faults initiated as dextral ductile to brittle-ductile shear zones as suggested by the presence of preserved lozenges of mylonite within the fault zones and along their margins. Early ductile to brittle-ductile movement along the faults overprints ca. 1810 Ma granite of the Hudson Intrusive suite, and is followed by two distinct brittle deformation events: (1) a prominent dextral strike-slip event bracketed between ca. 1780 Ma and ca. 1720 Ma, which displaces the Schultz Lake Intrusive Complex upwards of 14 km and is characterized by near horizontal slickenlines with step and tool mark kinematic indicators on steeply-dipping fault planes; and (2) a dextral oblique-slip event, which is loosely constrained between ca. 1667 Ma and ca. 1267 Ma and is observed as oblique (pitch of 50°) slickenlines overprinting earlier horizontal slickenlines along fault planes. The prominent brittle dextral strike-slip movement created a Riedel shear array comprising NNW-trending sinistral R' shears, E-trending dextral R shears, NE-trending dextral P shears, and NW-trending T veins. These structures are present within and adjacent to the Thelon and Judge Sissons faults. As a result, an extensive fracture and fault network was created that allowed extensive fluid migration into and along these faults during slip events. After the Thelon Formation was deposited, late oblique-slip events along these fault zones reactivated this complex structural and hydrothermal fluid flow network, which led to the creation of unconformity-type uranium deposits in the area.

The heat of orogeny: The importance of uniformly hot backarcs prior to orogenic collision

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An unresolved problem in orogenic belts is the origin of the regional high temperature Barrovian metamorphism. For models using standard cool initial crust, sufficiently high temperatures can only be achieved by the special condition of upper crust radioactive heating being distributed downward within the deforming orogenic belt, or by substantial viscous heating. In this discussion I summarize an alternative explanation, that most orogens involve a pre-collision uniformly hot subduction backarc where Barrovian conditions are already present, and which make up the main part of the subsequent orogen. A previous compilation showed that continental backarcs globally, commonly several 100 km wide, are uniformly hot with the exception of infrequent flat slab subduction. Recent crustal extension is not required. The estimated time constant for backarc cooling after subduction stops is about 300 m.y. In 10 backarcs studied with no recent extension, the heat flows are high, ~75 mW/m_2, there are low seismic velocities in the upper mantle characteristic of high temperatures, and volcanic xenoliths from the lower crust that indicate high temperatures. Sporadic backarc basaltic volcanism is also common. For the North American Cordillera backarc I have carried out a new thermal review. There are six principal constraints, heat flow-radioactive heat generation measurements, upper mantle temperature-dependent seismic velocities, mantle xenoliths, receiver function lithosphere thicknesses, thermal elevations and effective elastic thickness. Regional temperatures at the Moho are surprisingly constant, 800-850C, compared to 400-450C for stable cratons, with temperatures in the lower 10 km crust of 750-850C, i.e., within the peak Barrovian P-T field. The high temperatures in the former backarc also explain why deformation is concentrated on one side of orogens, for example the hot and weak former backarc Tibet side of the India collision. These temperatures are high enough for lower crust ductile flow prior to orogenic crustal thickening. For the Himalaya-Tibet orogeny, recognizing that much of the Tibet Plateau and adjacent areas were in the former hot backarc can resolve the difficulty in collision models of generating high enough temperatures for the inferred lower crust channel flow. High temperatures were present before collision and crustal thickening. Similar high temperatures likely were present on one side of the Grenville, Appalachian, and most other orogens prior to deformation, providing an explanation for the observed Barrovian metamorphism. Understanding the origin of metamorphism in orogenic belts requires knowledge of the distribution and temperatures of the former hot backarcs before collision.

Lower crust detachment and channel flow everywhere in the North American Cordillera: The crust moves independently of the mantle

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Lower crust detachment and channel flow with the crust moving independently of the upper mantle has previously been argued for Tibet, the high Andes, and the currently extending Basin and Range. A detachment example is in northwest Canada, where the upper crust is inferred to be driven 800 km northwestward from the coastal Yakutat terrane collision to the current thrusting in the Mackenzie Mountains and arctic Mackenzie Delta thrust front. It also has been argued that detachment is required for tectonic continuity in foreland thrust belts. Here we present the surprising conclusion that lower crust detachment and channel flow are occurring in most of the North America Cordillera and in other continental hot backarcs. A clear indication comes from seismic structure data that show the Cordillera Moho is remarkably flat at a depth of 33±3 km, from Mexico to Alaska, in spite of a complex history of extensional faulting, large shortening deformation, and terrane accretion. The constant crustal thickness must result from lower crust detachment and flow associated with Cordillera-wide high temperatures. Any perturbation to the Moho boundary relaxes to a nearly horizontal gravitational equipotential in the order of 10 Ma and significant mountain belt elevations wider than the flexural wavelength of ~100 km are similarly short-lived unless maintained by ongoing shortening. Support for the conclusion of detachment and flow comes from the uniform high temperatures in the lower crust that are now evident throughout the Cordillera, 800-850°C at the Moho compared to 400-450°C in the adjacent craton from: heat flow measurements; upper mantle seismic velocities; mantle xenoliths; receiver function lithosphere thicknesses; and thermal elevations. Similar high temperatures and a weak ductile lower crust are required by the effective elastic thicknesses Te of less than 20 km. These temperatures are high enough for viscosities of 10^{19} Pa s in the lower crust, allowing detachment and ductile channel flow. Other indicators of shear and flow are: the common lower crust horizontal seismic reflectors interpreted to result from ductile shear; outcrops of former lower crust sheared at high temperatures; and areas where the upper crust of the Cordillera has been thrust over the adjacent craton. Large-scale regional tectonic motions such as in oroclines seem to require that horizontal crust transport involves only the upper crust. The evidence for detachment indicates that mantle origin volcanics and mineral deposits may not lie over their mantle source in the Cordillera.

Converging morphometry of Proterozoic and post-vegetation rivers

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Barren landscapes dominated the Proterozoic Earth, and their rivers had no proven interaction with any macroscopic organism. It is a widely held view that, in the absence of vegetation, fluvial systems featured barely entrenched, shallow channels that promptly widened over floodplains in response to floods. Surprisingly, this hypothesis has never been tested because of an enduring lack of data on Precambrian fluvial-channel morphometry. Here we show, through a novel integration of remote sensing and outcrop sedimentology, that large and deeply channelled rivers were developed in the Proterozoic despite a lack of vegetation. Our dataset comprises 156 fluvial-channel forms from selected rock units exposed in the Canadian Arctic and the Scottish Highlands. These channel forms are dated from 1.9 to 1.0 Ga, and were originally deposited a few tens to thousands of kilometres from their headwaters. Most forms represent large channel bodies, likely the record of basin- to craton-scale fluvial systems. These Proterozoic channel forms consistently present width:thickness ranges fully matching those of Phanerozoic counterparts, and sedimentology pointing to low discharge variability. This evidence suggests that morphometric parameters for large fluvial channels might have remained within a narrow range over almost 2 billion years. We suggest closer parallels between Proterozoic and Phanerozoic fluvial dynamics, which may better inform analyses of extraterrestrial planetary surfaces and related comparisons with pre-vegetation Earth landscapes.

Keynote (40 min): Understanding the metamorphic architecture of large hot orogens: Tools and limitations with examples from the Grenville Province

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Geodynamic modeling has provided a stimulating framework for the metamorphic interpretation of large hot orogens. Several models were inspired by and adapted to the Grenville Province, however, the metamorphic record of the orogen is still sketchily understood.

Key issues are the duration and P–T paths of granulite-facies metamorphism (and the resulting anatexis) that prevailed in the mid-P to high-P portions of the hinterland and in the southern Parautochthonous belt. Studies of anatectic aluminous rocks in the central Grenville where these three structural levels are juxtaposed provide insights on anatexis, but also highlight current limitations in the understanding of the metamorphic history. Rocks in all structural levels show evidence for: anatexis by breakdown of micas, melt escape and retention of some melt (6–8% predicted by phase equilibria modeling). Sites of retained melt and retrograde domains linked to melt crystallization are well documented using SEM–MLA false-color mineral maps of thin sections, and Cl-imaging of fine textures combined with trace element signatures in quartz and kyanite.

These data in conjunction with mineral chemistry and phase equilibria modeling suggest contrasting P–T patterns in the three granulite-facies segments of the central Grenville. However, there are several limitations, such as the inability to model metamorphic pressures in apatite-bearing rocks using currently available thermodynamic databases, and the difficulty to obtain metamorphic temperatures above the P–T field of biotite melting. The use of trace element thermometers is an attractive alternative, but their application in anatectic rocks is still not straightforward.

A first order distribution of the metamorphic ages available for the Grenville is consistent with long-duration Ottawan-age metamorphism in the hinterland and short-lived Rigolet-age metamorphism in the Parautochthonous belt. Yet, most of these are zircon and monazite ages which in anatectic rocks likely represent melt crystallization events rather than the age of the metamorphic peak, and the meaning of the wide range of Ottawan metamorphic ages is still not well understood.

In addition, one of the key findings in the mid-P hinterland of the central Grenville is Rigolet ages recorded by a texturally distinct generation of monazite rims on Ottawan-age cores. These are coeval with widespread ultrapotassic magmatism in the same crustal segment and bring to attention another aspect of the orogen that has to be accounted for: the diversity and abundance of Grenvillian-age magmatic rocks, which are particularly widespread in the hinterland of the central and eastern Grenville Province.

Aragonite facies in an Ordovician calcite sea

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Kingston Ontario is known as 'The Limestone City' because most historic buildings are constructed of beautifully preserved Upper Ordovician limestone. From a geological perspective the numerous outcrops and many quarries expose one of the most important global, late Ordovician carbonate successions deposited during a Calcite Sea time. The Black River – Trenton Groups are traditionally interpreted as a deepening–upward succession deposited in a progressively subsiding Appalachian Basin that contained warm-water photozoan deposits that pass upward into cool-water heterozoan carbonates. This succession has traditionally been interpreted to reflect an incursion of cold, high-latitude ocean waters into the area. This view is herein revised in the light of recent advances in the understanding of cool-water carbonates and calcite-aragonite seas. The succession is now interpreted as a thermo-stratified ramp whose depositional surface sank into deep, cold waters below the shallow thermocline, and remained there until latest Ordovician time when shallow water facies, sequestered to the west, migrated eastward again. Although in a calcite sea, shallow tropical facies were, because of high neritic ocean water temperatures and slightly elevated seawater salinities, aragonite-dominated. This interpreted geohistory confirms recent concepts of calcite sea carbonate polymorph modeling. Diagenesis of the photozoan deposits is typical warm-water but the deeper-water, heterozoan cool-water sediments are typified by seafloor aragonite dissolution, numerous omission surface hardgrounds, and local precipitation of calcite cement.

Compositional and diagenetic partitioning of cool-water carbonate marine and aeolianite sediments, SE Australia; Resolution of a conundrum

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Cool-water, temperate shelf-ramp marine carbonate sediments go into the rock record as mostly low-mg calcite particles. Temperate, seabeach calcareous dunes however, do not and are instead rich in aragonite grains, much like warm-water, tropical carbonate aeolianites. This apparent conundrum has been resolved by studying Quaternary deposits in SE Australia, the most extensive such system in the modern world, extending back ~ 1 my. Aragonite particles in the dunes come from numerous bivalves, particularly infaunal forms that thrive in the surf zone. Whereas a proportion of the dune carbonate also comes from the offshore carbonate factory, most of the delicate biofragments generated there, such as bryozoans, are physically destroyed in this hydrodynamically active zone. Thus, aeolianite sediment is a mix of calcite and aragonite components, like tropical calcareous sediments – but for different reasons. Such cool-water carbonate partitioning has important diagenetic consequences. Open shelf-ramp sediment, because of the loss of aragonite over ~ 30,000 years, is largely unaffected by subaerial exposure and remains unlithified until buried. By contrast, the aeolianites, because of abundant molluscan aragonite grains, are lithified early via dissolution-reprecipitation during meteoric diagenesis in ~ 200,000 years, with a distinctive meteoric geochemical signature. This is because the sediment is transported landward before aragonite is lost via seafloor diagenesis. Thus, neither aeolianites nor offshore marine carbonates faithfully record the composition of the original sediment; dunes lack the important bryozoan constituents while neritic deposits lack the prolific mollusks.

Application of automated mineralogy in human health risk assessment at the Giant Mine, Yellowknife

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The use of Scanning Electron Microscopy coupled with automated mineralogy software has proven to be a valuable tool in understanding the origin, speciation, and health risk associated with a large and complicated legacy mine site in northern Canada. Giant Mine produced more than 220 tonnes of gold over 50 years of production. Poor pollution control from roasting arsenopyrite-bearing ore in the early years resulted in roaster waste co-deposition with flotation tailings and the release of 20,000 tonnes of roaster generated arsenic trioxide from stack emissions. Understanding the distribution and mineralogy of As-hosting phases within tailings dust, soils, and lake sediments is key to mitigating the human health hazards and to assist in remediation, which is currently projected to cost the federal government over $1,000,000,000.

The bioaccessibility of arsenic varies significantly with the host mineral, so identifying the arsenic-hosting phases and calculating the relative distribution is critical to assessing risk. Quantitative automated mineralogy allows us to determine if the origin of arsenic is natural or anthropogenic, if roaster-generated arsenic-bearing phases are likely to persist in contaminated soils and sediments, and to evaluate the risk to human health associated with the ingestion of these materials - particularly arsenic trioxide, the most soluble and bioaccessible solid arsenic phase. In many of our samples, only 1 in 50,000 grains was identified as arsenic trioxide. In other cases, low amounts of arsenic were present in some iron oxides, but not others. Subtle differences in chemistry and morphology can be used to determine if an iron oxide is natural or roaster-derived.

Three types of contaminated materials from the surrounding environment have been studied. Tailings dust, an ongoing concern to the local community due to the distance wind can carry the material, contains arsenic mainly in the form of arsenopyrite and roaster-generated iron oxides - both of which are less bioaccessible than arsenic trioxide. Near-surface soils on the property and beyond the lease can have total arsenic concentrations as high as the tailings, which is predominantly hosted in arsenic trioxide. Arsenic trioxide also persists in the sediments of nearby lakes. Study of the sediment column indicates that arsenic trioxide is slowly converting to arsenic sulfide, a less bioaccessible phase. While originally developed for metallurgy, quantitative automated mineralogy is a new tool for environmental geochemists to determine textural and chemical relationships that are not evident using conventional methods.

Keynote (40 min): Cryptic structures revealed - Where and how they form, and why it matters

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Cryptic structures in crustal-scale thrust zones have received considerable attention recently (e.g., Cottle et al., J.Struct.Geol. 78, 119-133, 2015), as if they were somehow new and enigmatic. In fact, these features are entirely predictable and have been observed and understood for decades. They are “cryptic” in the sense that a discontinuity within an apparently continuous metamorphic sequence can be revealed from a range of structural and metamorphic criteria, including abrupt, foliation-parallel lithological changes and significant contrasts in pressure-temperature-time-deformation (P-T-t-d) histories over short distances. They are typically associated with inverted metamorphism, and are a predictable consequence of the way these sequences are constructed.

Numerical models for the Himalayan-Tibetan system published more than a decade ago (Beaumont et al., 2001, Nature 414, 738-742, 2001; JGR 109, B06406, 2004; Jamieson et al., JGR, 109, B06407, 2004; GSL Spec.Pub. 268, 165-182, 2006) predict that cryptic structures should have developed within the Greater Himalayan Sequence (GHS) and Main Central Thrust (MCT) zone during early thrusting and subsequent metamorphism and exhumation accompanying channel flow. Vertical protolith boundaries tracked through the models (Jamieson et al., 2006) become strongly attenuated and imbricated during transport beneath the plateau and exhumation at the flank of the model orogen. Early thrusts formed during construction of the model orogen survive burial, transport in the mid-crustal channel, and exhumation at the plateau flank. In the models, material emerging from beneath the plateau is juxtaposed with newly accreted material across a first-order discontinuity (“MCT” of Jamieson et al., 2004). Because it is syn-metamorphic, and therefore affected by structural reworking and metamorphic overprinting, the natural equivalent of this boundary may be difficult to detect from field observations alone. However, contrasting P-T-t paths (broad loops above the “MCT”, tight hairpins below it) and peak metamorphic ages (older above the “MCT”, younger below) reflect the contrasting trajectories of the corresponding materials through the orogen. Equivalent discontinuities form throughout the growth of the model orogen as footwall material is accreted deep in the crust, forming finite-thickness ductile thrust sheets. The accumulation of these accreted sheets and their bounding cryptic structures, in combination with their differential transport in response to velocity gradients within the orogen, contributes to the tectonic assembly of the resulting inverted metamorphic sequences. Despite claims to the contrary (e.g., Carosi et al. Geol.Soc.Am.Bull. 128, 1571-92, 2016), cryptic structures are entirely compatible with channel flow.

Deformation history of the Black Bay Fault

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The Black Bay Fault (BBF) is a major Paleoproterozoic northeast-southwest trending crustal-scale structure transecting the South Rae Province of the Canadian Shield. From the shore of Lake Athabasca in northern Saskatchewan (SK), the BBF extends 100's km northward into the Northwest Territories (NWT). Little is known about the fault, with only a few small-scale studies completed in the vicinity of Uranium City, SK. Timing of deformation remains poorly constrained. In the NWT, the fault has primarily been traced from aeromagnetic lineaments, and becomes more complex, with a large NW trending segment. As a part of the GSC's GEM2 South Rae project, in collaboration with the NWT Geological Survey, the continuation of the BBF into the NWT (NTS 75B, G and H map sheets) was examined to better understand the history the fault.

Overall, the BBF is observed to be a steep west dipping structure associated with a strong NE/SW trending fabric separating the Ena and McCann from the Firedrake domains with different tectonometamorphic histories. The BBF has experienced at least four phases of deformation, progressing from ductile to brittle-ductile through to brittle. Early deformation, D_1, produced NNE-SSW trending west-side up sinistral transpressional structures, and with deformation preserved in locations which contain a large amount of strain heterogeneity. D_1 appears to be the main exhumation driver of the western domains, with sheath folds observed in the S_1 fabric with steep stretching lineations. Rare NE plunging tonalitic L-tectonites were also developed during D_1. D_2 formed an overprinting southwest dipping foliation, shallowly-NW plunging lineations and sinistral kinematic indicators, developing the NW trending segment via sinistral shearing. D_3 is a well recorded dextral transpressional event which produced a pervasive steep west-dipping NE-SW trending foliation and moderately-SW plunging stretching lineation. D_3 deformation progressed from a mylonitic brittle-ductile regime around Uranium City towards a gneissic ductile regime in the north of 75 B. Late stage brittle deformation of the BBF occurred during D_4 in the Uranium City vicinity with a dextral component parallel to the fault trace along with a conjugate set of E-W-trending sinistral faults. A reemergence of the shallower level deformation resembling the deformation around Uranium City was observed around the northern extent of the NW trending segment and has been preserved from late normal south-side down motion on the segment.

3D numerical modeling of mantle lithospheric removal induced by eclogitization

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Numerous geophysical, geochemical and petrological studies have been dedicated to understanding the stability of lithospheric roots and removal mechanisms. Many rheological and compositional factors have been identified that lead to the onset of instability and subsequently to the removal of mantle lithosphere. Eclogitization of lower crust and the resulting density and viscosity modifications might be one of the leading factors to lithospheric instability in compressional stress regimes.

The attempt to reconcile any geodynamic model to surface kinematics and crustal deformations is more complicated than geophysical inversions. The challenge lies in the added number of rheological and thermo-mechanical parameters that plague the problem with non-uniqueness. Well-constrained numerical geodynamic modeling is the only tool capable of combining a number of tectonic processes and solve the governing equations of geodynamics to provide quantitative exploration of the respective effects.

Preliminary 2D and 3D numerical experiments will be presented that are designed to investigate the density and viscosity effects of lower crustal eclogitization on the decoupling process of mantle lithosphere from the crust and its delamination. These models consider a central orogeny undergoing shortening and thickening due to plate convergence. Through systematic modification of rheological parameters of lower and upper crust as well as activation energies of upper mantle and mantle lithosphere, the propensity and style of decoupling, and removal mechanisms are examined. These numerical experiments show how the evolution of surface topography is influenced by the degree of symmetry in subsurface processes.

Indicator minerals and pathfinder elements from a regional drilling program, Lac de Gras, NT; Insights into 3-D dispersion resulting from ice flow shifts

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The discontinuous till on the Canadian Shield displays surficial patterns derived from local bedrock sources and the net effect of ice flow and sediment transport history. This pattern reflects an incomplete mixing of older and younger tills. However, dispersal inheritance of the till is often from the most recent transport direction despite a more complex erosional record. In the Lac de Gras region, some dispersal patterns, such as the Coppermine indicator train, are difficult to explain because their source has not yet been identified despite considerable effort. One hypothesis is that the Coppermine train may be offset from the source due to an older transport direction. Thicker pockets of till occur in the region, such as in the tail of a rock knobs, and may contain the archives of till produced by older ice flow phases. Linking subsurface information from areas of thicker till to the surface information could reveal important insights into the real 3D dispersal patterns and potentially help explain the Coppermine Indicator train. This research utilizes shallow subsurface data from a regional drilling program consisting of 156 downhole till samples from 52 RC boreholes and 11 additional surficial till samples to complement available data. Kimberlite Indicator Minerals and geochemical pathfinder values were obtained from the collected samples. Results show contrasting subsurface and surface patterns, indicating the deeper till either represents a different stratigraphic unit in places or has a higher compositional inheritance from older ice flow phases. Three main regional ice flow directions progress in age from SW (oldest) to W, to NW (youngest). These are recorded in landforms and erosional indicators on outcrops. Our results show evidence for complex and discontinuous three-dimensional till dispersal patterns that match the ice flow history. The 3-D compositional patterns reveal greater complexity than previously recognized based on surficial data only. Three-dimensional reconstructions based on regional drilling campaigns can help enhance the abundant surficial information and improve the interpretation of the net effect of ice flow shifts on sediment erosion, transport, and deposition.

Structural control of mineralization and history of deformation at the Island Gold deposit, Superior Province, Ontario

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The Michipicoten Greenstone Belt of the Superior Province in northern Ontario lies to the southeast of the Hemlo gold camp and is proposed as the western extension of the Abitibi Greenstone belt. It contains the Goudreau Lake Deformation Zone (GLDZ) which hosts multiple gold deposits, most notably the Island Gold deposit. At least two generations of brittle-ductile to ductile deformation in the GLDZ have been recognized. D_1 consists of regional-scale folding and the formation of the GLDZ along a parasitic synclinal fold on the northern limb of the Goudreau Anticline. S_1, the prevalent, approximately 60°-striking foliation, as well as a camp-scale S-fold, are associated with this early folding. Stretching lineations on the S_1 surface, defined by elongated phenocrysts, display an average plunge of 62° to the northeast and were observed to both the north and south of the deposit. D_2 is defined by shallow, west-plunging Z-folds that are locally associated with dextral shear sense indicators. S_2 crenulation cleavage is locally pervasive. It overprints S_1 and forms sub-horizontal crenulation lineations. The Island Gold deposit forms a mineralized corridor within the GLDZ. It is comprised of the Island Gold, Island Deep, Lochalsh, and Extension 1 and 2 Zones, which lie along strike, and the Goudreau Zone which lies to the north. The Island and Extension Zones are hosted in intermediate to felsic volcanic rocks and consist of eight subparallel ore zones of predominantly smoky grey quartz veins within a silicate and sericite alteration package. The ore zones strike approximately 60° and dip approximately 80° to the south. The Goudreau Zone also consists of several ore zones and is hosted by both intermediate to felsic volcanic rocks and the Webb Lake Stock. Most mineralization in the Goudreau Zone is interpreted as similar to the Island and Extension Zones but another, earlier, type of mineralization is also observed which consists of horizontal extensional ore veins and associated moderate to nonexistent alteration package that are tightly folded with hinges plunging shallowly to the east. Most ore veins were emplaced during D_1. They were folded and underwent extension during progressive D_1 deformation, resulting in pinch-and-swell and boudinage structures. Shallow en echelon veins, associated with D_2, cross-cut the ore zones.

Geochemical and textural analysis of the cyclic units in the Peridotite zone, Stillwater Complex, Montana

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Geochemical and quantitative textural methods are applied to cyclic units in the Peridotite zone of the Stillwater Complex, a six-kilometer-thick layered mafic-ultramafic intrusion in south west Montana, USA, to identify and interpret variations in the cooling history and environment during formation of cumulate layers. The Peridotite zone represents the bottom two-thirds of the Ultramafic series of the complex and varies in thickness from about 360 m in the western part of the complex and to 1200 m in the east. Previous work has identified between 19 and 42 complete or partial cyclic sequences in the Peridotite zone. Each cyclic unit is composed, from top to bottom, of cumulate layers of orthopyroxenite, harzburgite, and peridotite and may or may not also include a massive chromitite layer near the base of the peridotite layer. Conventional models for the formation of the cyclic units have hinged on fractional crystallization of cumulus minerals in a large, slowly cooling magma chamber in which each cyclic section represents the injection of new magma into the chamber. We present geochemical and quantitative textural results for variations in composition and rock texture within and between cumulate layers in a 45 m section of drill core from the Mountain View area of the complex which includes as many as six cyclic units. Oxygen fugacity (f_{O2}) was tracked through the section by probing co-existing cumulus olivine and chromite to monitor the redox conditions of the system. The Mg-number and nickel content in olivine were measured to look for possible evidence of the infiltration metasomatic processes which have been identified at the base of cyclic units of some layered mafic intrusions. Crystal size distributions (CSDs) of chromite and olivine were used to examine the cooling history and grain coarsening processes throughout the section. Preliminary results show no systematic increase in olivine grain size with increased depth down a cyclic unit as observed by other authors. Additionally, variation in the CSD shape for olivine grains indicate that increased residence time or coarsening have influenced development of textures in a non-uniform way through a single cyclic unit. Finally, we summarize the cumulate textures found in the cyclic units which are dominated by orthocumulates and mesocumulates composed of varying amounts of cumulus olivine, bronzite, and chromite with or without oikocrysts of bronzite and augite and intercumulus plagioclase, augite, and phlogopite. Coarse-grained to pegmatitic olivine cumulates are often found in proximity to massive chromitite layers.

Adaptive Phased Management: Canada's plan for long-term management of nuclear used fuel the role of geosciences

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The Nuclear Waste Management Organization (NWMO) is responsible for the long-term safe management of Canada's used nuclear fuel. The Federally approved plan for long-term used fuel management being implemented by the NWMO is referred to as Adaptive Phased Management (APM). The APM approach ultimately envisions Canada's used nuclear fuel being emplaced within a multi-barrier Deep Geologic Repository (DGR) designed to provide passive safety at time frames relevant to repository safety (i.e., 1Ma) in a suitable sedimentary or crystalline setting. As part of APM, the NWMO fosters advances in Geoscience related to the characterisation and assessment of varied geologic settings to safely host a DGR at a nominal depth of 500 m. The Geoscience program is multi-disciplinary, with a focus on methods necessary to gather evidence regarding the past, present and future evolution of the geosphere as it influences understanding of geologic formation barrier properties, longevity and integrity. In this role, Geoscience provides a basis to develop a Descriptive Geosphere Model that supports science-based understanding of DGR containment and isolation, which is integral to a site-specific DGR Safety Case.

The APM Geoscience work program is intent on preserving knowledge and refining methods to enhance exploration of deep-seated low-permeability crystalline and sedimentary groundwater systems. The activities fall into four categories: i) development of laboratory and surface based in-situ borehole techniques to characterise sub-surface conditions governing, in part, site suitability; ii) illustrative numerical experiments and site-specific assessments at repository, local and regional geosphere scales to capture the time rate of change and magnitude of geosphere response to events, including natural and repository-induced perturbations; iii) assessment of uncertainty relevant to repository safety, including seismic hazard, geomechanical stability, Excavation Damage Zone (EDZ), coupled Thermal-Hydraulic-Mechanical phenomena, and long-term climate change resulting in glacial and permafrost advance and retreat over the North American continent; and iv) collaborative applied research and development within crystalline and sedimentary Underground Research Laboratories on phenomena directly linked to testing of, and ensuring confidence in, a case for DGR safety.

This presentation provides a description of the APM Geosciences technical program, with a focus on key activities aimed to continually improve the scientific basis on which the behaviour of the geosphere can be tested in its capacity as a natural barrier to passively contain and isolate used nuclear fuel for safety-relevant time periods.

Triassic transpressional deformation along the Shangdan Tectonic Zone and the tectonics of the Qinling orogenic belt in China

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The Shangdan Tectonic Zone (SDTZ) is the suture between a late Paleozoic (~350-320Ma) northward dipping accretionary belt, called the North Qinling Block (NQB), in the southern margin of the North China Plate and a sliver continental fragment (or fragments) called the South Qinling Block (SQB). The latter is considered to have been derived from the South China (Yangtze) Plate. The timing of the collision between the NQB and SQB along the Shangdan suture, the kinematic evolution of the SDTZ and its relation to the country rock deformation are crucial questions for Qinling tectonics but have been in debate for many decades. A popular current view is that the Shangdan suture formed in the Paleozoic but strong thrusting and folding in the country rock took place in the Triassic, in response to the collision between the SQB and the South China Plate along the so-called Mianlue suture zone. We recently conducted detailed structural and geochronological analysis along the SDTZ in areas of Heihe, Shagou and Danfeng. The fabrics in the SDTZ suggest that it experienced sinistral transpressional deformation in late Triassic. Subvertical foliations and horizontal stretching lineations are developed in mylonites and highly transposed metamorphic tectonites throughout the SDTZ. Shear sense indicators (including S-C-C' fabrics, rotated porphyroclasts, and asymmetric folds) are well developed on sub-horizontal sections on outcrops and in thin sections showing sinistral sense of shear. The U-Pb zircon age for granites mylonitized along the SDTZ is 220.8±1.3Ma. Some zircons show a core-mantle-rim texture, and the U-Pb ages from 13 zircons yield a weighted mean age of 210.3±1.5 Ma (MSWD=0.13). We identified two generations of deformation in the Paleozoic Liuling group (ca.401-373Ma), south of the SDTZ. F_1 folds have steeply-dipping axial planes and strike 120°. F_2 folds are recumbent and overprint on F_1, especially their steep limbs. We interpret the sinistral shearing along the SDTZ and F_1 folding in the Liuling group to represent a partitioned deformation field in response to sinistral oblique convergence between the South China Plate and the North China Plate. Such a Triassic kinematic field is at odds with any existing tectonic models. We propose a Pacific-North America type plate boundary for the ancient SDTZ which can better account for the tectonics of east Qinglin belt in Triassic.

Uranium and molybdenum isotope constraints on ocean redox conditions during deposition of the Upper Devonian Kettle Point Formation, Ontario

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The Late Devonian extinction event was among the most severe Phanerozoic mass extinction events, which led to a decline in the abundance and diversity of marine and terrestrial ecosystems, particularly tropical shallow-marine faunas. However, the key trigger of this event is still being debated. Here, a multi-proxy study using Mo and U isotopes and elemental data from black shales of the Kettle Point Formation (southwestern Ontario, Canada) in the Gore of Chatham core has been carried out to evaluate the role of local versus global ocean redox conditions on the Frasnian-Famennian mass extinction event.

High total organic carbon (TOC) (3.1-15.6 wt%), total sulfur (1.2-6.0 wt%), Mo (40-459 ppm), and U (10-62 ppm) concentrations, and high Mo/U ratios (at least three times the molar Mo/U ratio of modern seawater) are observed in the black shales, suggesting a locally euxinic depositional environment. Distinctive increases in the Mo concentrations, Mo/TOC ratios, and Mo/U ratios occur in the upper Kettle Point Formation. Accompanying these changes is persistent hyper-enrichment of V (700-1968 ppm), suggesting very high H_2S levels in the water column. Episodic Zn hyper-enrichments (>500 ppm; up to 1478 ppm) suggests that high H_2S levels were reached intermittently in the photic zone.

The δ^{98}Mo values in the Kettle Point Formation range from 0.55‰ to 1.73‰ (relative to standard NIST SRM 3134 = 0.25‰), and decrease in the upper part of the formation. The δ^{238}U values vary from –0.14‰ to 0.54‰ (relative to standard CRM145 = 0‰), and increase in the upper part of the formation. The moderate negative correlation observed between the Mo and U isotope compositions cannot arise from changes in global ocean redox conditions, which should shift both isotope systems in the same direction. Instead, changes in the local depositional environment, namely the extent of basin restriction and water column H_2S levels, likely influenced the magnitude of Mo and U isotope fractionation between the water column and underlying sediments. A shift to higher water column H_2S levels in the upper Kettle Point Formation may have increased the preferential removal of lighter Mo and heavier U isotopes to the euxinic sediments. After correcting for these effects to infer seawater isotope compositions, our data suggest a slightly greater extent of ocean anoxia and euxinia compared with today, implying that ocean anoxia was not the key driver of the Late Devonian mass extinction event.

Most of the modern-day coastal zone in the upper Great Lakes was established many millennia ago during the Nipissing phase

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The current coastal configuration of the upper Great Lakes (Superior, Michigan, Huron) became established during the Nipissing phase approximately 6,000 to 3,500 calendar years ago. Lake levels rose, peaked at approximately 4,500 calendar years ago and fell rapidly to a level similar to the historical average recorded by water level gauges, accounting for glacial isostatic adjustment. Coupled variations in the rate of water level change and sediment supply helped dictate shoreline behaviour several millennia ago and set up the conditions necessary to leave an imprint of a magnificent relict that encompassed the Superior, Huron, and Michigan basins. Evidence of this confluent system is seen today in the most prominent coastal landforms rimming all of the upper Great Lakes. It was not until recently that we targeted Nipissing sites near lake outlets (present and past) containing not only one but many relict shorelines individually splayed apart. Following an approach developed in strandplains of the upper Great Lakes we are able to significantly increase the level of detail and quantify more accurately natural variations in lake level, glacial isostatic adjustment, and lake outlet use. This information is urgently needed to improve coastal management plans and regulation reviews.

Ground penetrating radar is used to define the subsurface stratigraphic sequences required to interpret past shoreline behaviour; vibracores are collected to determine accurate elevations of stratigraphic contacts essential to interpret lake level, glacial isostatic adjustment, and outlet conveyance; and optically stimulated luminescence is used to place stratigraphic sequences and elevations into temporal context. Results thus far do not support two peak water-level stages separated by a lowstand during the Nipissing phase, but rather one peak water-level stage at 4,500 calendar years ago when the Superior, Michigan and Huron basins were joined. Importantly, a decrease in the rate of water-level rise leading up to the peak Nipissing elevation contributed to a transition in the coastal zone from primarily erosion to deposition as the rate of sediment supply caught up to the rate of water-level change. Many depositional features formed at this time. Some coastlines experienced aggradation (building vertically into barrier bar complexes), and others experienced progradation (building lakeward into strandplains of beach ridges). These landforms helped establish numerous coastal wetlands and inland lakes that we see today in the coastal zone.

Lithostructural controls of U mineralization in the Kiggavik Main and Centre zones, north-central Rae craton: A record of long-lived tectonism and ground preparation for U ore systems

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The Rae craton records a remarkably long tectonic history marked by rifting from an antecedent landmass to subsequently forming the nucleus of the Laurentia (Nuna). This history includes a final Paleo- to Mesoproterozoic amalgamation with incipient rifting and intracratonic basin development and an increase in atmospheric O_2 in which uranium ore systems flourished. The Kiggavik uranium deposits are part of this history and illustrate underlying factors important in the ground preparation and localization of such deposits. The Kiggavik Main, East, and Centre Zone deposits are hosted in Archean and Paleoproterozoic basement rocks proximal to, and underlying, the Thelon Basin. The basement rocks include three major unconformity-bounded sequences. The basal package comprises 2.71 Ga metagreywacke (Pipedream assemblage) of the Woodburn Lake group. This is succeeded by ~2.6 Ga meta-rhyolite and associated epiclastic rocks (Pukiq Lake Formation) of the Snow Island Suite (SIS), which is in turn overlain by <2.3 Ga Ketyet River group (KRg) quartzite. All units are strongly deformed and form a gently NE-dipping (10-20) sequence that is truncated by the Thelon fault. Structural relationships indicate early tight to isoclinal recumbent/sheath-style folding, with inferred thrusting and translation of SIS and KRg rocks over older, more rigid Pipedream metagreywacke. The driving force of this earliest ductile deformation (D_1) is uncertain but subsequent refolding about NNE-trending axes (D_2) is ascribed to Snowbird-Hudsonian orogenesis. Following the metamorphic peak at ~1.83 Ga, extensional/strike-slip faulting facilitated cooling, exhumation, and eventual subsidence of the basement rocks, and in turn deposition of mainly siliciclastic rocks within the Baker Lake and Thelon basins and contemporaneous volcanic-plutonic magmatism (~1.83 Ga Hudson and ~1.76 Ga Kivalliq suites). At Kiggavik, during the late-stages of the Hudsonian orogeny, regional-scale brittle structures developed in a Riedel shearing system in response to dextral strike-slip displacement along the ENE-trending Thelon fault. It is hypothesized that fluids scavenging uranium from Hudson and Kivalliq granites, as well as highly differentiated SIS felsic volcanic rocks, infiltrated along steeply dipping D- and P-shears during post Hudsonian reactivation and precipitated primary uranium mineralization in the Main, Centre, and East Zone deposits. At Centre Zone, some fluids permeated along foliation into the lower Pipedream metagreywacke, most were focused into more porous-permeable SIS volcanogenic rocks above and bounded by impermeable intervals of fold-thrust repeated KRg quartzite. This confluence of factors played a profound role in uranium sourcing, controlling fluid pathways, and transporting and precipitating uranium in these deposits.

The geochemical characterization and resultant exploration implications for the meta-sedimentary hosted Kiyuk Lake Au-prospect, Kivalliq region, Nunavut

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Exploration in Nunavut has been primarily focused in Archean greenstone belts in the north and coastal regions of the territory, resulting in large areas in the south of underexplored terrain. The Kiyuk Lake property is located in the underexplored southwest corner of the Kivalliq region of Nunavut. The study area, situated within the Hearne Domain of the Western Churchill Province, is composed of Proterozoic calc-silicate sediments of the Hurwitz Group (<2.4->1.9 Ga), the unconformably overlying Kiyuk Group (<1.9->1.83 Ga), and intrusions of the Hudson (1.85-1.81 Ga) and younger Nueltin (1.76-1.75 Ga) granites. Gold mineralization hosted by Proterozoic sediments is rare in the Canadian Shield, so this study aims to further the understanding of the enigmatic gold mineralization hosted in such sediments at the Rusty zone at Kiyuk Lake. The main host rock, a quartz-feldspathic wacke, is weakly metamorphosed and intruded by later dykes of intermediate composition. Textural relationships suggest that mineralization is post-deposition and likely syn-intrusion. The oxygen, hydrogen and sulphur isotopic data indicate a predominantly magmatic origin for ore fluids that interacted with marine carbonate units at depth. The Rusty zone is interpreted to have formed from magmatic-hydrothermal fluids being funnelled through basement breaching structures until fluid over-pressurization caused brecciation of the overlying sedimentary host rocks. These later intrusions are considered to have had associated hydrothermal fluids that resulted in the precipitation of the main mineralizing assemblage of Fe-sulphides (predominantly pyrrhotite) and Fe-oxides (magnetite). Iron and calcic alteration dominate the breccia and veins and form narrow halos in the surrounding wall rock. Stable isotope thermometry calculated the alteration phases formed between 450-600°C. The estimation of physio-chemical conditions such as fO_2, fS_2, pH and aqueous gold complexing, suggest gold precipitated in response to a reduction in pH and Cl concentration that was ultimately caused by cooling of the fluids and the precipitation of Cl-bearing minerals (Cl-bearing amphibole and scapolite). Pathfinder elements associated with this mineralization have been identified in drill core and include Ni, Mn, Co, Ca, Fe, As [W, V]. Surficial mapping in the area concluded that the Kiyuk Lake property is characterized by a semi-continuous till vaneer (2-10m thick), that is interrupted with dispersed glacial landforms including ribbed moraines, drumlins and large eskers limiting the outcrop exposure to <10%. Using property wide glacial till geochemistry this study aims to translate the mineralization and alteration chemistry into exploration criteria applied to more accessible media such as soil and till samples.

Keynote (40 min): The Ni-Cu-PGE prospectivity of mafic-ultramafic Large Igneous Province events and the use of lithogeochemistry in mineral exploration

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Large Igneous Provinces (LIPs) are large volume, short duration intraplate magmatic events that are generally associated with the extensive development of volcanic rocks (mainly flood basalts) and plumbing systems that may contain mafic dyke swarms, sill complexes, and mafic-ultramafic layered intrusions. The processes that form the mafic–ultramafic family of LIPs can also generate significant, if not world-class, magmatic sulphide mineralisation, as exemplified by the Noril'sk-Talnakh deposits in Russia (associated with the 251 Ma Siberian Trap LIP), Cu-Ni-PGE mineralisation within the Duluth Complex, Minnesota, USA (associated with the 1114-1085 Ma Keweenawan LIP), the 1885-1865 Ma Raglan and Thompson deposits in Canada and the Archean komatiite-hosted magmatic sulphide mineralisation in the Yilgarn Craton of Western Australia. These mineral deposits formed from fertile mantle-derived mafic magmas that were generated by high degree partial melting and ascended through the crust where they became sulphide-saturated and segregated the immiscible Ni-Cu-PGE sulphide melts that formed the ore deposits.

However, some mafic-ultramafic LIPs such as the Abitibi, Sudbury, Seal Lake, Ferrar, Parána-Etendeka, Deccan Trap, Kerguelen Plateau, and Ontong Java LIPs are considered to be generally unprospective hosts for major magmatic Ni-Cu-PGE sulphide mineralization. Equally, different parts of a LIP may be prospective and unprospective depending on variations in magmatic processes during individual LIP events. Mantle source regions and the magmatic processes may change over time; hence, the prospectivity of a given LIP may vary both spatially and temporally even though these differing LIP sections may have very similar geological and geophysical features.

Lithogeochemistry can be used to determine the Ni-Cu-PGE prospectivity of individual sections of LIPs as well as the processes that controlled the S-saturation status of LIP magmas such as magma fertility and crustal contamination, two of the prime requisites that are thought to be required for the formation of magmatic sulphide mineralisation. Equally importantly, combining lithogeochemical approaches with geochronology can outline the evolution of individual LIPs or multiple LIPs within a given area, providing insights not only into magmatic sulphide prospectivity but the geological history of an area and potential links between mafic-ultramafic magmatism and the formation of other mineral deposit types. This presentation will provide an overview of key lithogeochemical techniques and their uses in mineral exploration, including case studies of the High Arctic Large Igneous Province in northern Canada and the LIP events recorded within the Arunta region of central Australia.

Alteration mineralogy and pathfinder element inventory in the footprint of the McArthur River unconformity-related uranium deposit, Canada

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The chemical compositions, modal mineralogy, and textural variability of interstitial minerals in sandstones of the Athabasca Group strata in the vicinity of the McArthur River unconformity-related uranium deposit were characterized using a combination of short wave infrared spectroscopy (SWIR), lithogeochemistry, scanning electron microscopy (SEM), electron probe microanalysis (EPMA) and laser ablation mass spectrometry (LA-ICP-MS) to determine the residence sites of pathfinder trace elements. The importance of integrating in-situ mineral chemistry with whole-rock analyses resides in the possibility to establish the mineralogical and paragenetic context of geochemical signatures in defining the footprint of the deposit.

Located in the Athabasca Basin, Saskatchewan, Canada, the deposit is situated below ~550 m of quartz arenitic sandstones that are strongly silicified between depths of approximately 200-400 m. The silicified layer exhibits significant control on the distribution of alteration minerals, and appears to have restricted both the primary and secondary dispersion of pathfinder trace elements, which include U, radiogenic Pb isotopes, V, Ni, Co, Cu, Mo, As, Zn, and REEs. Diagenetic background sandstones contain assemblages of illite, dickite, aluminum-phosphate-sulfate (APS) minerals, apatite, and Fe-Ti oxide minerals. Altered sandstones contain assemblages of Al-Mg chlorite (sudoite), alkali-deficient dravite, APS minerals, kaolinite, illite, and oxide minerals.

Throughout the sandstones, APS minerals account for the majority of the Sr and LREE concentrations, whereas late pre-ore chlorite, containing up to 0.1 wt.% Ni, accounts for the majority of Ni concentrations. Cobalt, Cu, Mo, and Zn occur predominantly in cryptic sub-micron sulfide and sulfarsenide inclusions in clay mineral aggregates and in association with paragenetically-late Fe-Ti oxides. Uranium occurs predominantly in cryptic micro-inclusions associated with pyrite in late-stage quartz overgrowths, and with paragenetically late Fe-Ti oxide micro-inclusions in kaolinite. Additionally, up to 0.2 wt.% U is cryptically distributed in post-ore Fe-oxide veins. Early diagenetic apatite, monazite and apatite inclusions in detrital quartz, and detrital zircon also contribute significant U and HREE to samples analyzed with an aggressive leach such as Aqua Regia. Detailed LA-ICP-MS chemical mapping of interstitial assemblages, detrital grains, and cements provides new insights into the distribution and inventory of pathfinder elements in the footprint of the McArthur River uranium deposit.

Middle-Upper Devonian of the central-northern Mackenzie Corridor: Multiproxy stratigraphic framework and sedimentary environments of a black-shale basin

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Huge fossil energy resources locked in fine-grained rocks (black shales) and advancing technology of their extraction stimulate multifaceted research, and one of such frontier prospects is the gas prone Givetian-Frasnian Horn River Group (HRG) of the study area (NTS areas 96 and 106). The stratigraphic framework of the HRG and bounding strata is part of Mackenzie GEM Project.

The HRG rests on a drowning unconformity and includes three formations: the Hare Indian shale, the Ramparts carbonate, and the Canol siliceous shale and chertstone. Three paleogeographic zones recognized in the study area are the central bank-and-trough (BAT), southern off-bank (SOB) and western off-bank (WOB) zones. The BAT zone is characterized by thick (up to 250 m) grey-shale Hare Indian, isolated carbonate banks of the Ramparts Formation, and overall thinness of the basal Hare Indian and Canol black-shale units. Fine-grained Hare Indian siliciclastics in this zone accumulated as easterly sourced prodeltaic complexes. In SOB and WOB zones, the HRG is dominated or composed entirely of black shales. The SOB zone occurs south of the largest Norman Wells carbonate bank in the Mackenzie Plain and adjacent mountain ranges. The WOB zone is developed westward of 131° meridian. Thickness variations of formations and members are visualized on TVT isopach maps.

The HRG is studied in most detail in the SOB zone where the Hare Indian Formation is subdivided into Bluefish, Francis Creek, and Prohibition Creek members. The Canol Formation there is subdivided into Vermillion Creek and Dodo Canyon members. The Prohibition - Dodo Canyon package, ≥100 m thick, is composed of brittle organic-rich mudrocks with median TOC 4.5%. The Dodo Canyon is the “sweet bed” with high brittleness (median SiO_2 75-79%), median TOC 5.1%, and trace-metal signatures of strongest anoxia. The overlying Mirror Lake Member is an illite-rich and organic-lean ductile shale. Conodont data do not support time gaps between lithostratigraphic units and place the Canol base close to Givetian-Frasnian boundary. This contact is younging to the Lower-Middle Frasnian in thin Canol sections on top of Ramparts carbonate banks. Further refinements on conodont dating are pending.

Cigar Lake: Geometallurgical ore characterization in support of mining and milling

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The Cigar Lake deposit, the second highest grade uranium deposit globally, is a polymetallic (U-Ni-As-Co-Cu-S) uranium orebody with a complex geochemistry and mineralogy. Minerals and mineraloid phases represent significant elemental controls and have specific properties that affect strategies for mining, milling and mine tailings management. Geochemical, mineralogical, geological and geospatial characteristics of the Cigar Lake orebody need to be are integrated to provide a geometallurgical, or geologically predictive, overview to guide uranium mining and milling.

Mineralogical and geochemical characterization of the uranium minerals, and arsenide and sulfide gangue minerals have been characterized using semi-quantitative techniques including XRD, mineral liberation analysis (MLA), and optical petrography. Electron microprobe analysis and laser ablation ICP-MS were used to measure the chemical compositions and element deportment of selected minerals. To further extend the spatial coverage of the mineralogical data, mineral stoichiometry and ore-zone whole-rock geochemistry were used to quantify mineralogy throughout the deposit. The spatial distribution of environmentally sensitive elements such as As, Co, Mo, Ni, Se and their corresponding minerals were implicitly modelled with Leap Frog 3D software.

Over 35 minerals were identified within the Cigar Lake orebody, with 20 minerals, including uraninite, coffinite, illite, muscovite, chlorite, hematite, gersdorffite, chalcopyrite, cobaltite, galena, kaolinite, pyrite, niccolite, bornite, chalcocite, sphalerite, pyrrhotite, quartz, calcite, and siderite (in order of decreasing overall abundance) account for >98wt. % of the deposit and determine the main elemental control. The empirical spatial distribution of the deleterious elements and minerals is controlled by a combination of the original mineral paragenesis, but also by redox and pH conditions of later fluids that accessed the deposit through lithostratigraphic permeability and structures. Using these techniques, the geometallurgy at Cigar Lake can now be used to optimize and reduce risk during long-term mine and mill planning.

Stratigraphy and sedimentology of Ordovician outliers in the northern Ottawa-Bonnechere graben, central Ontario: An ongoing study of their significance for depositional systems within the Laurentian interior

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Ordovician strata constitute small outliers within the northern Ottawa–Bonnechere graben in the Canadian Shield, central Ontario. The outliers identify the breadth of marine strata once covering the Laurentian craton interior. Details of stratigraphy and sedimentology of the outliers remain poorly studied. Here, the succession occupying Brent Crater and an outlier along the Ottawa River, near Deux Rivières are used to evaluate correlation with surrounding regional stratigraphy in southern Ontario, and the Ottawa Embayment, eastern Ontario.

About 250 m of sedimentary rock are preserved in the center of Brent Crater, representing two general units. The lower 139 m contain finely interlaminated sandstone, siltstone, dolostone, and lime-mudstone. Fragments of the chitinozoan Conochitina schopfi of early Turinian age occur near the base of the section. The upper 111 m contain thick alternating subunits of marine carbonates and siliciclastics. The initial carbonate facies is represented by a laminated stromatolitic mudstone, and is overlain by a succession of immature fossil-bearing red and green lithic wacke. Upsection, higher-energy open-marine skeletal- and ooid-bearing pack/grainstones are interbedded with mature quartz and feldspathic arenites, illustrating increased reworking at source or during deposition. Conodont taxa (Belodina compressa Zone) in the upper 70 m of the section identify a late Turinian age. The stromatolitic limestone may be correlative with a thin stromatolitic biostrome in the lower Pamelia Formation extending across the Ottawa Embayment. If correct, the red and green wacke represent facies similar to the Shadow Lake Formation in southern Ontario. If the entire sedimentary succession of the Brent Crater is of Turinian age, the section records very local rapid subsidence in the craton interior compared to equivalent thinner successions in southern and eastern Ontario.

The outlier near Deux Rivières contains a 17-meter-thick succession. A lower part of silty dolostone, skeletal limestone, and interbeds of feldspathic arenite identify quiet-water deposition whereas the upper part, with ooid and oncolite grainstone, defines a higher-energy marine setting. Fragments of cryptostomatid bryozoans (Stictopora labyrinthica labyrinthica Hall and Pachydictya acuta tabulata Ross) and calcareous worm tubes (Tymbochoos sinclairi Okulitch) support a Turinian age. Conodont analysis is ongoing, but a $\delta^{13}C$ profile through the succession is similar to profiles associated with upper Turinian strata in the Ottawa Embayment. The upsection change to more open-marine facies also fits a similar environmental change in Turinian strata documented across southern and eastern Ontario. Altogether, these outliers demonstrate a connectivity among Late Ordovician depositional systems in the Laurentian interior.

Field, petrologic and geochemical evidence for structurally-controlled hydrothermal dolomitization in a compressive-extensional tectonic regime: An example from the Cretaceous Qamchuqa carbonates, Zagros Basin, Kurdistan Iraq

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Despite the presence of vast economic petroleum reservoirs worldwide, the formation of structurally-controlled hydrothermal dolostone reservoirs remains relatively understudied and/or unexplored in many sedimentary basins. In Kurdistan Iraq, the Cretaceous carbonates host several hydrocarbon reservoirs, which are highly affected by the tectonic evolution in this foreland basin during Zagros orogeny. Qamchuqa Formation is highly fractured and faulted with fractures occluded by hydrothermal saddle dolomite and later by calcite cement. Integrated field, core, petrographic, stable C, O and Sr isotopes, and fluid inclusion investigations were used to link diagenetic alterations to the origin and geochemical evolution of fluids in the basin. Hydrothermal fluid fluxes during Zagros Orogeny at the end of Cretaceous resulted in the formation of a complex array of zebra textures of saddle dolomite in vugs and fractures. Six types of pervasive matrix dolomite, three type of saddle dolomite and four types of calcite cement are recognized. The host rock dolostone has been affected by shortening, folding, fracturing, and thrust faulting. Saddle dolomite pipes found associated with en-échelon folding. The morphology and areal extent of zebra dolomite are controlled by pore geometry of host dolostone in relationship to fracturing and faulting. The stable isotopic values of both matrix and saddle dolomite cement are overlapping but departed from the postulated values for carbonates precipitated in equilibrium with Cretaceous seawater. This indicates the high alteration of host rock by hydrothermal fluid circulation. In contrast, the isotopic signature of later calcite cements shows extremely negative $\delta^{13}C$ values, suggesting incursion of meteoric water during later diagenetic stage. The $^{87}Sr/^{86}Sr$ ratios of pervasive matrix dolomite fall close to Cretaceous seawater values. In contrast, saddle dolomite shows similar or more radiogenic values resulted from mixing of basinal brines with connate waters. However, calcite cement shows a more radiogenic Sr ratios possibly related to late diagenetic processes upon subaerial exposure. Fluid inclusions (FI) of saddle dolomites show a wide range of homogenization temperatures (Th) (82.3-185.6, with an average of 103.2°C), and salinity averaging 21.4 wt.% eq., which reflect the effect of hydrothermal fluids in the formation of these dolomites. FI of earlier calcite cements, which postdate saddle dolomite but predate latest calcite cements, fluoresce under UV light and have Th values comparable to saddle dolomites. This demonstrates that hydrocarbons migration occurred under high temperatures. The composition of diagenetic fluids fluctuates from an earlier basinal, saline, high temperatures to later meteoric fluids. This phenomenon is linked to Zagros tectonic events at the end of Cretaceous and Pliocene times.

Keynote (30 min): Dating fault zones using the K-Ar decay system

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The timing and duration of fault slip and shear zone deformation are critical parameters for understanding the role of these structures in assembling and reorganizing the Earth's crust, channelling ore-bearing fluids, and generating geohazards. However, direct dating of fault materials can be elusive. The K-Ar decay system has shown great potential for direct dating of certain types of fault materials, including fault-generated illite in brittle fault systems and dynamically-recrystallized white mica in low-temperature mylonites. Interpretation of fault-related white mica or illite age data, however, must consider Ar behavior. For example, radiogenic ^{40}Ar in white mica may be disturbed or reset by a variety of processes including intra-grain deformation, recrystallization and thermal diffusion.

We have investigated Ar behavior within white mica in a reactivated ductile shear zone. The white mica occurs in Late Silurian syn-tectonic granitoids emplaced into the trailing edge of the Ganderian microcontinent, Newfoundland Appalachians. The broad Wing Pond shear zone formed here during subsequent regional metamorphism, and is interpreted to record docking of the Avalonia microcontinent to Ganderia (composite Laurentian margin) by sinistral-oblique transpressional collision. The suture was later reactivated as a lower temperature, narrow, dextral-sense shear zone. The window for sinistral and dextral slip is constrained by emplacement of the syn-tectonic granitoids and a post-tectonic pluton that stitches the shear zone at 377±4 Ma.

In this case study we combined in situ ^{40}Ar/^{39}Ar analyses of white mica with deformation temperatures from quartz c-axis fabrics to investigate the influence of deformation on Ar retention in white mica for differing structural positions. Zircon U-Pb ages indicate granitoid emplacement ca. 430-422 Ma. During 422-405 Ma, high temperature metamorphism and deformation partially recrystallized igneous monazite and reset ^{40}Ar/^{39}Ar ages in igneous white mica to ca. 405 Ma. Subsequent patchy Ar loss in white mica occurred during low temperature shear (<400 °C), and locally via post-deformation fluid interactions. Low-temperature dextral reactivation of a narrow segment of the shear zone occurred at ca. 385 Ma (^{40}Ar/^{39}Ar). K-Ar dating of authigenic illite in fault gouge indicates subsequent brittle reactivation of the terrane boundary occurred at ca. 351 Ma.

As demonstrated in this case study, application of the K-Ar decay system to direct dating of faults requires, at a minimum, in depth knowledge of the wall rock ages and materials, temperature history of deformation, and microstructural analysis.

Glacial dispersal patterns in three dimensions from a pair of buried kimberlites, Lac De Gras region, NT

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Drift prospecting has been a successful mineral exploration tool in previously glaciated terrains. Based on the concepts of glacial dynamics, and related sediment production, transport and deposition, drift prospecting surveys assess compositional variability within glacial sediments and trace indicators of mineralization back to a buried bedrock source. The time-transgressive nature of shifting ice flow direction and related till production is an important factor, controlling the shape and extent of dispersal patterns in till. The effect of changing ice flow on the composition of till has been well-studied in both map view, as well as longitudinally in cross section (i.e., dispersal curves). Fewer studies have looked at dispersal patterns holistically in three-dimensions. Here, we use 94 reverse circulation (RC) boreholes, yielding 254 till samples, to reconstruct the subsurface geometry of a dispersal train from a pair of buried kimberlite pipes (DO-27 and DO-18) in the Northwest Territories. Discrete smooth interpolation modeling in SKUA-GOCAD based on downhole data allows for visualization of geochemical anomalies within the till column, as well as the subsurface density of kimberlite indicator mineral grains. Through the combination of borehole data, field work, and modeling, we are able to compare three-dimensional dispersal patterns in the subsurface with local ice flow records, measured from erosional ice flow indicators in the field. This dataset allows us to evaluate the role that changing ice flow, as well as local bedrock surface topography, play in controlling dispersal and deposition of clastic sediment by past ice sheets. Our modeling documents buried palimpsest terrains along older ice flow trajectories, demonstrating lateral and vertical variability within a single, relatively thin and discontinuous till sheet. Furthermore, we observe relationships between local indicator mineral concentrations and bedrock topography, with indicator mineral dispersal concentrated along a bedrock-controlled topographic low aligned with the most recent ice flow. This work demonstrates the benefit of detailed mapping and visualization of a dispersal plume, even in areas of relatively thin and discontinuous till cover, highlighting the role basal topography and shifting ice flow plays on shaping the surface expression of a dispersal train.

Physical and chemical controls on the localization and precipitation of gold at the Archean Hislop and Grey Fox deposits

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The Archean Hislop and Grey Fox gold deposits, owned by Kirkland Lake Gold Ltd. and Primero Mining Corporation, respectively, are located in the Hislop Township adjacent to the Porcupine-Destor deformation-zone (PDDF), about 85 km east of the gold-rich Timmins district. The PDDF, and other similar large-scale deep-seated fault-zones, serve as conduits for fluid-flow and magmatism, and while they serve a key role in the localization of gold deposits on a large scale, it is the physical and chemical characteristics of the local host rocks that will control fluid flow and hence mineralization. At the Hislop and Grey Fox deposits, the gold-associated veining is concentrated in mafic-intermediate to felsic, tholeiitic volcanic rocks characterized by an abundance of flow-top features (dominantly hyaloclastite). These features lend a higher intrinsic permeability, in addition to the increased competency, than is present in the surrounding massive mafic volcanic rocks. Collectively, these attributes make the felsic to intermediate rocks prone to brittle failure during deformation, hence it generates greater permeability. Additionally, the increased permeability in these rocks has resulted in more extensive fracturing and fluid infiltration, which has formed a larger, more continuous ore zone than is observed in the surrounding units. The size of the ore zone can also be further enhanced through pre-existing alterations. At the Grey Fox deposit, an early, discrete bleaching of the host rocks resulted from an albite-carbonate-silica alteration, and intervals of mineralized veins are more extensive in such zones. Chemically, the tholeiitic volcanic rocks have a high Fe-content, which is favorable for precipitating gold transported as a bisulfide complex; Fe in these rocks react with the S in the fluid which leads to pyrite mineralization and deposition of gold. Subsequently, the mineralization at Grey Fox and Hislop is characterized by abundant pyrite containing up to 3% As, as well as ankerite and minor REE-phosphate phases (monazite, xenotime). Trace element signatures related to gold enrichment are similar at both deposits and include Mo, W, As, Cu, Pb, S, and Ag. A more widespread alteration halo present outside of the gold-mineralized zone is characterized by dolomite and conversion of titanite to rutile. Recognition of the primary nature of volcanic rocks can provide an important screening method in exploration, and when used in conjunction with geochemical signatures associated with gold, may prove to be valuable in the search for new deposits here and elsewhere.

Unravelling the history of high-pressure granulite-facies rocks: The metamorphic record of kyanite

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High-pressure (HP) granulite-facies rocks are an important constituent of large hot orogenic (LHO) systems, as they record the burial of crustal material to great depth during orogenesis, and commonly preserve evidence of anatexis at deep crustal levels. Interpreting their metamorphic history is therefore vital to understanding the nature of the lower crust in LHOs. Kyanite is an essential mineral in aluminous HP granulite-facies rocks and participates in dehydration melting reactions of micas. Consequently, its growth history is strongly connected to the process of anatexis in such rocks. This study presents a novel approach to interpreting the growth and P—T history of kyanite in HP anatectic aluminous rocks, in this case from the central Grenville Province. Cathodoluminescence (CL) maps reveal a complex multi-step history of prograde and retrograde growth and corrosion within individual kyanite crystals; trace element analysis further supports that these are composite crystals. These textures can be linked to a reaction history consistent with phase equilibria models for these samples, and can also provide additional constraints to the interpreted P—T evolution of the rocks. Two generations of kyanite comprise the cores of the crystals, and provide a rare window into the prograde path of metamorphism. The earliest generation of kyanite may be linked to the breakdown of staurolite near the water saturated solidus at amphibolite-facies conditions. The more abundant second generation of kyanite likely formed as a peritectic product of muscovite dehydration melting, and was subsequently corroded during biotite dehydration melting; the final generation of kyanite grew during melt crystallization upon retrogression. Estimations of the proportion of retrograde kyanite in the samples based on CL textures can be combined with modelled trends of kyanite production and consumption in P—T space to further constrain the slope of the retrograde P—T path. All generations of kyanite are found as cores and mantles within individual crystals instead of replacing other prograde phases, necessitating the use of CL maps to identify prograde and retrograde kyanite. This study illustrates that important information about the growth of metamorphic minerals can remain hidden when investigated with traditional methods — unconventional techniques such as CL imaging can be valuable complementary tools for interpreting metamorphic history.

The Molaoi Pb-Zn(-Ag) deposit in South Eastern Peloponnese, Hellas

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The Molaoi Pb-Zn-Ag deposit is syngenetically included within the 250-200 Ma 'Tyros volcanics'. These consist mainly of subaerial andesites with SiO_2 ~54-62 wt.%, felsic pyroclastics with SiO_2 65-69 wt.% and renown sill lithologies such as the 'Krokeatis Lithos', a plagioclase-phyric andesite widely used in the past for the construction of Roman baths. Probable ore reserves are reported to be 2.9 Mt of Zn ~7 wt.%, Pb ~3 wt.% and of Ag up to ~1,500 mg/kg. In the years from 1980 to 1988 approximately 150 exploration drill-holes were drilled, however, Molaoi never developed into a mining area. The core data reveal that mineralization is often stratified and included within felsic tuffs containing SiO_2 ~65-69 wt.%. Clear and milky quartz veinlets cross-cut the tuffs and interbedded chert layers are commonly observed mineralized. Fluid inclusion data were obtained from mineralized chert, mineralized clear-quartz vein, clear-quartz vein containing pyrite and from brown and yellow sphalerite. Fluid inclusion microthermometry suggests that the hydrothermal ores were deposited from low-temperature (maximum 190° to 230°C) and low- to moderate-salinity (0.7 to 23.1 wt.% NaCl equivalent) mineralizing fluids. The Molaoi volcanic units display extensive alteration to epidote, chlorite, kaolin and hematite. The δH_2O versus δD plot constructed from alteration chlorite data indicates that the hydrothermal fluid is mixing product of magmatic fluids and meteoric waters; oxygen isotope data from mineralized clear-quartz vein support the dual, magmatic-meteoric, origin of the fluid. Calculated δH_2S compositions indicate magmatic origin of sulfur. Pb isotopes, He isotopes and He-Ar isotope distributions indicate a mantle origin for the ore fluid of the Molaoi mineralization. Major and trace element geochemical data of the 'Tyros volcanics' reveal a complex imprint of subduction and rift elements. The palaeoenvironment of the proximal 'Arna basalts' is that of an oceanic floor transform fault. The Tyros succession is overlain by shallow water limestones and evaporites. Textures of some of the mineralization and a volcanogenic breccia are indicative of debris-flows. A rift-related palaeoenvironment with periodic inundation cycles of a shallow sea is alluded to. The whole Tyros and Arna packages are probably related to the separation of the Cimmerian microcontinent from Pangaea and its subsequent subduction under Laurasia. Molaoi is compared to the Salton Sea metallogenetic environment.

1020-975 Ma LIP on the southeastern margin of the Siberian Craton: The Sette-Daban mafic magmatic event

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The ca. 1020-975 Ma mafic magmatic event on the southeastern margin of the Siberian Craton (the Sette-Daban event) is represented by mafic sills and few east-trending dykes. Mafic intrusions related to the Sette-Daban event were documented in the southern and central part of the study area with cumulative thickness increasing eastward and exceeding 1 km in the easternmost exposures. Our new U-Pb baddeleyite dating extended the event farther north including into the Goronstakh Anticline. The mafic intrusions are tholeiite basalts in composition and were documented over an area approximately 500 km in length and 70-100 km in width. Immobile element distributions are close to those in E-MORB basalts. REE patterns as well as Nd isotopic compositions are typical for MORB. Compositions of most samples represent mixtures of MORB with continental crust and follow a continental flood basalt trend. Based on immobile element distributions, magmatic rocks have MORB and within-plate basalt settings. However, the mafic intrusions were affected by hydrothermal processes that resulted in moderate sodic and propylitic alteration and large variations in Na_2O/K_2O ratio, CaO, Pb, Rb and Sr concentrations as well as in unusually high radiogenic Sr contents.

The ca. 1020-975 Ma mafic intrusions do not have known correlatives elsewhere within the Siberian Craton. The closest in age are mafic intrusions of the Udzha paleorift in northern Siberia dated by Ar-Ar as ca. 1075 Ma. Farther to the east from Sette-Daban area, Meso- and Neoproterozoic rocks that may host mafic intrusions are covered by Paleozoic sediments, but the Nd isotopic compositions of Ediacaran sandstones and shales provide evidence for a mafic source to the east, potentially linked to the ca. 1020-975 Ma event. Other potential links are ca. 1020-1015 Ma carbonatite in the Baikal region 2000 km to the west, and the Khakdon volcanic rocks 1000 km to the east in the Prikolyma terrane. By its intraplate character and large scale, the ca. 1020-975 Ma mafic magmatic event would closely fit the definition of a LIP.

Mineral deposit potential of the ca. 1020-975 mafic magmatic event is poorly studied. Approximately coeval carbonatites in the Baikal region are enriched in REE. In the Sette-Daban area, Ediacaran sandstones locally contain products of erosion of alkaline ultramafic intrusions and/or kimberlites likely also related to the ca. 1020-975 event.

An allochtonous terrane in the Korean Peninsula: The Neoproterozoic Sangwon unit

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The Neoproterozoic tectonostratigraphy of the Sangwon unit, overlying the Archean-Paleoproterozoic basement rocks in the Korean Peninsula, is contentious partly because of the lack of geochemical and geochronologic data. We investigated the provenance and crustal evolution of metasedimentary rocks in this unit with reference to the Precambrian massif, using the U–Pb and Hf isotopic compositions of detrital zircon. The Sangwon unit primarily occurs along the southern margin of the Nangrim massif in North Korea, and its contact relationship with Archean-Paleoproterozoic basement rocks has been traditionally regarded as angular unconformity. Metasedimentary rocks of the Sangwon unit crop out mostly in the North Korean territory, and some exposures, the focus of this study, are extended to the south on small islands of the Yellow Sea in the South Korean territory. The lithology of this unit mainly consists of quartz sandstone, schist, phyllite, and stromatolitic limestone and dolostone metamorphosed up to the greenschist facies condition. The U–Pb age spectra of zircon grains are typified by the population ranging from 1.0 Ga to 1.9 Ga, with two strong peaks at ~1.2 Ga and ~1.6 Ga. These Mesoproterozoic age peaks are rarely reported from the Precambrian massifs of the Korean Peninsula where the ~1.87 Ga orogenic event predominates. On the other hand, ~1.67 Ga tonalitic gneisses and ~1.2 Ga migmatitic gneisses are distributed in small islands of the Yellow Sea, suggesting a local delivery of Mesoproterozoic zircon grains into the Sangwon unit. The Hf isotopic compositions of detrital zircon from metasedimentary rocks are primarily subdivided into two groups. The majority of Mesoproterozoic zircon grains has positive εHf(t) values, and their crustal model ages are in the range of 1.5–2.0 Ga. In contrast, Paleoproterozoic zircon grains are typified by negative εHf(t) values projected to 2.4–3.0 Ga crustal model ages. These ranges are in marked contrast to those measured from the magmatic zircon crystals of Mesozoic granites in South Korea (0.4–1.5 Ga and 2.0–2.5 Ga). The age spectra and crustal model ages of detrital zircon in the Sangwon unit suggest a disparate crustal evolution with respect to the Precambrian massifs in the Korean Peninsula. The age spectra of detrital zircon in this unit are reproduced in the Devonian strata of the Korean Peninsula, and therefore the allochthonous Sangwon unit is most likely to be amalgamated in the Late Permian during the collisional orogeny between the North and South China cratons.

Frictional-viscous deformation at the source of slow earthquakes

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Slow earthquakes, with durations or slip velocities between seismic slip and aseismic creep, are observed to occur in a wide variety of tectonic settings suggesting that the mechanisms that control these events are common to many major faults. Seismological and geophysical data indicate shear failure on critically stressed faults, likely under low effective stress conditions, is required for slow earthquakes. However, the range of depths, and corresponding pressures and temperatures, at the source of slow earthquakes indicates the metamorphic grades and potentially grain-scale deformation mechanisms vary. Geological observations could add additional insight into the specific failure mechanisms if the structures that form during tremor episodes can be identified. Shear zones exhumed from a variety of slow earthquake sources have some similar characteristics: mechanically heterogeneous lithologies, phyllosilicate-dominated foliations, numerous veins, and evidence for distributed deformation and cyclical fracture and viscous flow. Examples from a Cretaceous transpressional continental shear zone in the Sierra Nevada, CA, include quartz-filled veins meters to tens of meters long with millimeters to centimeters of shear offset that preferentially developed along foliation planes in a high strain zone. Ambient temperatures during deformation were ~400-600°C, and opening mode vein orientations and abundance suggest fluid pressure was near lithostatic at times. The orientation and spatial distribution of the veins indicate they formed under differential stress large enough for shear failure with pore pressures sufficiently high for the rocks to be critically stressed along mechanically weak foliation planes. Bulk deformation of the surrounding rock was accommodated viscously by crystal plastic deformation mechanisms. The mode of fracturing and overall behavior of the system was controlled by the local competition between the rates of stress recovery following fracture and stress drop, and pore pressure build up. The inferred rheology recorded by the veins is phenomenologically similar to slow slip and tremor. Comparison to deformation across a wide range of slow earthquake source regions suggests transitional deformation involves contemporaneous shear fracture and viscous creep transients.

A geochemical study of the intracaldera tuffs of the ca. 25 Ma Underdown caldera, western Nevada caldera belt, north-central Nevada, U.S.A.

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During the middle Cenozoic, a subduction-related ignimbrite flareup occurred in the western USA that resulted in the formation of the NW-SE Nevada caldera belt. Within this belt is the ca. 25 Ma Underdown caldera located in the Shoshone Mountains, north-central Nevada. The Underdown caldera lies within a single, 10° west tilted fault block and contains three volcanic formations. The 24.95±0.05 Ma Underdown Tuff, the stratigraphically lowest unit, is exposed on the east side of the caldera. The densely welded, moderately rheomorphic, columnar-jointed Underdown Tuff includes quartz and feldspar phenocrysts and contains aphyric pumices and uncommon abundantly porphyritic pumices. Pumice present in the Underdown Tuff is flattened and stretched from rheomorphism. The tuff of Clipper Gap (24.95±0.07 Ma), the correlative outflow tuff, extends hundreds of kilometers eastward almost to the Utah border. The Underdown Tuff is overlain by the poorly welded Bonita Canyon Formation, which contains lithic and pumice fragments with minor biotite, quartz and feldspar crystals, and is rarely reworked by secondary processes. An unnamed 24.72±0.05 Ma, densely welded tuff lies unconformably on both Bonita Canyon Formation and on basement rock outside the caldera. The light brown gray, crystal-rich 24.72 Ma tuff contains diverse, abundantly to sparsely porphyritic pumice but lacks lithic fragments.

We present new major and trace element geochemistry of the Bonita Canyon and Underdown Tuffs within the Underdown caldera to help resolve the relationships of the two tuffs, the origin of the felsic magmas, and their relationship to the pyroclastic flow units outside the caldera. The Underdown and Bonita Canyon Tuffs are dacite to rhyolite (69-83 wt.% SiO_2). Silica values above 78 wt.% indicate post-emplacement silicification that was also observed in the field. Normalized incompatible element patterns show LREE-enrichment and negative anomalies in Sr, Eu and Ti, indicating fractionation of Fe-Ti oxide minerals and plagioclase within the Underdown Tuff. These rocks have negative Nb and Ta anomalies and LILE enrichment that suggest melting of older crustal rocks and or a subduction environment. Potential magma sources with be determined with the help of radiogenic and stable isotopic data.

A new look at VMS and Au mineral endowment in the Slave Province through detailed bedrock mapping of the Beaulieu River Volcanic Belt at Sunset Lake, Northwest Territories

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The Northwest Territories Geological Survey has undertaken a multi-year bedrock mapping initiative along the Beaulieu River Volcanic Belt in the southern Slave Province. In 2016, a five-week program was focused in the Sunset Lake study area that is approximately 110 km east-northeast of Yellowknife. This work focused on lithology, alteration types, alteration intensity, and structures (primary, ductile, brittle). This work will increase the understanding of economic potential of this volcanic belt and the Slave Craton as a whole. Due to a recent forest fire, the exposure is superb and allows for detailed mapping at 1:10 000 scale; a significant improvement from previous 1:50 000 scale maps.

The Sunset Lake map area is situated in a part of the Beaulieu River Volcanic Belt with known mineral endowment and has potential for additional discoveries. The area contains volcanogenic massive sulphide (VMS) deposits including the “Sunrise” and “Bear” deposits. The rocks also host several gold showings. The Beaulieu River Volcanic Belt has rock types, metallogeny, and a relationship to a long lived Archean structure that shares many similarities with the Yellowknife Volcanic Belt.

The volcanic rocks of the Beaulieu River Volcanic Belt sit structurally on top of rocks of the Central Slave Basement Complex (Sleepy Dragon Complex) and, where preserved, the Central Slave Cover Group. The Archean volcanic rocks and associated sedimentary rocks are dominantly tholeiitic basalts (pillows, massive, pillow breccias etc.), andesites, dacites, rhyolites, interflow argillites, banded iron formation, and volcaniclastic deposits with compositional and textural variations. The known volcanogenic massive sulphide deposits are spatially and temporally associated with basalt and rhyolite flows and are proximal to an argillite unit. Rocks in this map area are intruded by related volcanic feeder dykes, Amacher Granite and younger mafic Proterozoic dykes. The region has experienced greenschist- to lower amphibolite-facies metamorphism, multiple distinct ductile deformational events, and several periods of movement along the Beaulieu River fault at different crustal levels. Gold mineralization is hosted in quartz veins that are associated with late shearing.

Despite previous mapping, multiple generations of mineral exploration, and relatively close proximity to Yellowknife; fundamental questions about the rocks and mineralizing systems remain. The present mapping program, utilizing unparalleled rock exposure, is advancing our understanding of this area and aims to provide new tools for future exploration efforts.

Diagenetic and mineralising fluids are more than just wt. % equivalent NaCl!

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Fluids are essential components in the formation of a range of sedimentary-rock-hosted ore-deposit systems, referred to as MVT, Irish-type, SEDEX or CHD, red-bed Cu, and grey-bed Pb. In all cases these systems are long-lived in terms of fluid migration from large-scale reservoirs during evolution of buried basins. Fluid chemistry in such systems should reflect the mineralogy and chemistry of the fluid-flow pathway, and so it is important to have some understanding of where fluids are sourced and what rocks they interact with when considering the metal source; the fluid pathway dictates the element budget and strongly influences ore endowment. For example, in the central African copperbelt, the magnitude of contained metal (i.e., endowment) and elemental association (i.e., Cu-Co-Ag) must in some way reflect the source and pathway of fluids; the same can be said for the other sediment-hosted ore deposits. The answer to how this occurs lies in part in determining chemistry of the mineralizing fluids. Currently, the only direct constraint on the chemistry of mineralising fluids is derived from fluid inclusion studies, from which salinity is derived and expressed as wt. % equiv. NaCl. The chemistry of the solutes in mineralising fluids is in reality more complex, encompassing Na, Ca, Mg, Fe, K, S, F, and metals, but this information is seldom acquired, which severely limits ore deposit models. Evaporate mound analysis is a simple way of obtaining this information. The analytical protocol involves formation of salt mounds on the surface of a fluid inclusion wafer by overheating in a heating stage, followed by imaging (SEM) and analysis (EDS or EMPA detectors) to produce semi-quantitative information about the resulting precipitates. Depending on fluid salinity, the detection limit for solutes in fluid inclusions can range between 200 ppm (10 wt. % equiv. salinity) and 500 ppm (25. wt. % equiv. salinity). As with in situ LA ICP-MS analysis, the inclusion salinity can be used to generate quantitative data or relative enrichment, the latter expressed in ternary plots (e.g., Na-Ca-K). Case studies will be presented to highlight the complexity of fluid chemistry preserved in fluid inclusions, which must be considered in ore-deposit systems, rather than perpetuating the over-simplification of the wt. % equiv. NaCl approach, which is a poor reflection of natural fluids.

Structural controls on gold mineralization at the Dogpaw and Dubenski deposits in the Rowan-Kakagi greenstone belt, western Wabigoon Subprovince, northwestern Ontario

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WITHDRAWN

Several gold occurrences in the Neoarchean Rowan-Kakagi greenstone belt are hosted in discrete shear zones related to the crustal scale Pipestone-Cameron fault zone. However, the structural controls on these occurrences is poorly understood. Furthermore, the study of gold mineralization in the Rowan-Kakagi greenstone belt has largely been limited to respective property lines and ownership has been sporadic. The project aims to provide a comprehensive, cross-property study of two known gold occurrences, the Dogpaw and Dubenski deposits, with the goal of creating a structural framework relating deformation, alteration and mineralization to aid future exploration efforts. Detailed mapping of several trenched exposures at the Dogpaw deposit have identified a set of discrete, gold-bearing conjugate shear zones. Preliminary results suggest there is a geometric relationship between the orientation of reported gold-bearing quartz veins and the intersection of the identified conjugate set. At the Dubenski deposit reconnaissance mapping has identified a series of shear zone-related folds that may have caused difficulty for previous workers in delineating the orebody at depth. Regional mapping along segments of the Pipestone-Cameron fault has revealed that the discrete, gold-bearing shear zones of the Dogpaw and Dubenski deposits share similar structural characteristics to the Pipestone-Cameron fault zone. These preliminary results suggest a temporal and genetic relationship between the Pipestone-Cameron fault zone and gold-hosting shear zones at the two deposits. They also emphasize the need for a comprehensive structural study of other shear zone-hosted gold occurrences in the Rowan-Kakagi greenstone belt.

Freshwater dinoflagellate cysts as proxies of cultural eutrophication

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Dinoflagellates are common phytoplankton in lacustrine ecosystems. Some species produce a fossilizable dinosporin resting cyst during their life cycle that represents an important link between the organisms' motile ecology in the epilimnion and preservation in the paleontological record. Recent studies in northeastern North America illustrate their potential as paleolimnological proxies, relating the stratigraphic and biogeographic distribution of cysts of several species of dinoflagellates to environmental conditions in lakes with documented anthropogenic impact. Dinoflagellate cysts are found in slides processed for pollen analysis, which remains the best proxy of human impact in the watershed, so their identification by palynologists would prove useful in reconstructing pre- and post- impact conditions in the water bodies where the pollen accumulates. However, many non-pollen palynomorphs are destroyed in the lab by protocols that include the use of KOH and acetolysis. The dinoflagellate affinity of most cysts – other than proximochorate cysts produced by "Peridinium" wisconsinense and Peridinium limbatum – is not immediately obvious, so they are rarely reported by pollen analysts.

Dinoflagellate cysts could be valuable in the management of lakes, since the response of critical freshwater resources to environmental perturbations (both natural and anthropogenic) can be assessed using time series of environmental data recorded by microfossils preserved in lake sediments in a way that synoptic measurements of water quality cannot. They thus appear to have the potential to be a useful and efficient tool in studies of eutrophication, as they have in marine environments. When combined as part of a multi-proxy study, they become a very viable and reliable identification tool for anthropogenic caused eutrophication.

Searching for the Cheshire cat: Biases in Ediacaran taphonomy

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The Ediacaran Period is marred by controversy. Deciphering the complex nature of the Ediacaran fossil record requires a detailed understanding of the biases that affect soft-tissue fossilization. Recent work in setting realistic limits on the tempo and mode of Ediacaran cast-and-mold fossilization have taken a two-prong approach, utilizing advanced instrumentation to investigate Ediacaran fossils, all the while monitoring decay experiments of model organisms. These targeted research directions have been central in testing the hypothesis that the disappearance of the Ediacara biota at the dawn of bilaterian diversification was directly linked to a closing of a taphonomic window reliant on extensive microbial mats in normal marine settings. Studies from Newfoundland and Namibia both suggest an important link to clay minerals in helping to cast and mold Ediacaran fossils, while decay experiments also support these findings. These targeted research directions have refined the factors that govern Ediacaran preservation, and have helped in our continued investigations into the biases that govern fossilization and ultimately the fossil record of life on Earth.

Siderite synthesis from iron-bearing acidic solutions combined with flue gases from combustion of fossil fuels

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Acid Mine Drainage (AMD) remains a serious environmental problem in the mining industry, and at the same time most future mines, at least in Canada, will be remote from electrical grids and have to generate their own power from fossil fuels, thereby emitting CO_2 and related compounds. We have developed a patented method to sequester the carbon compounds and treat AMD by stripping CO_2 from flue gases and reacting it with an iron-bearing aqueous AMD stream to create a solid with composition $FeCO_3$ (siderite). An electrochemical cell is used to produce a basic solution that is circulated through an absorption column where it picks up CO_2 from the flue gases. The resultant alkali carbonate solution is then reacted with iron sulfate under controlled conditions to produce siderite.

The siderite rapidly precipitates as particles which are filtered out of the neutral solution, and the solution is recycled. The particles form as microspheres ranging in size from 5-40 micrometers diameter, depending on the specific conditions used in the precipitation stage.

Experiments have been conducted at varying temperatures, from 20-70 °C, at varying solution addition rates, different ratios of carbonate to iron, and with different "rest times" before exposure to oxygen and drying. Resting, or aging, time appears to be a critical variable in the low-temperature synthesis of well-ordered siderite. When aged for less than one hour, siderite seems to be amorphous and highly reactive with oxygen. At the earliest stage of crystallization, siderite from our experiments is not detected by X-ray diffraction, and readily oxidizes. Identical synthesis experiments, aged for more than approximately one hour, show increasingly defined siderite diffraction patterns and better resistance to oxidation. These results agree with literature discussions of the crystallization steps in siderite formation.

Use of chromite chemistry for correlation of PGE-bearing reefs within the Bushveld Igneous Complex

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The most studied rock suite of the Bushveld Igneous Complex is the Rustenburg Layered Suite (RLS), which contains the largest platinum group element (PGE) reserves in the world. The RLS cumulate rocks have exposure mainly at three limbs: Eastern, Western, and Northern. These limbs host PGE mineralization in layers referred as 'reefs', namely: UG-2, Merensky Reef, and Platreef. The Western and Eastern limbs host PGE ores within the UG-2 (massive chromite) and the Merensky Reef (chromite- and sulfide-bearing pyroxenite), whereas ores in the Northern limb are associated to the Platreef (also a suite of chromite- and sulfide-bearing pyroxenites). Comparison between the Platreef and the Merensky Reef has been difficult because the Platreef is usually in contact with host rocks meaning that units below the Platreef are missing or there is evidence of magma interaction with the footwall. However, deep drilling at the Turfspruit farm intersected sections of the Platreef and a massive chromitite seam below it, which have been proposed, based mainly on lithology and stratigraphic position, to be the lateral equivalents of the Merensky and UG-2 reefs, respectively. In addition, a previous detailed study on chromite chemistry from the top to the bottom of the UG-2 have shown some sharp variations in chromium number (Cr#) and magnesium number (Mg#), which was attributed to cryptic layering caused by accumulation of discrete chromitites layers that segregated sequentially during magmatic differentiation. We used EPMA and LA-ICP-MS to obtain major and trace element chemistry of reference samples from the UG-2 (from the Western Limb) and the UG-2 equivalent (Northern Limb) to: (a) establish possible correlations between the UG-2 equivalent in the Northern Limb and UG-2 elsewhere in the Bushveld, and (b) determine whether certain trace elements also keep record of cryptic layering. Preliminary results and compilation of published data show that the UG-2 equivalent in the Northern Limb have slightly lower Cr# at the same Mg# than UG-2 samples from the rest of the Bushveld. The results also show that certain trace elements, such as Ga and Mn seem to also document cryptic layering, consistent with formation of massive chromitite seams via the coalescence of discrete seams (which formed via in-situ crystallization), as has been proposed previously. Further assessment is needed (e.g. to determine whether chromite composition is affected by post-cumulus diffusive equilibration) but preservation of cryptic layering does not seem consistent with the origin of the chromitite via chromitite-rich slurries.

Characterizing strain in the East Athabasca mylonite zone

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The East Athabasca mylonite zone (EAmz; also referred to as the Tantato domain) of northern Saskatchewan comprises more than 20,000 km^2 of late Archean to Paleoproterozoic lower continental crust. It can be separated internally into three domains with broadly similar pressure-temperature-time (P-T-t) paths that include late Archean granulite facies metamorphism and deformation ca. 2.60-2.55 Ga and a subsequent granulite facies event at 1.9 Ga. These include the Chipman (or Southeast) domain in the east, separated from the Lower Deck (or Northwest domain) to the northwest by the 1.88 Ga Cora Lake shear zone, and the Upper Deck (or Southern domain), which occurs to the south of the Lower Deck. The interface between the Upper and Lower decks is marked by a fabric transition from heterogeneous mylonites below (in the Lower Deck) to homogeneously developed mylonite above (in the Upper Deck). The boundary is a curved structure that is concave to the south. In the east it strikes southeast and dips shallowly southwest with down dip lineations, while in the west it strikes northeast and dips moderately to steeply southeast with lineations that are nearly strike parallel. Higher P recorded in the Upper Deck has been interpreted to indicate that it was thrust over the Lower Deck, however, the contact has a general lack of macroscopic shear sense indicators. The rare outcrop-scale shear sense indicators that have been reported generally record dextral shear indicating an overall top-down-to-the southwest, or extensional, shear sense along the boundary contact. This study presents new quartz c-axis data from 11 specimens collected across the Upper Deck/Lower Deck transition in the Axis Lake region of the EAmz. The fabrics outline a strain gradient across the boundary consistent with its interpretation as a shear zone. The c-axis fabrics record sinistral shear across the structure with deformation temperatures of ˜575 - 700 (± 50) °C, which is compatible with thrusting of the Upper Deck over the Lower Deck post-peak metamorphism. Finally, the specimens examined in the Upper Deck, near the curved portion of the boundary, tend to record constrictional strain. This is compatible with the curved shape of the boundary being a primary feature of the thrust panel geometry and consistent with the strike-slip dominant, steeply dipping western limb acting as a lateral ramp and the dip-slip dominant, shallowly dipping eastern side of the boundary acting as a frontal thrust ramp.

A diamictite dichotomy: Glacial conveyor belts and olistostromes in the Neoproterozoic of Death Valley, California, USA

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Multiple intercalations of glacially derived and slope-derived diamictites testify to the drawbacks of correlating Neoproterozoic diamictites more widely, but shed new light on the close interrelationship of these processes in the Cryogenian world. In the Neoproterozoic of Death Valley, California (USA), rifting of Rodinia occurred concomitantly with a major glacial event that deposited the Kingston Peak Formation. A new sedimentologic investigation of this formation in the Silurian Hills demonstrates, for the first time, that some diamictites are ultimately of glacial origin. Abundant dropstone textures occur in interstratified heterolithic deposits, with clasts of identical composition (gneiss, schist, granite, metabasite, quartzite) to those of boulder-bearing diamictites suggesting a common source (the glacial conveyor belt). In stark contrast, megaclast-bearing diamictites, yielding clasts of carbonate and siliciclastic preglacial strata as much as 100 m across, are interpreted as olistostromes. The occurrence of syn-sedimentary faults within the succession allows glacial versus slope-derived material to be distinguished for the first time.

Precambrian continental landscapes and paleoclimates: New perspectives from 1.2 Ga Meall Dearg Formation, Torridonian of Scotland

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The classic Torridonian sedimentary succession in northwestern Scotland has been studied for over 200 years, and has provided remarkable insight into Precambrian continental landscapes and their response to climate, tectonism, and bolide-impact events. Despite extensive research, some portions of the Torridonian succession remain unstudied due to remote accessibility. One example is the Meall Dearg Formation, a 1.2 Ga sandstone so far tentatively described as a braided-fluvial deposit. We document the hitherto unrecognised evidence of coeval fluvial, aeolian, and lacustrine depositional environments, a rare assemblage seldom described in the Precambrian rock record. Interpretation of Precambrian terrestrial processes and paleoclimates has been criticised as unreliable, owing to fragmented rock records that may lead to misinterpretation of climate regimes. This study attempts to address this issue, by providing a consistent depositional model and a critical comparison of paleoclimate indicators from coeval and interacting depositional environments. Facies analysis revealed that fluvial deposits contain abundant sheet sandstones with upper flow-regime structures, something that can be ascribed to ephemeral discharge. Ephemeral discharge has been in turn related in the past to enhanced climate seasonality. Aeolian facies are dominated by large-scale cross-bedding, with rare interdune and adhesion structures. These aspects are consistent with deposition in dry settings, interposed with episodic damp spells. Lacustrine facies consist of wave-rippled and cross-bedded sandstone. A clastic rather than evaporitic lake fill can be reconciled with positive water budgets, and thus relatively humid conditions. While ephemeral-fluvial and dry-aeolian deposition can be influenced by external forcing such as catchment properties and intra-basinal topography, clastic lake fills are more confidently related to local climate regime. An outcome of this study is that caution should be used when considering fluvial and aeolian facies alone for reconstructing pre-vegetation paleoclimate. This study also provides new insight into an overlooked rock unit of the classic Torridonian succession of Scotland, providing a refined set of critical tools to interpret paleoclimate regimes from Proterozoic terrestrial environments.

Geological Survey of Canada (GSC): Peering into the future, teaming for geoscience excellence and results

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Recently, we reflected on the issues that matter to Canada in the complex socio-economic landscape of the 21st century world, to plan the main thrusts of the GSC's 2018-2023 Strategic Plan. The bird's eye view of planet Earth is daunting: it has never been so populated, facing so many critical sustainability challenges, and moving so fast with technological changes, the latter representing hope and opportunity. The human and natural world in which the GSC was born 175 years ago is completely changed from what it was in 1842 and it is dramatically different than at our 150th anniversary.

The GSC aims to remain a leader in geoscience, and serving Canadians well. A critical issue is therefore to determine how we adapt to changing times to continue to exercise geoscience leadership together with provinces and territories, universities, the private sector and other stakeholders.

In a world awash with data, polarized by right and left-wing politics, strained by socio-economic issues, and sometimes paralyzed by uncertainty, science can be used as a diplomatic lever for evidence-based decision-making. Citizens expect a return from science investments, to inform policy and decision-making on issues of critical importance. There are many examples of geoscience integration into policy that has empowered society and help achieve consensus on difficult societal decision-making. More needs to be done.

Over the next five years, the GSC will deliver geoscience-based program based on three principle outcome axes: 1) Resource for Future Generations: Geoscience evidence to support the sustainable development of Canada's lands and natural resource, as well as the shift to a low carbon economy; 2) Keeping Canada Safe: Geoscience to reduce disaster risk and build capacity to enable resiliency to climate change and disasters; 3) Geoscience for Society: Geoscience to engage in societal, economic and environmental geoscience issues and foster Canadians' interest in geoscience.

In examining global and national trends that will shape the country's future and shape our geoscience activities, we will need to further learn through interaction with our scientists and stakeholders and draw conclusions from client and policy needs. We are engaging stakeholders to firm up our objectives; this will enable all our staff and partners to achieve results of common interest, and will benefit all Canadians.

There will be many challenges to implement this direction and we will get through those building on the strong values that are held by all of GSC: commitment, excellence and knowledge.

Identification of Early Cretaceous extensional granitic domes along the southeastern China-Mongolia border and its tectonic implications

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Several granitic domes are developed along the southeastern China-Mongolia border area, which are asymmetric sy-kinematic extensional domes. There are extended along the border for over 500km with NE trend. These domes consist of core Early Cretaceous granitic pluton(~130Ma), ductile shear zone and brittle detachment fault from center to outside. The hanging walls are undeformed Early Permian granodiorite, Devonian schists and Early Cretaceous basin. Ductile shear zone and detachment fault only developed in the southwestern part of these domes. Detailed field observation and microstructures showed that all the core pluton and ductile shear zones were formed in a same tectonic stress field, which indicated a unified top-to-the-NW shearing. The deformation grade increased toward outside. All those implied that formation of foliations of those domes are closely related to emplacement and uplift of the core plutons. Thus, these domes are similar to other extensional domes in NE Asia, which reflected geological features of syn-kinematic magma emplacement during collapse of thickened crust caused by the closure of Mongol-Okhotsk Ocean.

Fault interpretation from multiple data sources in central BC

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In the past decades, geological mapping and remote sensing focussed on the Canadian Cordillera have provided a much clearer picture on the general geology of the various arc-terranes and particularly, the formation history of a series of major porphyry deposits. However, large parts of the Cordillera, especially valley floors which are covered by Quaternary sediments are inaccessible for direct mapping. Geophysical data provides insight into the distribution of lithologies at depth, as well as continuous sampling and systematic coverage over large spatial extents. Integration of geophysics with other geoscience data, such as regional geological maps, high-resolution digital elevation models and satellite data, can refine the mapping over covered areas. In this study, we use aeromagnetic data, digital elevation models, and radiometric data, together with mapped faults and intrusive rocks to re-evaluate the distribution, geometry and alteration characteristics of structures.

The study area is the area covered by the 2016 Search II airborne aeromagnetic and radiometric survey, covering approximately 28.000 square kilometers and is located almost entirely within the Stikinia Terrane. More than 9.000 square kilometres are covered by quarternary sediments.

Analysis of the strike orientations of faults in the study area shows that faults with an expression in the magnetic data are mostly northwest-striking with a minor north-northeast striking set. The north-northwest striking faults are the regionally most prominent fault set and are parallel to the terrane boundaries. West-northwest, and east-northeast-striking lineaments apparent in the topographic data are rare in the mapped faults and in the magnetic data.

Some of the faults are associated with an increased potassium, as indicated by a low Th/K ratio in the airborne radiometric data. As thorium enrichment generally does not accompany potassium during hydrothermal alteration processes, Th/K ratios provide excellent distinction between potassium associated with alteration and anomalies related to normal lithological variations. The dominant orientations of faults with nearby potassic alteration are northeast, north-northeast and northwest.

The interpretation identifies locations where the geophysical data can enhance the existing geology maps. The re-interpretation of the structural framework adds characteristics to the known faults. The geometry of faults and contacts at depth is augmented with geophysical modelling.

Characterization of gold in the W-Cu skarns at Cantung, NWT: Results from in situ LA ICP-MS, SEM, and Micro-XRF analyses

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The gold-bearing Cantung W-Cu skarn is situated within the Canadian Cordillera in the Northwest Territories and is approximately 400 km to the northeast of Whitehorse, Yukon Territory. It is genetically associated with a group of Mid-Cretaceous felsic plutonic suites known as the Tombstone-Tungsten suite, which intruded into the ancient North American continental margin resulting in the formation of a range of types of magmatic-hydrothermal systems. At Cantung, a peraluminous biotite monzogranite intruded into Lower Cambrian marbles in the Selwynn Basin, which resulted in the formation of a zoned array of reduced anhydrous and hydrous skarns.

Previous studies identified gold mineralization using whole-rock lithogeochemistry of samples from the E-zone orebody. A strong positive correlation was found between Au and Bi, Ag, Fe, and Cu. An assemblage containing native bismuth as well as bismuthinite and various bismuth tellurides and selenides was found in samples that contained gold; however, no gold-bearing phases were successfully identified. Using LA ICP-MS spot analyses to ablate the various bismuth-bearing phases attempted to detect any sub-microscopic inclusions of gold were successful at detecting high concentrations of gold (800-1100 ppm Au), possibly from nanoinclusions, but could not optically identify the gold-bearing phase.

Samples were taken from drill hole U2083 through part of the orebody that contains high concentrations of W and Au (up to 6.16 % and 10.85 g/t, respectively) at the contact between the Swiss Cheese and the Ore limestones. Polished thin sections were prepared from samples throughout the orebody. The top of the orebody consists of pyroxene-pyrrhotite skarn, which transitions into amphibole-pyrrhotite skarn. After the sulfide facies pyroxene skarn, the skarn turns into hydrous skarn (mainly biotite) with < 1% sulfides. There are also some zones of muscovite (greisen) skarn facies. This hydrous skarn facies with no sulfides contains the highest scheelite and Au contents. Within the biotite facies hydrous skarn, gold is present with native bismuth, as well as bismuth tellurides and selenides. SEM-EDS analyses of the gold grains suggest they are electrum (~ 30 wt.% Ag) and they often share mutual grain boundaries with native bismuth. The textures exhibited by the gold and bismuth minerals suggest they formed as low-temperature melts during initial saturation of the fluid. Within the muscovite-bearing greisen-skarn, gold is present in even higher concentrations and bismuth is completely absent from this assemblage. This suggest that more than one mechanism is responsible for concentrating and precipitating gold.

Extreme fractionation in various felsic magmatic systems: Constraints from thermal modelling with examples from ore-forming granophile-element systems

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Extreme fractionation is evident in many LIPs, including evolved felsic magmatic systems, although considerable focus in the literature has been on volatile complexing (alone) in explaining metal enrichment in felsic systems. Few researchers conduct experiments and highlight studies presenting primary magmatic processes as responsible for generation ore-forming systems in various granitoid magmas (SLIPs). Incompatible element behavior during partial melting and (or) fractional crystallization is well known, although the effects of the duration of a magmatic system from a thermal perspective is rarely considered.

However, the efficiency of crystal-melt partitioning and crystal-melt separation is mostly a function of the duration of a cooling system. Thermal modeling techniques, with various magma injection scenarios are examined, in particular mafic magmas cogenetically emplaced with felsic magmas, to illustrate the range in cooling times for several different fractionating magmatic systems. The thermal energy modeling was done using the program HEAT by Ken Wohletz (Kware), which is versatile and enables input of variable thermal gradients, and emplacement of different timing of intrusions into any package of rocks. It is easily shown that the duration of crystallization of felsic magmatic bodies can be easily extended by >> 10 times, such that crystallization from a typical granitoid solidus temperature of 700°C to << 600°C could be over 1 million years, which could overcome the viscosity issues with crystal fractionation in low T systems. If correct, any magmatic system can now be geochronologically constrained by dating each phase of a magmatic system, and the associated ores formed, i.e., the importance of thermal models can be tested in ore-forming systems. The specific purpose of which is to determine the lengths of times that specific magmatic systems were above their liquidi through to their lowermost solidus. Extreme fractionation to very evolved magmatic systems like Li-Cs-Ta (LCT-type), Nb-Y-F (NYF-type), Sn, Mo, U, and LREE apogranitic to granitic pegmatite systems to extremely low T's consistent with each of their solidi, i.e., well below 600°C. Partitioning of elements between crystal and melt thus approaches ideal distribution coefficients for incompatible elements. As well efficient crystal – melt separation (Rayleigh fractionation and partial melting) in increasingly viscous magmas has time to separate and migrate promoting fractionation and concentration of fluxing volatiles in those derivative melts. Numerous geochronologically well constrained examples have been modeled, a show that prediction of economic potential of any particular felsic magmatic system is now possible by appropriate thermal modeling of these SLIP complexes.

The ups and downs of magmatic Fe-Ni-Cu-(PGE) sulfide melts in large igneous complexes

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The localization of magmatic Fe-Ni-Cu-(PGE) sulfides within footwall embayments, within jogs in dikes, within or near the throats of magma conduits, and within the horizontal parts of dike-sill complexes in large igneous complexes indicates that these are areas where fluid dynamic conditions changed, facilitating deposition of dense sulfide melts ± xenoliths. In all of these cases, but especially in subvertical conduits/chambers, the ore-localizing features have been interpreted to have operated as divergent 'nozzles' that collected sulfides. Because conservation of mass dictates that Q = p u A (where Q is mass flow rate, p is bulk density, u is velocity, and A is cross-sectional area), continuity requires that at constant Q, increasing A (i.e., unconstricting flow) in the embayment/conduit/chamber leads to a decrease in u, favouring deposition of dense sulfide melt ± xenoliths. However, there are several problems with upward transport models: 1) Sulfides are very dense (~4.2 g/cc) and therefore difficult to transport as fine (<2 cm) dispersed droplets in significant abundances (>10-15%) in much less dense magmas (2.6-2.8 g/cc) rising through only slightly denser crustal rocks (2.7-2.9 g/cc), and almost impossible to transport as larger droplets or slugs. 2) In almost all deposits S isotopic data indicate local crustal rather than deeper crustal sources of S. 3) In most deposits containing xenoliths (e.g., Voisey's Bay), they are derived from local crustal sources rather than deeper crustal sources. 4) Except where there is geological evidence for a local S source (e.g., Alexo, Kambalda, Raglan), sulfides are rarely present in volcanic rocks even where they are clearly related to mineralization in underlying feeders sills/chonoliths (e.g., Duluth, Noril'sk-Talnakh). For these reasons it is more likely that sulfides ± xenoliths in most systems were generated locally or settled downward, and were trapped in the same locations that have been proposed to have trapped upward-transported sulfides. There may be situations where fine dispersed sulfides were transported vertically and collected on xenolith/phenocryst "filter beds", but dense sulfides are more likely to have been concentrated by downward transport than by upward transport.

Crustal-scale modelling for the UK 3D Geological Model

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The UK National Geological Model (NGM) was conceived from the outset as a way to help inform both the general public and non-geoscience specialists (e.g. engineers, regulatory authorities, government and politicians) about the 3D sub-surface composition and structure of the UK. This broad framework is necessary to inform debate on key issues of public concern, such as the management of aquifers, exploration for non-conventional hydrocarbons, the location of future nuclear repositories, nuclear new build, storage of natural gas and CO_2, and other new national infrastructure.

The NGM is constructed from a number of components, and constrained by the range of geological information available. In the northern part of the UK (Scotland, Northern Ireland), complexly-structured metamorphic rocks crop out and these regions have been most appropriately modelled using the GSi3D modelling package to generate a series of representative structural sections. In northern England, an extensive seismic reflection database from hydrocarbon exploration has allowed detailed 3D sub-surface models to be incorporated into the NGM. In southern England and Wales, a dense intersecting network of cross-sections, constrained by borehole and seismic information (where available) has been compiled to illustrate the geology down to the level of the Neoproterozoic basement at 15 km depth. Where possible, these sections have been modelled against the gravity and magnetic potential fields as a first check of their validity. The stratigraphic and structural information from these regions has also been integrated into the current NGM using the GSi3D package, and will evolve and develop as new data and understanding becomes available, particularly for the offshore region.

Very limited information on the morphology of the Moho is available in the onshore area of the UK, due to the sparsity of appropriate (refraction and teleseismic) data. The crustal model will be upgraded as such data become available.

Alteration zonation associated with Au mineralization along the northern Bug Lake gold trend of the Archean La Martinière gold system, west-central Quebec

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The Bug Lake gold trend (BLT), a highly prospective mineralized corridor that constitutes part of the La Martinière gold system, is located in the Harricana-Turgeon greenstone belt in the northern part of the Archean Abitibi subprovince. The BLT is interpreted to be a NNW-trending, moderately to steeply eastward-dipping fault-zone marked by the presence of the Bug Lake quartz porphyry (BLP) with associated gold mineralization along the Bug Lake fault zone (BLFZ). The BLP defines the contact between a package of coherent mafic volcanic, metasedimentary, and mafic to felsic dyke rocks to the east and a multi-phase mafic intrusion to the west. Mineralization is structurally controlled with gold grades ranging from >10 g/t over a few metres to ~1 g/t over several tens of metres. High-grade gold (>5 g/t) typifies both the upper and lower margins of the BLP where rare "bonanza-type" gold grades are present (e.g., 8550 g/t over 0.57 m). Hydrothermal alteration along the BLFZ is characterized by distinct alteration haloes proximal to mineralized zones, hence their characterization is paramount to ongoing exploration.

The gold-bearing zones in the footwall rocks of the BLFZ are associated with quartz-carbonate veining and/or wall-rock metasomatism and are locally distributed along discrete shears. In the northern part of the mineralized trend, demagnetization of "magnetic quartz gabbro" to "quartz gabbro" near zones of mineralization is made evident by the chlorite-calcite-magnetite assemblage in the least-altered intrusive rocks, which is overprinted by sericite-quartz-chlorite-pyrite containing high-grade zones characterized by a quartz-carbonate-pyrite assemblage. Mineralization in the hanging-wall mafic volcanic rocks is characterized by zones of shearing, in situ brecciation, and minor quartz-carbonate veining. The host mafic volcanic rocks display quartz-sericite-calcite-chlorite alteration in low-grade gold-bearing zones that progresses to a quartz-sericite-pyrite (phyllic) assemblage as the grade increases. By integrating these observations with ongoing studies and future work (i.e., fluid inclusions, stable (O, D) isotopes), it is hoped that a better understanding of the conditions under which the gold mineralization occurred will emerge. Subsequently, these findings will be used to improve gold exploration models for this and similar deformation corridors.

Radon risk management initiatives: Geoscience for geohazard risk management and public safety decision making

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This geoscience radon risk for public health and safety research will provide guidance for future initiatives. Overarching questions that will be addressed in this program include:

- What does geochemistry tell us about the risk posed by radon?
- How can geochemistry be used in the public health and safety decision making process?
- What challenges do provincial and municipal decision makers face in responding to the threat of radon?
- What actions can provincial and municipal decision makers take to prepare for the risks posed by similar environmental geohazards? What other actions could be taken?
- How can studies of the geology of radon (uranium and radon sources distributed in rocks and soils, radon formation within rocks and soils, and how radon moves) be communicated effectively to decision makers and the public?

Informed by research from participatory community development, information ecology, and geospatial information for geohazard risk management, methods used included: interviews with key informants (face-to-face, telephone and email), literature review and case study analysis.

This paper presents research results:

- Actionable information products provided by Health Canada and others;
- A comparsion of provincial public safety geoscience legislation to support land use planning and public health and safety initiatives.

We conclude that in general, fit-for-purpose actionable information products created to communicate radon risk ensures more positive changes in community resilience to radon risk.

Building aquifer vulnerability literacy in southern Ontario: Applying emergent technologies in groundwater geoscience education

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Since the Walkerton Tragedy, many Canadians in Southern Ontario closely follow media coverage of groundwater issues (Renzetti and Dupont 2017). The 24/7 news' cycle use of social media platforms often provides content for activism and social outrage rather than reporting the value added by current groundwater geoscience research. Indeed, the anticipated rise in Internet traffic from Citizen Journalists, coupled with the 24/7 news cycle, raises new questions about how to increase the digital footprint of geoscience providers. That is, how to adapt emerging information technology and communication (ICT) to engage stakeholders with forthcoming groundwater science, particularly those who monitor groundwater risk.

Informed by post Walkerton Inquiry groundwater risk policy changes (Renzetti and Dupont 2017), research from information ecology (Babcock et al., 2016), this project builds on our earlier research. This project involves analyzing how Ontario Groundwater Geoscience Consortiums have built aquifer vulnerability literacy, thereby supported groundwater resource exploration economic cost and benefit analysis and groundwater hazard risk assessments.

Methods used included: interviews with key informants (face-to-face, telephone and email), literature review and case study analysis.

We present some preliminary research results:

a) A critical review of existing geoscience-based aquifer hazard risk information which has been examined for the purpose of addressing stakeholders' risk perceptions of water, rocks and soil.

b) A community engagement concept map developed for the purpose of digitally building stakeholder groundwater risk literacry and knowledge.

New questions raised for further study on stakeholders seeking ICT options for groundwater geoscience research, practice, and uptake.

South China as an accretionary orogen

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South China, one of the largest cratonic blocks in eastern Asia, has traditionally been interpreted to have formed by the amalgamation of two blocks, the Yangtze Block to the northwest and the Cathaysia Block to the Southeast. The proposed timing of amalgamation varies wildly, corresponding to the various tectono-thermal events documented in South China, from early Neoproterozoic (ca. 1.0-0.9 Ga; "Grenvillian" age), middle Neoproterozoic (ca. 820 Ma), Early Paleozoic (ca. 460-420 Ma; "Caledonian" age), to Mesozoic (ca. 250-230 Ma; "Indosinian" age). Here, we propose an alternative interpretation. That is, South China formed by accretion/collision of multiple terranes, and each of the above tectono-thermal events corresponds to an accretional/collisional event.

The Cathaysia Block is divided into two parts, West and East, with contrasting histories. West Cathaysia is a composite terrane formed by amalgamation of multiple terranes/arcs at ~1.0–0.88 Ga. West Cathaysia and the Yangtze Block collided at ~820 Ma. The resulting Yangtze-West Cathaysia continent collided with a postulated (continental?) terrane to the east in the early Paleozoic (~460-420 Ma). East Cathaysia, characterized by a ~1.9–1.8 Ga basement and ~250–230 Ma high-grade metamorphism, possibly originated from an Early Mesozoic orogen in the Paleo-Tethyan regime to the south. It accreted to the east of West Cathaysia in the Mesozoic, potentially through large-scale strike-slip movement. Before or during the process, the eastern part of the Early Paleozoic orogen and the postulated terrane moved away from South China through rifting and/or strike-slip motion.

A collision of Avalonia and Cadomia at 540 Ma?

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The Cadomian orogen in the NE Bohemian and in the North Armorican massifs shows a distinct orogenic zoning from recent NW to SE consisting of (i) an outboard sitting continental crustal unit comprising Neoproterozoic rocks associated with c. 2.0 Ga old Icartian Basement, (ii) a magmatic arc and a back-arc basin, (iii) a foreland or retro-arc basin, respectively, and (iv) the passive margin of the back-arc basin. U-Pb zircon ages of detrital zircon of Neoproterozoic to Fortunian siliciclastics identify the West African craton as the hinterland for Cadomia demonstrated by zircon populations in the range of 1.8-2.2, 2.5-2.7, 3.0-3.1, and 3.4-3.5 Ga. Dominant zircon population (c. 50-70% in each sample) is derived from Cadomian magmatic arc activity in a time slice of c. 565-750 Ma. The magmatic activity of the Cadomian arc became extinct at c. 565 Ma. Closure of the back-arc basin by arc-continent collision occurred at c. 542-540 Ma accompanied by the formation of a foreland (retro-arc) basin. A short-living remnant basin existed between c.542 and 540 Ma. Granitoid plutonism at 539 to 540 Ma document the final pulse of the Cadomian Orogeny. Among the zircon populations of volcano-sedimentary complexes of Cadomia a significant portion of zircon exists, which are clearly derived from Avalonia and/or Baltica. Especially, this is the case for deposits of the Cadomian retro-arc basin. Thus, closure of the Cadomian back-arc basin was caused by a 542-540 Ma old collision of Cadomia with a microcontinent showing an Avalonian or peri-Baltic affinity. The relation of Baltica, Avalonia, and Cadomia during late Neoproterozic-early Cambian time is closer than expected.

Deciphering the crystalline metasedimentary rocks exposed in the Hellenic Volcanic Arc, Santorini, Greece

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Most of the rocks on the Cycladic Islands are formed as direct consequences of high-pressure subduction processes of the African plate beneath Europe, and the subsequent exhumation of the subduction channel. The island of Thera (Santorini) resides in the Hellenic Volcanic Arc, and is composed primarily of Pliocene eruptive volcanic material atop pre-volcanic Triassic meta-sediments. Although the island is a world-class example of arc volcanism, the meta-sedimentary unit is less understood. Composed of crenulated pelitic schists, meta-conglomerates, and marbles, the unit exhibits blueschist facies metamorphism conditions with clasts in the conglomerate possessing relict glaucophane and crossite. Most lithologies are strongly sheared as evidenced by aligned mica, stretched quartz defining the foliation plane and abundant kinematic indicators documenting a top-to-S directed shear. Indented boundaries of bulging quartz grains indicate low temperature dynamic recrystallization. Despite high-strain, the Ms-Chl-Ab±Bt mineral assemblage is indicative of greenschist facies metamorphism overprint, likely associated with crustal unroofing as has been shown on other Cycladic islands. A dacitic intrusion within the meta-sediments has been documented in drill core beneath the volcanic rocks, and small, slightly deformed apophyses are exposed at the surface. A previous K-Ar biotite date of ca. 9 Ma on the drill core sample suggests middle Miocene magmatism that is common in the Cyclades, which may have slightly altered the basement rocks with centimeter- to decameter-scale Cal + Fe-oxide + sulphides veins which are parallel and perpendicular to foliation. New (U-Th)/He zircon (ZHe) thermochronology from the dacite, schist and the matrix of conglomerate exposed along the caldera wall documents cooling through ~180°C at 9-7 Ma, directly following magmatism. Zircon from an inland schist sample yielded ZHe ages of 19-16 Ma, which maybe be a more accurate record of crustal unroofing during Miocene extension. Additional Ar-Ar thermochronology and U-Pb geochronology will be presented to further resolve the age of the basement and subsequent cooling history. A better understanding of active, mid crustal processes will improve models of crustal architecture of island arcs.

Tectonic affinities of microcontinents in the Central Asian Orogenic Belt: A case study from the Chinese Tianshan Orogenic Belt

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In the Central Asian Orogenic Belt (CAOB), there are many microcontinents with Precambrian basement. Tectonic affinities of these microcontinents are key issues related to the geological studies of this huge accretionary orogenic belt. The Yili Block and the Chinese Central Tianshan Block are two ancient continental segments within the Chinese Tianshan Orogenic Belt, which is located in the southern CAOB. Based on the review of recent studies, we conclude that Paleoproterozoic crustal materials probably exist in the Yili Block and the Chinese Central Tianshan Block and the ancient nucleus of the two blocks were mainly formed in the Mesoproterozoic (ca.1.4–1.3 Ga). These crustal materials and rocks were intensively reworked and finally formed a united crystalline basement in the early Neoproterozoic (0.97–0.85 Ga). Our newly studies on detrital zircons indicate that two phases of synchronous crustal growth and reworking happened in the Yili Block at late Paleoproterozoic (1.8–1.7 Ga) and early Mesoproterozoic (1.6–1.3 Ga), and then changed into continuous crustal reworking until the Mid- Neoproterozoic (1.0–0.78 Ga). As to Chinese Central Tianshan Block, previous studies on early magmatic rocks reveal that this block experienced a crustal growth event in the Mesoproterozoic (1.6–1.3 Ga) and was then characterized by extensively Neoproterozoic crustal reworking. After that, these two blocks were in a continental rifting or extensional setting in the Mid-Neoproterozoic (0.76–0.71 Ga). According to the differences on the basement, magmatism, deformation, metamorphism and detrital zircon studies between the two blocks and the Tarim Craton and other around old blocks, we conclude that these two blocks have similar Precambrian crustal evolution history, which are distinct from that of the Tarim Craton and the surrounding old blocks. This further suggests that these two blocks have no close tectonic affinity to the Tarim Craton, but were most likely originated from the nearby Kazakhstan block.

Keynote (30 min): Diagenetic yearnings and learnings from light stable isotopy of clay minerals – Looking backward and going forward

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The oxygen and hydrogen isotope compositions of clay minerals have been part of the geochemist's toolbox since the fundamental principles for clay-water systems were first elucidated in the late 1960s. So – half a century later – is there much more to be said? There are several challenges! (1) For clay minerals that achieved and preserved O- and H-isotope equilibrium with water in supergene and hypogene environments, verifiable geothermometers over the temperatures of interest are still required that fully account for variations in octahedral and tetrahedral cation compositions, charge and siting, and intra-clay isotopic fractionation between inner and outer hydroxyls. Semi-empirical bond strength and modified increment models have moved us someway towards calculating O-isotope geothermometers for more complex clay-water systems, but understanding H-isotope fractionation in all but the simplest systems continues to challenge. (2) The potential decoupling of O and H isotope exchange during clay-water interactions even at low temperatures, and the ensuing implications of proton versus hydroxyl exchange for interpreting clay mineral light isotopic compositions, throbs with complexity, particularly in diagenetic systems where fluid flow continues long after first formation of clays in the pore system. (3) Clay (and hydroxide) minerals – being tricky little beasts – can confuse by retention of apical oxygen from tetrahedral sheets during desilication at low temperatures and low rock/water ratios or inheritance of tetrahedral sheets from precursor structures during diagenetic and hydrothermal processes. (4) We are still not much closer to quantifying temperature-dependent, intra-clay mineral O-isotope fractionation between octahedral and tetrahedral sites. Except for a few valiant attempts, the single mineral O-isotope geothermometer remains elusive. Likewise we await a tried and true method to measure this intra-mineral fractionation with aplomb. (5) The interaction of interlayer and adsorbed water on clay surfaces during its acquisition and release can lead to changes in the measured isotopic composition of both clay and water, depending on clay structure, fluid composition, temperature, and the method of clay dehydration. (6) Some poorly crystallized clay minerals occlude organics during formation, thus affecting their isotopic compositions. Turning these lemons into lemonade can be fun! Careful measurement of clay mineral isotopic compositions and yields of O and H released during stepwise heating and ensuing dehydration, organic combustion and dehydroxylation can reveal much about clay crystal-chemistry. Such measurements can hold clues to climatic and diagenetic history in terrestrial and marine environments, aqueous alteration history in more extreme environments, and perhaps even to clay-organic signals of biogenicity.

Relevance of fluid:rock interaction in Proterozoic pegmatites near Sudbury, Ontario to mineralization in rare-metal pegmatite settings

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Rare-metal (RM) mineralization (Li, Sn, Ta, Nb, REEs) in pegmatite settings (e.g., Tanco, MB; Strange Lake, LB; Thor Lake, NWT) is considered by some to be of magmatic origin whereas for others there is an important role for upgrading of earlier magmatic proto-ore due to fluid:rock interaction. In some cases the latter fluid is exotic to the pegmatites. The exceptional exposures of simple, graphic-textured Proterozoic pegmatites forming a 10 km long discontinuous swarm cutting Proterozoic para- and orthogneiss close to Sudbury, Ontario, Canada provides an ideal setting to investigate fluid:rock interaction as the simple quartz-two-feldspar pegmatites, which lack significant RM mineralization, contrast markedly with the mafic amphibolitic wall rocks. Two main types of pegmatites are recognized: 1) those displaying internal zonation from a K-feldspar border to a megacrystic quartz core; and 2) those lacking a quartz core. The presence of intense metasomatism in these pegmatites is evident from abundant reddening of feldspars, both K-feldspar and albite, and formation of texturally complex zones of muscovite and garnet within and along border zones. Quartz samples (n=50) are being analysed in situ (SIMS) for $\delta^{18}O$ and trace elements (LA ICP-MS) to assess source controls and possible contamination. In one case, an exceptional exposure (3 × 30 m) mapped in detail provides the bases for a more detailed study of metasomatism, which involved mapping the distribution of minerals, textures and alteration, in addition to $\delta^{18}O$(quartz) analysis. Preliminary SEM-EDS imaging and analysis of the latter pegmatite reflects extensive modification of the primary feldspars, the following features being noted: 1) development of pitted and sponge-textured secondary K-feldspar (Or_{90-100}); 2) formation of albitic and calcic plagioclase ($<An_{30}$); 3) presence of veinlets of Fe-rich (3-4 wt. %) muscovite replacing feldspars that is similar to coarse secondary muscovite in the border zone; 4) coatings of Ca-S phase (anhydrite?); and 5) disseminated hematite and uraninite. Alteration is currently attributed to two fluid sources: 1) a magmatic fluid released from the quartz core, as suggested by core-proximal hematization of K-feldspar in addition to garnet and muscovite clusters aligned parallel to the core margins; and 2) externally sourced fluids carrying Ca-Fe-S that migrated through fractures normal to the pegmatite border and represented by finger-shaped muscovite-quartz symplectites and the hematization of adjacent K-feldspar crystals. These results provide support therefor for the importance of external fluids in modifying the magmatic minerals of pegmatites which is relevant to RM mineralized pegmatites.

An exquisitely diverse assemblage of organic-walled microfossils from the Proterozoic of Arctic Canada and implications for the early evolution of eukaryotes

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Organic-walled microfossils, a group of microorganisms including acritarchs, filamentous and multicellular forms, are preserved through numerous Precambrian geological successions worldwide. The transition from the Mesoproterozoic to the Neoproterozoic constitutes a particularly important period for the evolution of eukaryotic organisms, during which major biological and environmental changes occurred and crown groups started to diversify. In this PhD project we are investigating the diversity and the paleobiology of microfossils for the late Mesoproterozoic and early Neoproterozoic of several successions in Northwestern Canada (Shaler Supergroup, Amundsen basin and Dismal Lakes Group, Hornby Bay basin), using a combination of microscopic and microchemical analyzes (optical microscopy, SEM, TEM, RAMAN and FT Infra-red microspectroscopy), and fieldwork. Preliminary results from our study of the lower Shaler Supergroup reveals a beautifully preserved and exceptionally diverse assemblage of organic-walled microfossils, comprising eukaryotes, prokaryotes and other taxa that are not yet taxonomically resolved. We record sixty-five taxa, comprising twelve new undescribed morphotypes, increasing the total known acritarchs diversity for this time of the Earth history. Using morphological features (wall ornamentation, presence of processes, pattern of oppening), we report twenty-five species of unambiguous eukaryotes (including seven acanthomorphs). The assemblage shows taxonomic similarities with other contemporaneous worldwide assemblages but also new taxa, evidencing an high eukaryotic diversity comparatively to other pre-Ediacaran assemblages, with implications for the overall pattern of early eukaryote evolution.

This research project is part of the ERC Stg ELITE project "Early life Traces and Evolution, and implications for Astrobiology" (E Javaux, PI) and part of a collaboration with the multidisciplinary and international Agouron Foundation project "Eukaryote evolution in the Proterozoic of Arctic Canada" (G Halverson, PI; R Rainbird, H Turner, T Skulski, J Brocks, N Butterfield, C Hallman, E Javaux, co-PIs).

Fine fraction indicator mineral signatures of porphyry, VMS and other deposits

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The use of indicator mineral methods for mineral exploration in glaciated terrain has been slowly expanding since the 1960s when they were first used for gold and diamond exploration. Today, indicator minerals are used for exploration for a broad range of commodities including diamonds, gold, PGE, and base metals. For indicator minerals to be effectively recovered from till samples, they must be sufficiently dense to allow separation and concentration from till using gravity methods. Indicator minerals are generally present in low concentrations within till (ppb levels), and therefore large samples (10-20 kg) are commonly necessary to obtain significant and useful numbers of grains in a sample. After density separation, the resulting heavy mineral concentrate (HMC) samples are sieved to a desired fraction for examination under a binocular microscope.

Grain size has traditionally been a limiting factor on analysis, as material smaller than 0.250 mm is too small to manipulate accurately and increasing grain counts make thorough examination impractical. This study plans to utilize a scanning electron microscope equipped with an energy dispersive x-ray spectrometer (EDS) and Mineral Liberation Analysis (MLA) automated quantitative mineralogy software to enable rapid quantification of the modal mineralogy and grain size/shape characteristics of <0.250 mm HMC.

The first phase of study has focused on the handling and effective separation of <0.250 mm HMC material into meaningful size fractions. The fine grain size makes material loss and contamination a serious concern, and thus the authors have designed proprietary, single-use sieves that can be disposed of between sample runs. This eliminates the chance of cross contamination between samples due to ineffective cleaning. Protocol for the effective handling of this fine material, focusing on minimizing loss and contamination while maintaining the efficacy of the sieving procedure, have been designed and implemented. The observed grain size distributions and material loss within the four size fractions chosen for study have given superior results than those obtained with standard stainless steel laboratory sieves.

The next phase of study (currently ongoing) sees the mounting of each size fraction into epoxy ring mounts, which are subsequently quartered and reassembled into a second mount, giving a planar surface with both basal and cross sectional surfaces available for SEM analysis. The resulting MLA scans will allow the construction of mineralogical databases for each sample and the characterization of each fraction of till.

Genesis and petrology of the Antamina Cu-Zn skarn deposit, Peru

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The giant Cu-Zn-Mo-Ag Antamina replacement skarn orebody records a protracted series of events. Intrusion of highly oxidized, metaluminous, porphyritic monzonite into folded Upper Cretaceous carbonates produced marble containing scapolite and/or wollastonite in the pure limestones of the Jumasha Formation, the main exoskarn host-rock, and calc-hornfels and skarnoids ranging from distal phlogopite-bearing to proximal diopside-bearing in the overlying marly Celendín Formation. K-silicate alteration of the stock associated with disseminated and veinlet molybdenite ± chalcopyrite ± fluorite occurred at 10.15 ± 0.04 Ma, the average of four biotite $^{40}Ar/^{39}Ar$ plateaus. Ore-grade porphyry style Cu mineralization formed at this time has been overprinted texturally by endoskarning. Early, anhydrous, zoned, oxidized calcic exoskarn formed around the margin of the stock and contained disseminated and locally banded intergranular chalcopyrite ± sphalerite in brown to green Fe-rich grandite (Adr: 74-100) ± diopside exoskarn; while concurrent coarse-grained pink and maroon, Al-rich grandite (Adr: 37-62) + plagioclase ± epidote endoskarn overprinted porphyry-style and 'episyenitic' (quartz-destructive) alteration in the stock, which was accompanied by fluorite. Locally a laminated 'wriglitic' bornite-wollastonite ± grandite ± vesuvianite ± chalcopyrite ± sphalerite ± molybdenite skarn separates green garnetite and marble. Widespread intermediate argillic alteration converted endoskarn and phenocrystic plagioclase to montmorillonite + illite, which yields $^{40}Ar/^{39}Ar$ plateaus that average 9.98 ± 0.06 Ma. Resumption of monzogranitic porphyry intrusion accompanied uplift and exhumation as suggested by the decrease in the Al content of magmatic hornblende in the later porphyry. Renewed mineralization included i) rare phyllic alteration that comprises sericitic selvages to pyrite veins in unskarned monzogranite porphyry, and ii) skarn formation by conversion of coarse-grained endoskarn and unskarned porphyry to fine-grained, reddish-brown endoskarn, associated with a stockwork of pyrite-chalcopyrite-magnetite veins that grades into crackle breccia, mosaic breccia and heterolithic phreatic breccia, which occur along the endoskarn-exoskarn interface and also in fine-grained endoskarn zones that cut the porphyry; retrograded skarn vein selvages and phyllic vein selvages in porphyry both yield $^{40}Ar/^{39}Ar$ plateau ages of 9.80 ± 0.07 to 9.75 ± 0.7 Ma. This second pyrite-chalcopyrite-magnetite skarn, stockwork and breccia event, evolved from prograde to retrograde and introduced a significant amount of copper in endoskarn.

Skarn and sulphide paragenesis and mineral zoning suggest Si-Cu-Zn metasomatism preceded Fe metasomatism in exoskarn, whereas Ca metasomatism preceeded significant Cu and Fe introduction in endoskarn, which itself evolved from prograde to retrograde skarn.

Automatic estimation of aquifer parameters using long-term water supply pumping and injection records from a highly heterogeneous glacial deposit

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Planning for the optimized use of groundwater resources is of paramount importance to water managers worldwide in the face of increased demands on groundwater resources, the protection of groundwater resources from contamination, and the increasing energy costs of community water systems. The optimized design and management of groundwater-based water systems requires the accurate estimation of transmissivity (T) and storativity (S), which are two important hydraulic parameters in predicting groundwater flow. However, for municipal water-supply well fields, it is logistically infeasible to cease pumping/injection for the entire aquifer to conduct dedicated pumping tests for hydraulic parameter estimation, considering that municipal water supply cannot be interrupted. In this study, we present an analysis of drawdown records obtained from existing, long-term, and variable pumping/injection events collected at the Mannheim municipal well field in Kitchener, Ontario. Such records are typically not considered for aquifer test analysis. Here, the water-level variations are fingerprinted to pumping/injection rate changes using the Theis model implemented in the WELLS code coupled with PEST. Analyses of these records yield a set of T and S estimates between each monitoring and production well. These individual estimates are found to poorly predict water-level variations at nearby monitoring wells not used in the calibration effort. This is likely due to the fact that the site is highly heterogeneous, consisting of glacial deposits of the Waterloo Moraine. On the other hand, the geometric means of the individual T and S estimates are similar to those obtained from previous pumping tests conducted at the same site and adequately predict water-level variations in other wells. Overall, this study reveals that long-term municipal water-level records are amenable to analyses using a simple analytical solution to estimate aquifer parameters. However, uniform parameters estimated with analytical solutions should be considered as first-cut estimates. More accurate hydraulic parameters should be obtained by calibrating these data with a three-dimensional numerical model that rigorously captures the complexities of the site. Therefore, we have begun conducting a hydraulic tomography (HT) analyses of data from the Mannheim wellfield to map the heterogeneity in hydraulic conductivity (K) and specific storage (Ss), their connectivity, as well as to obtain uncertainty estimates.

Hyperspectral characterization of mineralogy and mineral chemistry across the Canadian Malartic gold deposit, Quebec, Canada

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The Canadian Malartic gold deposit is located in the highly gold endowed Abitibi region of Québec. A large part of the mineralization is located within Archean metasedimentary rocks, which are often challenging to characterize by conventional core logging. We make use of a hyperspectral imaging system (Specim SisuROCK™) to acquire shortwave infrared spectra (SWIR, 1000-2500 nm) at high spatial resolution (0.2 - 1.0 mm/pixel) over several hundred meters of drill core from the ore zone, as well as on distal, unaltered samples. In SWIR spectra, characteristic cation-OH absorptions can be used to identify mineralogy and to estimate mineral chemistry of white mica, biotite and chlorite. The high-resolution spectral imagery allowed us to identify a correlation between mineral chemistry and downhole Au grades. Mineralized intervals are characterized by the presence of phengitic white mica (>2206nm, <3.3 AlVI apfu for 22O) and Mg-rich biotite/chlorite (Mg# > 70), and present texturally complex changes in mineral abundance and chemistry. In unaltered samples, white mica bearing beds show more muscovitic compositions (<2202nm, >3.5AlVI apfu), and are in sharp contacts to white-mica free greywacke beds. Biotite/chlorite are of intermediate composition (Mg# 50-60) and show no textural variability within a given sample. The SWIR analysis also included over 800 point measurements, collected with a portable field spectrometer (Terraspec®), from outcrops in an 8 × 12 km region surrounding the deposit. These data revealed a multi-km hydrothermal alteration halo surrounding the deposit.

Additional reflectance spectra were acquired from drill core using a thermal infrared system (TIR, 8000-12000 nm). The TIR spectra are responsive to Si-O bonds, therefore allowing us to estimate and map the relative downhole abundance of quartz. Estimated relative quartz abundance is well correlated to the degree of silicification estimated from conventional core logging.

Because data acquisition is rapid (1 minute per core box), spectrally detectable changes in mineral chemistry make hyperspectral imaging a useful tool for delineating mineralized intervals in drill core, as well as for estimating silicification. Portable infrared spectrometers allow for rapid characterization of mineral chemistry directly on outcrop, and have potential for vectoring towards mineralization in similar geologic environments.

Microstructural style and relative timing of deformation along the Bathurst fault, western Nunavut

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Crustal-scale basement faults can be long-lived structures that can localize renewed deformation and fluid migration. The Bathurst fault in the eastern Slave craton is a NNW-trending crustal-scale structure that sinistrally displaces the ~2.0-1.9 Ga Thelon tectonic zone, which separates the Slave and Rae cratons. The Bathurst fault intersects the 1.7 Ga Thelon basin that hosts unconformity-type uranium deposits, which are spatially associated with basement faults that underwent brittle reactivation. While the Bathurst fault may have initiated during the Slave-Rae collision, its late brittle evolution remains unclear. We characterize the style and relative timing of deformation through field and microstructural analysis, which will guide future U-Pb and $^{40}Ar/^{39}Ar$ dating of fault rocks.

Hornblende-bearing monzo- to syeno-granite in the fault zone and minor sillimanite-bearing metapelite east of the main fault trace both preserve high strain fabrics. Because of their predominance, alkali and plagioclase feldspars likely control the rheology of the quartz-poor fault zone granitoids. Bent and tapered albite twins and subgrain recrystallization indicate feldspar crystal-plastic deformation, whereas intracrystal fracturing and micro-faulting indicate brittle deformation. However, intracrystal fractures may have initiated grain size reduction as they promote shear localization and subsequent fine-grained albitic recrystallization. We interpret the intracrystal brittle and plastic features in feldspars to be coeval since fracturing and dynamic recrystallization in feldspars can occur together over a wide temperature range. Through-going fractures occur as late brittle deformation features that overprint the penetrative ductile fabric. The relative chronology of fractures is identified by the type of infill, and few cross-cutting relationships: (1) fine-grained recrystallized albitic feldspar and sericite, (2) chlorite, and (3) quartz. Few kilometres east of the fault zone granitoids, syn-kinematic sillimanite, core-and-mantle feldspar porphyroclasts, and quartz grain boundary migration recrystallization structures correlate to high deformation temperatures (>500°C). These exposures show very limited brittle overprint.

These observations suggest the fault zone granitoid initially deformed under ductile conditions (~500°C) followed by pervasive brittle overprint at low temperature. Meanwhile in the east, high metamorphic grade metapelite and monzogranite exhibit only high temperature deformation and lack brittle overprint. Thus Bathurst-related brittle deformation appears localized to the granitoid rocks along the main fault trace. This may reflect brittle reactivation of a wide Bathurst ductile shear zone after it cooled and exhumed to shallower crustal levels. The ductile fabric in the high metamorphic grade exposures east of the shear zone may represent either an early Bathurst shear zone, or pre-Bathurst deformation.

Sedimentary-hosted Pb-Zn mineralization in the Paleoproterozoic Karrat Group, west Greenland

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Recent expeditions to study the Paleoproterozoic Karrat Group (~2.0-1.9 Ga) are focused on understanding the context of regional sedimentary-hosted Pb-Zn mineralization, which occurs around 71ºN in arctic west Greenland. The most notable Pb-Zn mineralization is hosted in two units of the Karrat Group: the Marmorilik Formation (carbonate-hosted), home to the historical Black Angel Mine, and the recently defined Qaarsukassak Formation (shale-carbonate-hosted). These sedimentary units of the Karrat Group were deposited directly on Archean crystalline basement rocks and might be of similar age, but since the units are not in contact with one another and are separated by a basement topographic high, their stratigraphic correlation is unclear. If it can be shown that the mineralization is epigenetic or structurally controlled, then the two units might host the same mineralization event regardless of their relative depositional age. The drive of this study is to analyze regional ore sulfide samples to better characterize the isotopic geochemical characteristics to understand the origin of Pb-Zn mineralization in both formations. Methods include petrography, pyrite and ore sulfide sulfur isotope analysis, and lead isotopic analysis on galena to determine possible fluid source(s) and potential similarities in fluid source(s) for the two host formations. Initial pyrite sulfur isotope analyses by conventional IRMS results show a range of $\delta^{34}S$ values between +0.2‰ and +7.2‰ (±0.2‰; n=14). Future work by SIMS analysis is expected to yield a greater spread in values, which would be expected if the ore sulfur has a sedimentary origin. Preliminary petrographic work on Marmorilik and Qaarsukassak mineralization exhibit textures that suggest a late stage remobilization/deformation event after the emplacement of ore mineralization. Two or more phases of sphalerite crosscut massive sphalerite and pyrrhotite in Qaarsukassak mineralization, suggesting multiple stages of ore emplacement. Observations in the field show Pb-Zn mineralization concentrated along antiformal hinge lines in the Qaarsukassak Formation trending to the southeast, similar to the trend of mineralization in the Marmorilik Formation. This study comprises part of the larger collaborative Karrat Zinc Project, led by the Geological Survey of Denmark and Greenland (GEUS) and the Ministry of Industry and Minerals (MMR), focused on reconnaissance mapping and mineral potential in the Karrat Group. The results of this research will be integrated into and bolstered by the broader research program that includes stratigraphy, structural geology, and geochronology.

Regional distribution of arsenic in soil in the Yellowknife region

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The roasting of gold-bearing arsenopyrite (FeAsS) ore at legacy mines in the Yellowknife area resulted in the release of arsenic trioxide (As_2O_3) to the surrounding environment via airborne emissions. Recent studies have highlighted a persistent legacy in local lake sediments and surface waters 50 years after the bulk of these emissions were released. Questions remain regarding the amount and nature of arsenic residing in soils. The objectives of this research are to: 1) characterize the regional distribution of arsenic in Yellowknife area soils; 2) identify factors that explain regional patterns of distribution; and 3) distinguish between natural and anthropogenic arsenic sources.

A total of 439 soil samples were collected within a 30 km radius of Yellowknife during the summers of 2015 and 2016 to explore the regional variation in soil arsenic concentrations. Sampling targeted four distinct terrain units, including: outcrop soils, forest canopy soils, forest canopy outcrop soils, and peatland soils.

Total element analyses have been completed on the Public Health Layer, which is defined as the top 5 cm of material. Peatland soils ranged from 4.1 to 4,900 mg/kg of arsenic with a median of 150 mg/kg. Outcrop soils ranged from 10 to 3,000 mg/kg with a median of 150 mg/kg. Forest canopy outcrop soils ranged from 6.1 to 1600 mg/kg with a median of 115 mg/kg. Finally, forest canopy soils ranged from 1.5 to 460 mg/kg with a median value of 32 mg/kg. Statistical analyses are being used to indicate how multiple variables, including distance from the roaster, elevation, organic content, and terrain type may explain the distribution of arsenic.

Select cores are being analyzed using scanning electron microscopy coupled with automated mineralogy to identify the solid species of arsenic present within the soil units. Anthropogenic sources of arsenic are characterized by the presence of As_2O_3 and distinctive arsenic-bearing iron-oxides derived from roaster stack emissions. Using analytical methods to identify the mineralogy of arsenic provides value because speciation influences the bioaccessibility of arsenic – an important consideration for risk assessment.

This regional soil sampling initiative complements previous lake, sediment, and soil geochemical surveys undertaken throughout the area. This research will work towards understanding the connections between terrestrial and aquatic systems in the region by filling knowledge gaps in soil geochemistry, mineralogy, and mobility. This research will also supply important data that can support future assessment of risk to human and ecological health from arsenic-derived stack emissions.

Till provenance discrimination using iron oxides physicochemical characteristics; Case studies from Kiggavik uranium district (Nunavut, Canada)

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Magnetite from various mineral deposit types has been widely studied, yet iron oxides as geochemical fingerprints of host mineral deposits in dispersion halos remains poorly studied. This study presents the results of analyzing the shape, surface textures, and chemical compositions of magnetite and hematite grains from 0.5 to 2.0 mm ferromagnetic fractions of 10 till samples collected from the Kiggavik uranium district, and application of these characteristics in till provenance studies. The Kiggavik till samples were collected directly overlying, up-ice, and at various distances (50 m to 2 km) down-ice from the Kiggavik Main Zone with respect to the dominant ice flow phases to the N-NW and NW. Iron oxide grain shape and surface textures were characterized using optical and scanning electron microscopy, whereas their minor and trace element compositions were determined by electron probe micro analyzer and laser ablation inductively coupled plasma mass spectrometry.

In Kiggavik till, the majority of iron oxide grains are rounded (40%), sub-rounded (38%), or sub-angular (24%). These iron oxide grains are mostly imprinted by mechanical microtextures such as crescentic gouges, arc-shaped and linear steps, troughs, and fracture faces that are indicative of glacial transportation. In places, these microtextures are masked by iron oxide coatings (1 to 10 µm thickness) that formed postglacially and that variably cover the surface of 70% of studied grains.

To distinguish the source of iron oxides in Kiggavik till, a combination of principal component analysis (PCA) and linear discriminant analysis (LDA) was applied to the mineral chemical data. First, the data for 121 iron oxide grains from various Kiggavik igneous basement, metasedimentary, and sedimentary bedrock, including granite, leucogranite, syenite, quartz arenite, quartzite, and metagreywacke, were classified by PCA, followed by LDA from PCA factors to predict till geochemistry. A high proportion of iron oxide grains in local till were classified as being from local bedrock lithologies, whereas 2% are unclassified. More than 50% of iron oxides in Kiggavik till were classified as being derived from quartz arenite. One sample, 2 km down ice, displays an iron oxides signature of leucogranite. In contrast, a metagreywacke chemical fingerprint (450 ppm U in hematite) is not detected in local till. These PCA and LDA classifications suggest that Kiggavik bedrock lithologies in which iron oxides are commonly ≤0.2 mm in size are absent in the 0.25 to 2 mm fraction of till examined in this study. This emphasizes that the grain size range of iron oxides in mineralization and host rocks must be understood when examining indicator minerals in till.

Geochronological constraints on the dextral strike-slip motion along the Acadian Grand Pabos fault in Gaspé Peninsula, Canadian Appalachians

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An accretionary orogen resulting from continental collision implies several orogenic events which took place on distinct continents or terranes. This implies that some large-scale orogenic features after the final amalgamation will be spatially and kinematically unrelated. These orogenic features, however, may have occurred at the same time. Therefore, dating of tectonic structures is critical to unravelling the orogenic history of an accretionary orogeny.

The Grand Pabos fault is a major dextral strike-slip fault in the Gaspé Belt, the largest middle Paleozoic belt in the Canadian Appalachians. In Gaspé Peninsula, it consists of Upper Ordovician to Middle Devonian sedimentary rocks, with minor volcanics, resting unconformably on Cambrian-Ordovician rocks of the Humber and Dunnage zones and unconformably overlain by flat-lying Carboniferous rocks. The Gaspé Belt sequence is affected by a penetrative deformation which involved the development of a northeast-trending cleavage and upright folds, reverse and strike-slip faults. The two angular unconformities, the sub-Caradoc and the sub-Carboniferous, are used to constrain the timing of the deformation of Upper Ordovician to Middle Devonian rocks in Gaspé Peninsula. The penetrative deformation is ascribed to the classical Devonian Acadian orogeny based on stratigraphic relationships between rock sequences.

U-Pb dating of a felsic dyke that crosscuts the Grand Pabos fault provides new age constraints on the deformation of the Gaspé Belt. The Grand Pabos fault is characterized by a ductile high stain zone bordered by brittle-ductile, low strain zones. Shear sense indicators and offsets of stratigraphic markers indicate a horizontal dextral strike-slip displacement of several kilometers. Felsic dyke swarms of granitic to granodioritic composition are found in southern Gaspé Peninsula. One of these dykes, northerly-trending and vertical, cuts across the east-trending ductile high stain zone. It contains small, euhedral zircon crystals dated at 376.5 Ma using U-Pb SHRIMP analytical techniques and interpreted to represent the crystallization age of the dyke.

The Grand Pabos fault must be post-Emsian (post-397.5 Ma), because it affects and displaces Upper Ordovician to Lower Devonian rocks, and pre-376.5 Ma because the ductile high strain zone is cut by the felsic dyke. The motion occurred during the Middle to early-Late Devonian time span in Gaspé Peninsula which corresponds to the late stage of Acadian orogeny in the Canadian Appalachians.

Facies analysis of Ediacaran deposits in southern Namibia

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The Ediacara biota, the oldest known large complex eukaryotes in fossil record, represent a diverse group of organisms with a worldwide distribution, the youngest of which have been documented to straddle the Ediacaran-Cambrian boundary in Namibia. Detailed sedimentary analyses utilizing facies-based approaches can provide valuable insight into the paleoecology of the Ediacara biota. The Nama Group of southern Namibia hosts abundant and diverse Ediacaran fossils, which were deposited in a foreland basin associated with the Damara Orogen during the assembly of Gondwana (580 to 680 Ma). The Kuibis Subgroup is of particular interest in the southern subbasin because it hosts an abundance of Ernietta, a classic Ediacaran fossil that has received a considerable amount of study in recent years. Our fieldwork at Farm Hansberg resulted in the collection of more than 240 Ernietta specimens from 10 distinct horizons at 6 sites. A thorough facies analysis of these sections was conducted and all specimens of Ernietta were photographed and their morphology quantified. The resulting database was analyzed using the package MCLUST R to investigate the life habit and growth of the individual organisms with respect to different facies. Our facies analysis will aid in determining how each paleoenvironment affected the population of Ernietta in terms of size distribution, abundance, and taphonomic grade. The emphasis on integrating both sedimentary and paleontological data into a single study of Ediacaran population dynamics will provide valuable insight into ecosystem development at the base of the metazoan tree.

Replacement textures in arfvedsonite granite and associated HFSE-enriched felsic veins in the Eastern Cobequid Highlands, Nova Scotia

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Arfvedsonite granite is considered the most evolved intrusive rock in the Late Devonian-Early Carboniferous Wentworth Pluton in the Eastern Cobequid Highlands, Nova Scotia. It originated from a felsic melt enriched in alkalis and iron, and consists predominantly of hypersolvus alkali feldspar, quartz and arfvedsonite. Felsic veins enriched in high field strength elements (HFSE) are also present in the area, and crosscut most of the intrusive and associated extrusive lithologies in the Eastern Cobequid Highlands. The HFSE-enriched veins are interpreted to be genetically related to the arfvesdonite granite of the Wentworth Pluton based on their close spatial association, similar mineralogy and comparable textural features.

Petrographic observations of the arfvedsonite granite and felsic veins reveal the subsolidus transformation of the original homogeneous alkali feldspar to perthitic K-feldspar, and the pseudomorphic replacement of the sodic amphiboles by a mineral assemblage consisting predominantly of Fe (±Ti)-oxides and quartz. Electron microprobe analyses of the arfvedsonite granite show that silicates and oxides enriched in HFSE often accompany the Fe (±Ti)-oxides and quartz as replacement products, forming veinlets that crosscut the arfvedsonite crystals and aggregates in close proximity to sodic amphiboles. In the felsic veins, the HFSE-minerals are spatially associated with Fe (±Ti)-oxides, quartz and occasionally fluorite. This mineral assemblage appears to comprise a pseudomorphic replacement as indicated by the presence of amphibole relics and the orientation of Fe (±Ti)-oxide crystals which follow the cleavage planes of the replaced amphibole. The replacement textures examined in the amphiboles from the granite and the felsic veins reflect the gradual breakdown of this mineral phase and the remobilization of HFSE during the post-magmatic stage. Partial replacement of the amphibole is evident in the granites, while more advanced to complete pseudomorphic replacement predominates in the veins with the abundance of HFSE-minerals greatly increasing in the latter.

Field, geochemical and mineralogical data suggest that the HFSE-enriched felsic veins originated from an evolved silicate liquid characterized by low viscosity. It is plausible that this liquid was internally derived and genetically related to the evolved late melt that generated the arfvedsonite granite.

Ultramafic arc cumulates in an accretionary orogen: Tracing the geochemical evolution of the Giant Mascot ultramafic suite in the southern Coast Plutonic Complex of southwestern British Columbia

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Ultramafic arc plutons represent the fossil pathways of subduction zone magmatism from their source in the mantle wedge to emplacement as juvenile additions to continental crust in accretionary orogens. The chemical and isotopic signatures of these ultramafic cumulates record source compositions and subsequent petrologic processes during magma ascent and crystallization. The 93 Ma Giant Mascot ultramafic suite is a crudely elliptical, ~4 km^2 plug that intruded the 95 Ma Spuzzum pluton in the southwestern Coast Plutonic Complex, and is host to the only past-producing nickel mine in the Canadian Cordilleran of British Columbia. The Giant Mascot ultramafic rocks, including dunite-harzburgite-websterite-hornblendite, span a wide range of major element oxide compositions (Mg# = 0.71-0.90; SiO_2=38-54 wt.%; MgO=10-43 wt.%; Al_2O_3=0.6-17 wt.%) that mostly result from mixing of variable proportions of cumulus phases (olivine-orthopyroxene, hornblende-clinopyroxene) and minor amounts of late-crystallized interstitial material in individual samples. In contrast, the dioritic rocks of the Spuzzum pluton are calcic and characterized by higher SiO_2 (47-65 wt.%), significantly lower MgO (2.5-8.4 wt.%) and Mg# (0.55-0.67), and elevated Al_2O_3 (17-22 wt.%). Relative to N-MORB, both rock suites reveal enrichments in large ion lithophile elements (Cs, Ba, Rb, K, Sr, U) and Pb, and slight negative Nb and Ta anomalies, typical of magmas generated in subduction zone settings. Chondrite-normalized rare earth element patterns in the ultramafic cumulates are depleted in LREE compared to HREE ([La/Sm]N=0.3-1.1], reflecting accumulation of pyroxene and amphibole; the older Spuzzum diorites have elevated LREE relative to HREE and prominent negative Eu anomalies that formed as a result of feldspar fractionation. High-precision radiogenic Hf-Nd-Pb isotopic compositions of whole rocks from the Giant Mascot ultramafic suite (n=9; εNd = +3.9 to +6.4, εHf = +8.3 to +11.7, $^{208}Pb/^{204}Pb$ = 38.207–38.523, $^{207}Pb/^{204}Pb$ = 15.590–15.611, $^{206}Pb/^{204}Pb$ = 18.588–19.031) directly overlap most of those determined from the Spuzzum pluton (n=4; εNd = +4.2 to +6.2, εHf = +8.4 to +11.3, $^{208}Pb/^{204}Pb$ = 38.284–38.416, $^{207}Pb/^{204}Pb$ = 15.587–15.600, $^{206}Pb/^{204}Pb$ = 18.814–18.879) indicating common source components for these compositionally diverse plutonic rocks. The Hf-Nd-Pb isotopic geochemistry of the Late Cretaceous Giant Mascot and Spuzzum rocks is strikingly similar to the isotopic compositions of younger volcanic rocks (Eocene-Recent) from the Cascade Arc in the western United States indicating the presence of common mantle components during long-term mafic magmatism within the Cordilleran orogen.

A novel approach using detrital apatite and till geochemistry to identify buried mineral deposits from the Nechako Plateau, central British Columbia

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Resistant indicator minerals or RIM's have been used in mineral exploration in recent years to help identify and locate buried deposits because their compositions reflect their source rocks and, in some cases, specific types of mineral deposits. Apatite is a potential RIM because in addition to its resistance to physical and chemical weathering, it is widespread in most rocks and mineral deposits. Mao et al. (2016) analyzed approximately 600 apatite grains from the major types of mainly magmatic-hydrothermal mineral deposits (30 localities) and carbonatites (29 intrusive complexes) as well as 300 apatite grains from various unmineralized igneous rocks by EPMA and LA-ICP-MS. Results showed that apatites from carbonatites, unmineralized rocks and different deposit-types have distinct trace element compositions that are readily discriminated by linear discriminant functions using Mg, V, Mn, Sr, Y, La, Ce, Eu, Dy, Tb, Pb, Th and U. Step-wise discrimination diagrams permit the subdivision of apatites by origin. Rukhlov et al. (2016) tested this approach on 4 porphyry Cu-Mo-Au deposits in south-central BC and found that detrital apatite grains in down-ice basal till were correctly classified as originating from porphyry deposits. We have extended this approach to 10 separate areas in the glaciated and underexplored Nechako Plateau of central BC. A subset of 40 mineral concentrates were selected from a larger group of 609 basal till mineral concentrate samples (10-12 kg) collected as part of the regional "Targeting Resources for Exploration and Knowledge" (TREK) project. Picked apatite grains (n=459) were subsequently mounted in epoxy and polished for EPMA and LA-ICP-MS analysis. To aid in the interpretation of these apatite data, we also used till geochemistry from smaller basal till samples (2-3 kg) that were collected at the site of each of the mineral concentrate samples, plus those collected elsewhere within the TREK project area (n=650), and archived basal till sample pulps (n=1456). A total of 342 apatite grains (344 analyses) were classified as associated with mineralization, whereas 41 apatite grains were classified as derived from barren rocks, and 2 grains were classified as "unknowns". Mineralization-related apatite grains were classified as alkalic porphyry Cu-Au (80), porphyry Cu-Mo-Au (28), porphyry Mo (72), porphyry-related Cu-Au breccia (16), orogenic Au (26), orogenic Ni-Cu (7), Kiruna–type IOA (3) and W skarn (112) deposit-types. No apatites were associated with Au-Co skarn or IOCG deposits. This study demonstrates the usefulness of detrital apatites in identifying prospective new zones of mineralization buried up-ice.

Geodynamic development of the South China block from Precambrian to Cretaceous: Constraints from geochemistry, geochronology and geology

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Geotectonic evolution of the South China block is subject to debate. Most articles subdivide the South China Block in two (Yangtze and Cathaysia), with a central Sibao orogeny, although there are also suggestions for a separate eastern (Toll) block. Debate primarily relates to timing of amalgamation of the Yangtze and Cathaysia blocks and processes causing episodic magmatism. Some publications indicate amalgamation between 800 and 900 Ma but others infer amalgamation between 400 and 500 Ma. The eastern portion of Cathaysia may have only collided with Cathaysia in the Jurassic. We bring together multiple data sets to develop a more constrained plate tectonic model for the South China block between 1000 Ma and 100 Ma. Compiled data include geochronology, zircon and whole rock Lu-Hf isotopes, whole rock Sm-Nd and Rb-Sr isotopes, and rock major and trace element data. Geochronology data concentrate on U-Pb zircon and monazite data for crystallisation of igneous rocks and near-peak metamorphism although some lower-temperature closure ages have also been compiled. Detrital zircon U-Pb data aid in understanding changing sources of sediments through time so as to further constrain potential geodynamic processes. Lithochemistry data are used to infer geodynamic setting for igneous activity or for protolith formation. Together, these various data permit one to distinguish between upper and lower plate settings and also to identify rifted environments. Precise location information are captured where available or approximated from published diagrams, correlated with available geological GIS maps. All data have been captured into the online StratDB and DateView databases. The various data, together with GIS lithostratigraphic maps and published conceptual geological models have been used to derive a plate tectonic model which is illustrated with either GPlates or Paleogis software.

U-Pb and Sm-Nd isotope data for rocks formed between 900 and 800 Ma demonstrate primarily juvenile sources whereas the 500 to 400 Ma igneous activity reworked substantially older crust. 200 to 100 Ma igneous activity primarily represents a volcanic arc, possibly associated with the approach of the easternmost, Toll, block. Detrital zircon data show that 900 to 800 Ma grains were eroded and deposited soon after formation of their igneous protoliths whereas to 500 to 400 Ma igneous grains were only introduced to sediments at about 200 Ma. The combined data thus support models inferring collision of Cathaysia with Yangtze between 900 and 800 Ma with later accretion of an eastern (Toll) block after 160 Ma.

Timing of deformation in the Central Metasedimentary Belt boundary zone (CMBbz), southern Ontario, Canada from electron microprobe dating of monazite

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In the Grenville Province of Southern Ontario, the CMBbz is a crustal-scale tectonic boundary between the older, granulite-facies Central Gneiss Belt to the NW and the younger, amphibolite-facies Central Metasedimentary Belt (CMB) to the SE. Although there are a range of tectonic models for the CMBbz, most workers agree it is a major tectonic boundary active during the Ottawan phase of the Grenville Orogeny (~1080-1020 Ma). Some studies suggest that ductile deformation in the CMBbz accommodated extensional collapse beneath a rigid orogenic lid. Previous geochronological studies also provide evidence of earlier deformation and/or metamorphic events in the CMBbz during the Elzeviran (~1230 Ma) and Shawinigan (~1180 Ma) orogenies. Our study is the first to report in situ electron microprobe monazite dates from amphibolite-grade gneisses of the CMBbz, and we interpret our monazite ages within the framework of previous studies. We present dates from five samples in three localities: Killaloe (a classic CMBbz locality), Fishtail Lake (also mapped as the CMBbz), and Whitney (within the Central Gneiss Belt, in the footwall of the CMBbz). Three samples are garnet-bearing gneisses with multiple generations of monazite domains defined by distinctive Yttrium (Y) concentrations. In both Killaloe samples, high-Y monazite cores yield dates of 1215 ± 9 Ma and likely date the Elzeviran age of an igneous protolith. Low-Y monazite domains within these cores are 1174 ± 6 Ma and likely date a significant Shawinigan deformation event during which metamorphic garnet grew. A suite of low-Y rims on some monazite grains are 1063 ± 7 Ma and may represent renewed deformation during mid-Ottawan orogenesis. A suite of low-Y rims are 1042 ± 8 Ma and may represent metamorphic retrogression during late-orogenic extensional collapse. One of the Fishtail lake samples is also a garnet-bearing gneiss, but monazite grains from this sample yield an entirely Ottawan history with different relations between date and Y concentrations: Low-Y monazite domains within cores are 1088 ± 12 Ma; high-Y domains within cores are 1053 ± 6 Ma; and low-Y rims are 1019 ± 12 Ma. The other two samples are felsic orthogneisses that yield only one generation of monazite dates: 1031 ± 4 Ma for the Whitney sample; and 1038 ± 17 Ma for the second Fishtail Lake sample. Young dates from all three localities cluster around ~1040-1030 Ma and are likely associated with retrogression and ductile deformation during syn- to late-orogenic extensional collapse.

Globules of fluxed silicocarbonatitic melt at Otter Lake, Quebec: A new complication in the Grenville Province

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The findings of Schumann et al., presented at this conference, show that the Otter Lake "skarn" occurrence, located 100 km northwest of Ottawa, is the site of emplacement of a fluxed silicocarbonatitic melt. The fluorapatite prisms at this noted mineral-collecting locality contain centimetric globules of orange calcite, commonly with deep purple fluorite as part of the globule. In detail, the fluorapatite contains a myriad of polymineralic "microglobules" containing quartz, fluorite, calcite, hematite, julgoldite-(Fe^{3+}), diopside, allanite-(Ce), thorite, cerite-(Ce), parisite-(Ce), synchysite-(Ce), baryte, and anhydrite, as does the calcite host, in fact. The polymineralic assemblages crystallized from globules of melt; the outline of the globules is roundish, and the assemblages are recurrent. We propose that at the time of emplacement, at roughly 1 Ga, the Grenville system was in a state of relaxation after major collisions. Asthenospheric mantle rising in response to the detachment of a slab of overthickened lower crust provided sufficient heat to melt units of marble as well as gneiss in the lower crust. Calcite does melt in the presence of H_2O and other fluxing agents at the ambient conditions, considered to be close to 7.5 kbar and 750°C. Such a low-viscosity carbonate melt is expected to react aggressively with silicate assemblages along its contacts, and to digest them efficiently. Thus is born a silicocarbonatitic melt of crustal origin. The calcite is crustal, according to its $\delta^{18}O$ value (12.4‰, VSMOW). The prisms of fluorapatite grew from this melt, and the P and F needed were at one time constituents of the gneisses associated with the marble. A granitic melt appeared coevally; at Otter Lake, dikes of granitic pegmatite contains xenoliths of marble. The juxtaposition of granitic pegmatite and diopside-bearing orange "marble" clearly impressed Denis Shaw (1928–2003), who interpreted the Otter Lake occurrence to be a skarn. Shaw also attributed a contact-metasomatic origin to pyroxenite, consisting of diopside, calcic amphibole, calcite, scapolite, phlogopite and titanite. Rather than being part of the skarn, we interpret the pyroxenite as a cumulate formed of crystals than sank in the silicocarbonatitic melt. The Mont Laurier terrane contains hundreds of localized occurrences of orange or pink calcite associated with pyroxenite, exploited in the early 1900s for fluorapatite or phlogopite. We believe that these are manifestations of anatexis of the Grenville crust; anatectic reactions can be expected to produce coeval silicate and carbonate magmas in this context.

Environmental (subglacial melt water) and glass compositional controls on the geochemistry of palagonite formed from Pleistocene glaciovolcanic sideromelane at Wells Gray (Canada) and Helgafell (Iceland Large Igneous Province).

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The effect of basalt composition on the palagonitization of glaciovolcanic, Pleistocene basaltic glass (sideromelane) is examined using an extensive major element (Electron Microprobe) and trace element (32 elements by Laser Ablation Inductively-Coupled Mass Spectrometry) data set for alkali basalts from Wells Gray Canada, and from Helgafell, which is part of the Icelandic Large Igneous Province (33 glass-palagonite pairs of analyses). Exploratory statistical analysis using all data simultaneously shows that the composition of both glass and palagonite reflects the locality of origin. A comparison of palagonite compositions shows that analyses from both localities are organized according to estimated water content, which ranges from 11 – 48 wt. % based on estimations from low major element totals. Further, a comparison of element behavior in the palagonites from both localities reveals a tendency for water-soluble cations (Cl, K, Na, Rb, Cu, Mn, P) to correlate with water concentrations. Plots of element ratios (Nb/Y vs La/Nd; Sc/Ta vs Zr/Th) calculated from “immobile” elements show that palagonites from Wells Gray and Helgafell are distinct, and many have ratios that are similar to sideromelane that produced the palagonite. Thus, some palagonite compositions reflect primary magma compositions based on immobile elements. Gresens mass transfer calculations confirm minimal movement of these elements during palagonitization. However, the same calculations reveal a pattern of Cu, Cl, Ni, Rb and U addition and Na, Ca, Mg, P, V and Mn removal that is similar at both localities. Microprobe traverses across the glass-palagonite interface and palagonite rim suggest that Si, Al, Ca and Na concentrations decrease (are removed) during palagonite formation whereas Ti, Fe and Mg increase (are added or concentrated). Locally, the palagonite has an inner Ti-rich zone. The gradual increase in Mg across the palagonite rim may be indicative of changes in solubility and pH.

Intact paleocaves linked to sediment fluidisation structures at the Precambrian-Cambrian boundary (Victoria Island, NWT)

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Paleokarst is typically expressed as an irregular, unconformable surface-underlying paleocaverns are rarely preserved. In this study, a regional Precambrian-Cambrian unconformity on Victoria Island (NWT, Canada) locally exposes exceptionally well-preserved, large, intact, epigenetic paleocaves, 30-60 m below the unconformity. The paleocaves are aligned along a paleo-horizontal plane and have an overlying gryke network, both of which are filled by distinctive, hematitic Cambrian sandstone. Preservation of the paleocaves requires that karstification occurred shortly before transgression and infiltration of shallow-marine sand, to prevent cave collapse. The karst network then acted as a conduit for groundwater during transgression, controlling the development of nearby submarine springs in the unconsolidated sand. Evidence for the springs includes ~0.5-1 m wide, concentrically layered, cylinders that cut across bedding, interpreted to represent feeder pipes of (eroded) submarine sand volcanoes. Sediment fluidisation is interpreted to have been caused by the hydraulic head of a meteoric lens near the paleo-coastline. Humid, tropical, probably seasonal rainfall caused variations in hydraulic head gradient and flow velocity of the springs. Similar fluidisation structures are present globally, including in basal Cambrian sandstones around the circumference of Laurentia, and have been difficult to interpret due to lack of data on hydraulics of the underlying aquifer. This is the first report linking fluidisation structures to hydraulics of an underlying karstic reservoir and climatic conditions.

Bioremediation of a hydrocarbon plume using biostimulation

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Petroleum hydrocarbon (PHC) plumes are a common groundwater problem globally. Though microbes effectively degrade PHCs in groundwater and generally limit the spatial extent of PHC plumes to a few hundred meters, existing PHC-contaminated sites remain a health hazard to local residents and wildlife and a liability to landowners. Improved approaches to remediating these sites thus holds value to Canadian society and industry. In this study we examined a PHC-contaminated site downgradient from a historical gas station tank source that was active from the late 1950s to early 1980s in Saskatoon, SK. The plume extends beneath a residential apartment building and has been the subject of in situ remediation efforts over the past four years. The remediation has proven effective for removing a considerable amount of the PHC from the site; however, the remaining contamination is relatively recalcitrant to removal. To address this challenge, we have injected sources of phosphate, fixed nitrogen, and iron to stimulate growth of indigenous microbes at the site and biodegrade the residual PHC. The objectives of this study are to: 1) track changes in groundwater geochemistry and microbiology arising from biostimulation of the indigenous microbial community; and 2) improve our strategies for in situ remediation of PHC in the region of study. We are using high-throughput sequencing to track microbial community changes in the groundwater, metabolite analyses to track PHC degradation, and PXRD to characterize aquifer sediment mineralogy. Our baseline results show that relatives of Fe(III)-reducing bacteria dominate groundwater from the PHC-contaminated regions of the site in comparison with groundwater from a control well off-site. Many of these microbes are closely related to bacteria that are known to couple PHC oxidation to Fe(III)-reduction. Groundwater from the contaminated area of the site contains high concentrations of PHC metabolites. Aquifer sediments from the contaminated areas are also enriched in magnetite, a mineral associated with biological Fe(III)-reduction. As we move forward with our second year of biostimulation at this site, we are tracking the influence of biostimulation on these Fe(III)-reducing bacterial populations in the contaminated aquifer sediments, to determine whether the biostimulation is altering community richness or diversity. We are also performing lab-based microcosm studies to evaluate surfactants we may use in future biostimulation amendments.

This research is part of Federated Co-operatives Limited's commitment to the Sustainable In-Situ Remediation Co-operative Alliance (SIRCA).

The significance of Mn-rich ilmenite in the determination of P-T paths from zoned garnet in metamorphic terranes

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Major element (Mg, Ca, Mn, Fe) core-to-rim zoning in metamorphic garnet has long been recognized as an important recorder of changing pressure (P)-temperature (T)-time (t)-composition (X) conditions during metamorphism. In this study, the THERIA_G software, which simulates garnet growth along user defined P-T paths, was used to determine P-T paths of garnet crystallization for metasedimentary rocks of the Jumping Brook Metamorphic Suite (JBMS) in the Western Cape Breton Highlands. An inherent assumption of any thermobarometry software is that the metamorphic rock under question has attained equilibrium, although this might not always be the case. As will be shown, systematic discrepancies between observations and model predictions led to the discovery of unusually Mn(Zn)-rich ilmenites, which are interpreted to have been metastable during prograde metamorphism.

Two distinct styles of garnet isopleth intersection were initially documented within the JBMS; (1) tight isopleth intersections at and/or near the garnet-in curve in samples containing Fe-rich ilmenite, and (2) tight isopleth intersections far removed (>30C) from the garnet-in curve in samples containing Mn-rich ilmenite (5-30 wt% MnO) both as inclusions in garnet and throughout the rock matrix. For the latter, Mn is interpreted to have been sequestered into ilmenite prior to garnet growth. The compositional similarity between matrix ilmenite and inclusions in garnet also suggests that ilmenite was metastable with respect to garnet throughout prograde metamorphism. To account for Mn sequestration into ilmenite, an amount of Mn associated with ilmenite was subtracted from whole rock values used as input for numerical modeling. Isopleth intersections were then recalculated using the adjusted whole rock compositions, yielding robust intersections on the garnet-in curve. Pressure-T paths of garnet crystallization were then determined for four samples containing either Fe-ilmenite or Mn-ilmenite from the garnet- and staurolite-zones of the JBMS. Model results with THERIA_G indicate that P-T paths in both zones were remarkably similar and that paths were steep, clockwise and tight over the P-T interval 525-590C and 6-8.5 kbar. The style of P-T paths and the observation that the different mineral zones of the JBMS are stacked along ductile shear zones is consistent with synmetamorphic extrusion during continental collision. The results of this study indicate that Mn-rich ilmenite, which remains unequilibrated with the reacting rock, may significantly depress the position of the garnet-in curve as predicted with commonly used modeling software such as Thermocalc, Perplex or Theriak. However, by carefully correcting model input parameters, robust model results may be achieved.

Metasomatic formational conditions of gehlenite in Crestmore, California as determined by mineral associations and textural relationships

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Metasomatic modification related to hydrothermal activity was the driving factor in the production of a rare, highly aluminous, melilite-group mineral, gehlenite ($Ca_2Al_2SiO_7$), in Crestmore, California. The fluid that drove the generation of gehlenite in Crestmore was derived from intrusive batholiths that penetrated the limestone country rock during the early Cretaceous. This fluid activity produced one of the only localities in the world that contains gehlenitic melilite, which is otherwise restricted to calcium aluminum inclusions (CAIs) within carbonaceous chondrites in meteorites. The gehlenite found within terrestrial rocks on Earth can be used as an accessible analogue to the CAI-forming environment in the solar nebula. Terrestrial gehlenite is rare and knowledge of its properties and relationships with other minerals is necessary to understanding its formational conditions. Petrographic studies and electron probe microanalysis were conducted at Western University on sample geh3461 from Crestmore, California. The data collected revealed that the gehlenite was consistently surrounded by monticellite and had a massive, anhedral crystal habit suggesting the melilite crystals grew at the expense of the monticellite. Metamorphic gehlenite cannot grow as a first phase metasomatic mineral (M_1) and its presence indicates multiple metasomatic pulses. It required the initial growth of an M1 mineral, in this case monticellite, followed by the growth of gehlenite in a later phase as an M_2 mineral. The transition to the M_2 phase corresponds to a change in fluid chemistry from Si-rich to Al-rich. Monticellite, an orthosilicate, has an open crystal structure which allowed the second pulse of Al-rich fluid to percolate into the grains and react with monticellite to produce gehlenite. Sample geh3461 contains a metamorphic assemblage of monticellite + gehlenite + wollastonite + grossular. In the Crestmore metamorphic environment, grossular will completely react to form anorthite + wollastonite + gehlenite at 845°C. The presence of prograde grossular within the sample, and lack of evidence of retrograde reactions, places an upper limit of 845°C on the temperature of peak metasomatic modification. One of the primary M_1 minerals in the Crestmore metamorphic environment is vesuviante, however this mineral is absent from this sample. At 825°C, vesuviante fully reacts to produce gehlenite + wollastonite + monticellite, all of which are prevalent within this sample. This suggests that the peak metasomatic temperature was above 825°C causing vesuviante to react out of the system. This initial temperature estimate (825-845°C) will be useful in the calibration of cation ordering in gehlenite as a potential thermometer.

Surficial and whole rock geochemistry of the Racecourse Cu-Au porphyry prospect, NSW, Australia

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The Racecourse Cu-Au porphyry prospect in the Macquarie Arc, New South Wales has been explored for by numerous companies over the past 26 years. Several geochemical and geophysical surveys have been complimented by a total of 19,819 meters of drilling, with only 4 holes reaching a depth greater than 300m. Positive lithogeochemistry, alteration, and mineralized intercepts indicate a prospective target, with a resource estimate reported in 2014 estimating 27.6Mt @ 0.45% Cu. However due to the project's history, the prospect has lacked a comprehensive geochemical survey outlining the extent of the mineralized target.

Soils as well as monterey pine (Pinus radiata) tree cores were collected to understand the surficial expression of the prospect, and to assess the prospectivity of the area for Cu mineralization. Soil samples were separated with the <60mm size analyzed, and show distinct anomalous populations of Au, Cu, Mo, Pb, and Zn. Tree cores also show elevated Au, Cu, Mo, Pb and Zn in areas that overlap soil anomalies, in addition to areas overtop known faults. Heightened tree core metal concentrations above faulting suggests that tree roots are directly tapping anomalies present at depth. When integrated with subsurface geology and the current understanding of the mineralized body, both geochemical media suggest that mineralization may continue down plunge at depth.

In addition to surficial media, whole rock analysis of drill core has been conducted to assess the prospectivity of the prospect at depth. The use of Peace Element Ratios has been conducted in order to quantify material transfer within the system, and understand the degree of hydrothermal alteration experienced. While the Racecourse prospect hosts mineralization, the degree of alteration experienced in the rocks analyzed is too low for substantial mineralization proximal to current drilling. Potential reasons for this are discussed involving source and trap methodology.

A tale of two massifs: Geochemical and geothermometric constraints on the history of the Nahlin ophiolite, Cache Creek terrane, northwestern British Columbia

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The Nahlin ophiolite within the northern Cache Creek terrane represents one of the largest and best-preserved of the Cordilleran ophiolites. Recent bedrock mapping approximately ~100 km southeast of Atlin, British Columbia, at Peridotite Peak (NTS 104K15), Menatatuline Range and Nahlin Mountain (NTS 104K16) shows that the ophiolite body is structurally disrupted and can be subdivided into two massifs: Hardluck and Menatatuline. Both massifs consist of fragments of oceanic lithospheric mantle intruded by gabbroic dike and sill complexes and lower crustal intrusions, voluminous mafic volcanic and volcaniclastic rocks, and sedimentary rocks. Spinel harzburgite and rare lherzolite samples of the Nahlin ophiolite peridotite are strongly depleted by melt extraction (<1 wt % $Al_2O_3$and ~45 wt % MgO). Inversion modelling of the clinopyroxene REE abundances in harzburgites yields ~10 – 20% melting, with melt compositions that are compositionally similar to the gabbro dikes ± sills, and volcanic rocks proximal to the ophiolite. All these magmatic rocks have an arc-signature, implying that the Nahlin ophiolite formed in a supra-subduction zone (SSZ) environment.

Preliminary results from 2Px and Ol-Sp Fe-Mg exchange thermometry imply along-strike variations in thermal history, with samples from Peridotite Peak recording consistently lower temperatures than samples from elsewhere within the ophiolite. Temperatures in the mantle increase towards the southeast in the Menatatuline massif, but towards the northwest in the Hardluck massif. Temperature-grain size relations for four different thermometers (2Px solvus, 2Px REE partition, Al-in-Ol and Ol-Sp Fe-Mg) having varying closure properties can be used to interpret this variable cooling history, which can be related to either mode of exhumation or position within the melt column. Spatial trends in the geochemical and geothermometric data can be used to examine whether the Menatatuline and Hardluck massifs originated as a single contiguous segment of mantle along a ridge, or as different segments brought into juxtaposition structurally.

A long term study of a oxidant injection into a fractured limestone aquifer

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A challenge with most injection and extraction contaminant mass reduction approaches is the back diffusion of the contaminants from low hydraulic conductivity zones in both unconsolidated and consolidated geologic media. A field study was conducted in a fractured limestone aquifer to evaluate the effect of an oxidant, persulphate, in addressing the back diffusion of petroleum hydrocarbon compounds. The study involved the injection of the oxidant, persulfate, on a periodic basis over a one-year time frame with the objective of maintaining a high concentration of the oxidant within a set of fractures, which would allow for the diffusion of oxidant into the limestone matrix. Injections were completed in both a non-impacted and an impacted area to allow comparisons of diffusion profiles. The results of the study indicated that persulfate diffused into limestone matrix in the both the non-impacted and impacted rock with the diffusion profiles extending further and lasting longer in the non-impacted matrix. The persulphate was degraded in both settings with degradation occurring significantly faster in the impacted matrix as expected. In the impacted matrix, persulphate was detected up to 3 months post injection but not 6 months post injection whereas persulphate was detected 6 months post injection in the non-impacted limestone matrix. The results suggest that a reaction front between persulphate and petroleum hydrocarbons could be created in the limestone after one year of periodic injections, however, the reaction front life span was less than 6 months suggesting that diffusion-controlled concentrations of PHCs would be re-established within the fracture after at least 6 months post injection.

Recovery of legacy marine geoscience data in the Great Lakes Basin: Application to Canada 3D

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The Great Lakes Basin in eastern North America covers about 765,000 square kilometres and encompasses the five Great Lakes and the surrounding lands of the province of Ontario and the states of Illinois, Indiana, Michigan, Minnesota, New York, Ohio, Pennsylvania, and Wisconsin. The lakes cover 244,106 square kilometres, representing 32% of the basin area. The Canada–United States boundary tracks along the major axis of four Great Lakes. One of the primary objectives of Canada 3D is to create a three-dimensional digital model of Quaternary sediment thickness and stratigraphy in the Canadian portion of the Great Lakes Basin. Knowledge of this sub-surface geometry would have many research applications, for example the elucidation of groundwater pathways that may extend across and beneath lake shorelines.

On land, geological mapping and borehole analysis provide insight into Quaternary sediment thickness and stratigraphy. Offshore in the Great Lakes, marine geoscience surveys provide comparable understanding. However, until recently, much valuable marine geoscience information collected by the Government of Canada in the Great Lakes has been unavailable for scientific analysis. During the 1960s and 1970s, Geological Survey of Canada staff at the Canada Centre for Inland Waters in Burlington, Ontario conducted geophysical surveys and geological sampling in the Great Lakes, with an emphasis on Lake Ontario. Although some of these data, existing only as hard-copy paper records and cores, have been lost over the intervening half century, significant quantities of these legacy data have been recently discovered.

The Lake Ontario legacy data comprise thousands of line-kilometres of high-resolution seismic reflection profiles that extend throughout the basin and – especially valuable to groundwater modelling – close to the northern and southern shorelines of the lake. The development of processing software at the Geological Survey of Canada–Atlantic enables scanned legacy seismic reflection profiles to be attributed with navigation and essential metadata. Once processed, these data are made web-available through Natural Resources Canada's Expedition Database and Google Earth.

Integration of the legacy geoscience data in this study with offshore surveys from the 1990s and published studies has highlighted exposed bedrock on parts of the lake floor along the north shore (Province of Ontario) of Lake Ontario. This erosional unconformity represents a break in groundwater flow paths within the Quaternary deposits. In contrast, paleo-valleys on the north shore and on the south shore (New York State) of Lake Ontario are infilled with thick sequences of Quaternary sediment, allowing uninterrupted groundwater transmission.

Till provenance across the terminus of the Dubawnt Lake Ice Stream, central Nunavut

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The composition of glacial sediments across the distal portion of the Dubawnt Lake Ice Stream (DLIS), central mainland Nunavut, was examined to assess the potential influence of fast ice flow on sediment transport. Major changes in clast content, texture and geochemical composition are observed in till collected throughout and beyond the ice stream footprint. The most significant changes coincide with an ice front position at the southern segment of the MacAlpine Moraine System which also marks the terminus of the ice stream. The till composition over the DLIS reflects a distal provenance, rich in Dubawnt Thelon Formation sandstone debris, relatively clay-rich, SiO-rich, and depleted in most trace and major elements. Although the SiO_2 content in the matrix (<0.063 mm) gives an indication of long glacial transport of exotic quartz sandstone from the Thelon Basin (up to ~80 km), it does not singularly reflect the Thelon component in the till because of the abundance of quartz-rich rocks in the local crystalline basement of the Thelon tectonic zone (TTZ). Instead, the till matrix clay content, related to the extent of erosion of poorly-indurated and clay-cemented Thelon Formation quartz-rich sandstone and/or sub-Thelon weathered regolith, and the ratio of total versus partial Sr concentrations, are better discriminators of basement versus Thelon Basin-sourced debris in till over the region. Total/partial Sr ratios below ~10 characterize till composition within the DLIS. Beyond the ice stream, till composition reflects more local sediment provenance, derived from the underlying basement rocks, and Sr ratios increase up to 24. Atypical clay contents in till, related to changes in till facies or stratigraphy, rather than changes in provenance, can have a significant influence on till composition and may complicate the interpretation of till geochemistry. This work has important implications for mineral exploration in the Rae geological Province of the Canadian Shield and areas affected by ice streams.

The identification of reworked sedimentary contexts and stratigraphic provenance of bones: A novel quantitative method for Pleistocene archaeological and palaeontological sites

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At many prehistoric sites, erosional processes rework and mix materials of different ages into the same sedimentary facies, producing time-averaged deposits. Archaeologists and palaeontologists must, therefore, consider and correct for this reworking when using natural stratigraphy to situate artifacts and remains in time. At Scladina Cave, a Neandertal site in Belgium, we developed a method based on the post-mortem trace element and crystallinity signatures of faunal remains to identify time-averaged contexts and the stratigraphic provenance of out-of-context bones. We analysed 62 faunal remains from throughout the site's sedimentary sequence with laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), X-ray diffraction (XRD), and Raman spectroscopy. Our novel approach for comparing intra-site variations in bone taphonomy, the 'First Spot Technique,' quantifies the trace element signatures (LA-ICP-MS) and crystallinity (Raman) from the most diagenetically altered part of the bone, along its periosteal surface, at high spatial resolution. These data are complemented by XRD crystallinity measurements that reflect average bone crystallinity at lower spatial resolution. Trace element concentrations, rare earth element patterns, and bone crystallinity are correlated for much of the Scladina sequence. These correlations systematically vary down stratigraphy between most sedimentary contexts. Based on where these relationships dissipate, we subdivided the Scladina sequence into four periods: two stages of early diagenesis, a transitional period, and a stage of later diagenesis. Linear discriminant analyses (LDA) were applied to the 'First Spot' data from adjacent sedimentary contexts in sets of two and three, both within and between the four diagenetic periods. Highly variable geochemical characteristics and crystallinity within a context, as well as poor discrimination by LDA between adjacent contexts, suggest reworking. The stratigraphic provenance of individual bones was evaluated by analysing descriptive canonical scores and predictive classification results (e.g., jackknifed classification matrices and Mahalanobis distances and probabilities). These tests consistently grouped bones either exhumed or likely reworked from the same context. Our method thus provides a valuable addition to archaeological analyses and is especially useful for verifying the integrity of assemblages exhumed from contexts that extend beyond the range of radiocarbon dating.

Sedimentary provenance of the Matinenda and Ramsay Lake formations in Drury Township using laser ablation detrital zircon analysis

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The Huronian Supergroup (HSG) was deposited between 2.2 to 2.4 Ga in a continental rift basin and is located along the southern margin of the Superior Province in Ontario, Canada. Recent bedrock mapping by the Ontario Geological Survey in the Sudbury area has identified a conglomeratic sandstone unit in the lower HSG that differs from the classic type sections of both the Matinenda and Ramsay Lake formations. This unit has tentatively been assigned to the Ramsay Lake Formation but proper classification is crucial to the subdivision of the HSG supracrustal rocks and understanding of structural deformation in the Sudbury area. The goal of this study is to assign the conglomeratic sandstone to its proper formation through the comparison of detrital zircon populations with Matinenda and Ramsay Lake formations. Previous provenance studies on the HSG have traditionally focussed on the Livingstone Creek, Matinenda, Mississagi, Serpent, Lorrain and Bar River formations. This study is the first to report detrital zircon data on the Ramsay Lake Formation.

Using LA-ICP-MS, 190 zircon grains with <10% discordance were analyzed: 1) 78 zircons from a "classic" Ramsay Lake Formation conglomeratic sandstone, Baldwin Township, 2) 63 zircons from a Matinenda Formation quartz arenite, Drury Township, and 3) 49 zircons from the conglomeratic sandstone tentatively assigned to the Ramsay Lake Formation, Drury Township. The resulting 207Pb/206Pb ages were used to create Probability Density Distribution Diagrams. The "classic" Ramsay exhibits a bimodal age distribution with peaks around 2730 Ma and 2680 Ma. These are characteristic peaks for much of the upper HSG formations and have been interpreted to be derived from early arc volcanism and accretionary magmatism and indicative of a Superior Province source terrane. The Matinenda, which is traditionally described as having a unimodal zircon population but in Drury Township the Matinenda contains an older population of Eoarchean age. This indicates that the Matinenda in the eastern portion of the Huronian Basin has sampled older more exotic terranes. The tentatively assigned Ramsay sample contains a much younger population of grains ranging from 2480-2580 Ma. Overall, results indicate that the tentatively assigned Ramsay zircon populations are distinct from that of the Matinenda. More importantly it is apparent that the detrital zircon populations within HSG rocks from Drury Township vary significantly from their counterparts in the western portion of the Huronian Basin.

Continental lithosphere was a warm blanket on the Archean Earth

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Models of the continental lithospheric thermal structure during the Archean often assume higher heat flux into the lithosphere from the asthenosphere than today. Heat preserved from the formation of the Earth, and higher heat production from higher concentrations of radioactive isotopes in the mantle, are commonly cited reasons for a hotter asthenosphere leading to higher heat flux into the lower lithosphere. However, the ability of rocks to conduct heat is temperature-dependent. Thermal diffusivity and conductivity both decrease as temperature increases, in most cases reaching minimum values near the rock's melting temperature. For mantle rocks, this effect reduces the potential for the lower lithosphere to accommodate high heat fluxes. Furthermore, the geothermal gradient within the lithosphere is highly sensitive to the concentration and placement of radioactive isotopes within the crust, as well as surface temperature and lithospheric thickness.

Here we present finite-difference models of purely conductive continental lithosphere, and show that higher heat production in the crust during the Archean led to lower temperature gradients in the lithospheric mantle. Consequently, heat flux from the asthenosphere was relatively low. In the literature, typical values of lower lithospheric heat flux during the Archean are assumed to have been between 20 to 40 mW/m^2 with higher values for the early Archean. However, our models show that this value was probably much lower: for a 100 km thick lithosphere with a 40 km thick crust, heat flux range from ~9 mW/m^2 at 3.5 Ga to ~17 mW/m^2 at 2.5 Ga. High crustal temperatures can still be achieved, even with low heat flux from the asthenosphere, as long as models account for the temperature-dependence of thermal diffusivity and conductivity. These results imply the ability of the Earth to cool conductively was reduced as continental lithosphere became more abundant towards the end of the Archean.

Hydrothermal alterations from Vulcano and Campi Flegrei volcanoes, Italy

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Vulcano and Campi Flegrei are two Holocene alkaline subduction zone stratovolcanoes related to the subduction / collision of Africa and Eurasia. Both volcanoes produce basaltic to trachytic ejecta displaying variable degrees of autometasomatism. The volcanic vapors at Vulcano reach up to 500°C, are acidic (pH ~ 1.6) and consist mainly of magmatic volatiles whereas the volcanic emissions from Campi Flegrei are lower temperature (< 150°C), neutral (pH ~ 6.6) and are dominated by heated meteoric fluids. The objective of this research is to construct a mass action model of the metasomatism observed at the two volcanoes in order to better constrain the mechanisms leading to variations in alkaline rock compositions. At Vulcano, the high-T alteration of trachy-andesites/trachydacites result in gradual silicification, hydration and sulfidation of the matrix glasses leading to the recrystallization of opal, cristobalite and sulfides. Whole rock analyses show that apart from SiO_2, all major rock-forming elements, all REE, most chalcophile (Cu, Zn, Pb) and most siderophile (Co, Ni, Mo) elements are remobilized during the alteration, while S, Cl, some chalcophile (Hg, Sn), some siderophile (W), some alkalis (Rb, Cs) and alkali-earth (Sr), actinides (U-Th) and HFSE (Zr-Hf, Nb-Ta) are gradually enriched. At Campi Flegrei, the low-T alteration of tephriphonolites/trachytes from the Solfatara crater result in opalization and cristobalization of the volcanic glass and minerals. The presence of alunite- and jarosite-like minerals result from episodes of K-S metasomatism which may have been effected by fluids hotter and more acidic that the ones which were sampled. The analyses of rocks showing increasing degrees of alteration suggest that alkali elements (Na-K-Li) were remobilized during silicification, and that K-Fe-S were enriched during de-silicification, potassic alteration and sulfidation, with the crystallization of alunite- and jarosite-like minerals. At Campi Flegrei the overall alteration result in the preferential depletion of heavy over light REE, the remobilization of HFSE (Th, U, Ta, Nb), and the enrichment in Pb, Ba and P. At both localities, the alkali-element budget is controlled mainly by the glass, but also by primary and/or secondary anorthoclase, nepheline and analcime. Laser ablation ICP-MS will be used to quantify the variations in alkalis and trace elements in primitive melt inclusions, variably altered groundmass glasses and tectosilicates, which should allow for greater insight into high-to-low temperature alkali autometasomatism common in magmatic-to-meteoric hydrothermal environments such as those encountered in intrusion-related metallic deposits.

Geochemical baselines and metal(loid) mobility in a changing northern climate

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In mineralized regions of Canada's North, accelerated climate warming may impact metal(loid) mobility and increase the concentration of arsenic in lake water and sediments. The influence of climate change on the mobility of arsenic is not well established, but has important implications for mineral exploration, environmental monitoring, and the development of remediation objectives. Tundra Mine, a former gold mine in the Slave Geological Province, Northwest Territories, produced arsenic-bearing tailings during two phases of mining in the 1960s and 1980s, resulting in contamination of downstream environment. The concentration and speciation of arsenic has been measured in four lake sediment cores spanning the Holocene period to examine arsenic mobility in both mining-impacted and un-impacted lakes over time. Microanalytical techniques, including X-Ray Absorption Near Edge Structure (XANES) and Mineral Liberation Analysis, have been applied in conjunction with a multivariate analysis of climate proxies (sediment organic matter, particle size analysis and inferred chlorophyll-A) to determine the influence of climate related variables on distribution and speciation of arsenic in regional lake systems. Results indicate that in shallow sediments, arsenic concentrations are higher in lakes proximal to the tailings impoundment (Bulldog Lake: 1,008 mg/kg, Powder Mag Lake: 270 mg/kg) as compared to a nearby un-impacted lake, Control Lake (224 mg/kg). However, in deeper pre-mining sediments, background solid-phase arsenic concentrations are higher in Control Lake (110 mg/kg). At depth, solid-phase arsenic concentrations are higher in lakes where porewater arsenic speciation indicates the presence of reducing conditions. An increase in arsenic concentration was observed in the shallow, near surface sediment of all lakes sampled. In lakes impacted by mining activities, this peak is associated with a change in dominant valence state from pentavalent arsenic (As^{5+}) at surface to more reduced forms of arsenic (e.g. As^{3+}, As^{2+}, As^{1-}) at depth which may correlate to the presence of arsenic-bearing sulphides. In Control Lake, this peak is not associated with a change in valence state and is instead dominated by pentavalent arsenic (As^{5+}) and may indicate the presence of arsenic-bearing iron oxide minerals. The occurrence of multiple solid phase arsenic species in the lake sediment downstream of the Tundra Mine, identified through combined XANES and electron microscopy analyses, suggests that sediment redox conditions are influencing the mineralogy and therefore mobility of arsenic within lake systems.

Paleoproterozoic metamorphism of the Thelon Tectonic Zone and margins of the Slave and Rae Archean cratons - insights into the nature and timing of the Slave-Rae Collision

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The Thelon Tectonic zone (TTZ), Nunavut, is a >500 km long geophysically, lithologically and structurally distinct N-NNE striking Paleoproterozoic boundary zone between the Slave and Rae Archean cratons. The central part of the TTZ comprises three ca. 2000 Ma charnockitic plutonic belts and a ca. 1910 Ma garnet-leucogranite belt with volumetrically minor enclaves of metasedimentary rocks and migmatites. A supracrustal belt of ultramafic to dacitic volcanic rocks and foliated metapsammites is located between the western and central plutonic belts. The Duggan Lake domain, located between the central and eastern plutonic belts, represents a package of Mesoarchean crust linked to the Rae craton. Paleoproterozoic metamorphism, which occurred throughout the TTZ and overprinted the Duggan Lake domain and the eastern margin of the Slave Province, is preserved within the study area, located 65-67 N and 104-107 W. Metamorphism is primarily upper-amphibolite to granulite-facies with lower to middle amphibolite-facies metamorphism occurring within the southern portion of the supracrustal belt.

The TTZ has been interpreted as a ca. 2.00 Ga continental arc on the western edge of the Rae craton, that was deformed ca. 2.00-1.90 Ga, from collision with the Slave craton ca. 1.97 Ga. Alternatively, the TTZ has been interpreted as an intra-continental belt, with the Slave-Rae collision occurring earlier during the 2.35 Ga Arrowsmith orogeny.

In-situ U-Pb dating of monazite defines at least four Paleoproterozoic metamorphic events. Metamorphism at ca. 1996 Ma, recorded in one high-grade gneiss from the central plutonic belt likely represents regional contact metamorphism associated with intrusion of ca. 2000 Ma plutons. Ages of monazite inclusions in garnet porphyroblasts across the study area, define prograde metamorphic ages of ca. 1962 Ma, possibly representing an early stage of continental collision. The most widespread and protracted event occurred ca. 1922 to 1883 Ma. This event is interpreted as the main compressional and anatectic event forming the extensive ca. 1910 Ma garnet-leucogranite belts. A few samples, located across the study area, record younger metamorphism at ca. 1814 Ma. This may represent post-collisional transpression coeval with movement along nearby regional-scale faults.

Monazite dating has provided no evidence for the 2.35 Ga Arrowsmith orogeny within the Thelon Tectonic Zone or the margin of the adjacent Slave cratons. Rather, the data set supports the interpretation of a 2.0 Ga continental arc followed by 1.97 Ga collision of the Slave and Rae craton with development of an orogenic belt ca. 2.0-1.9 Ga.

Aeromagnetic modelling of the sub-Athabasca basement

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The Athabasca Basin is a large-scale feature in the Canadian Shield of northern Alberta and Saskatchewan. This area is very well known as the location of much of Canada's high-grade uranium deposits. These deposits are typically unconformity-type in nature, and reside along the basement contact, underneath the Paleozoic sedimentary strata which make up the basin itself. Deposits are much more likely to be found in areas with "traps" that are structurally controlled, as well as reactivated fault systems. The pre-existing fault systems were reactivated into hydrothermal conductors, integral to the emplacement of the uranium ore by supplying deep groundwater. The overlying sediments across much of the basement can be more than a kilometer deep. Refining these basement structures, and fault systems, is beneficial for future exploration. The western basin in particular has seen much less exploration than the eastern basin, where sedimentary cover is thinner, and borehole data is now much more common.

The aim of this independent study is to analyze and interpret the publicly available geophysical data for a large area in the western basin, south of Lake Athabasca, and east of the Carswell impact structure. This area has thick sedimentary cover, generally over 1km in depth, therefore a better understanding of the Sub-Athabasca basement features is essential. Ground gravity surveys in the area are limited to a station spacing of approximately 12 km, which is not sufficient for the purposes of this study or any smaller scale basement geometry interpretation. An aeromagnetic and radiometric survey was flown in the area in 2010 with 400 m line spacing, and is the principle dataset used for analysis. This project involves the creation of a number of data enhancement products of the total magnetic field to understand the geometry of the Sub-Athabasca basement at depth. These data were compiled with pre-existing fault, dyke, and basement geology data provided by the Geological Survey of Saskatchewan. A first pass interpretation was performed from the integrated dataset. Subsequently, several cross sectional lines were selected on the map and modelled in 2.5D by means of using polygonal bodies of limited size across strike. The overall integration allows the construction of a 3D model of the basement, first as a number of sections compiled in 3D, and later as a grid of basement topography compiled from all the individual models.

The last gasp of the Skaergaard intrusion as recorded by zircon textures and trace element geochemistry

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The final stages of crystallization in layered intrusions associated with large igneous provinces (LIPs) are recorded by zircon textures and chemistry that reveal a range of crystallization environments in fractionated interstitial melts. The 56 Ma Skaergaard intrusion related to the >6 km-thick East Greenland flood basalts is a box-shaped 280 km^3 intrusion that cooled and crystallized as a closed system concentrically from the floor (Layered Series), roof (Upper Border Series) and walls (Marginal Border Series). Zircon from all major units occurs within either quartz, biotite, and Na-K-feldspar (±apatite, rutile) in interstitial pockets between primocrysts, or within quartz and K-feldspar granophyre patches near the center of the intrusion. Zircon is present in the Layered Series and Marginal Border Series as small (<70 µm) anhedral grains and typically sector- to oscillatory-zoned with a strong positive correlation between abundance and estimated trapped liquid contents from whole rock chemistry. Upper Border Series zircon is coarser (<150 µm) and significantly more abundant than in the Layered Series due to the overall enrichment in incompatible elements (e.g., Zr, Nb) in the upper part of the intrusion. A diverse range of zircon morphologies is present in the Upper Border Series, including euhedral zircon with stubby or prismatic terminations, coarse skeletal to hopper grains, and oriented clusters or acicular needles of zircon. Trace element concentrations determined by LA-ICP-MS of Skaergaard zircon are also highly variable (e.g., U = 27-2000 ppm; Hf = 6000-22,000 ppm; Ti = 0.6-60 ppm). Using Ti-in-zircon thermometry, estimated crystallization temperatures range from approximately 825°C (initial zircon saturation) down to 600°C (solidus conditions). Layered Series zircon is increasingly enriched in incompatible elements (i.e., Hf) with decreasing temperature consistent with fractional crystallization from evolved interstitial melt. In contrast, skeletal zircon from the Upper Border Series does not show such simple trends, which is interpreted to be due to non-equilibrium crystallization during undercooling and rapid crystallization. Zircon textures and chemistry indicate that the crystallization environments near the solidus of the Skaergaard intrusion were remarkably diverse, being locally influenced by melt chemistry, porosity, cooling rate, and degree of undercooling. The crystallization paths of fractionated interstitial melt recorded by the textures and chemistry of zircon in the Skaergaard intrusion are distinct compared to those determined for larger, open-system layered intrusions (e.g., Bushveld Complex, Stillwater Complex).

(U-Th)/He thermochronology of the Aishihik batholith, central Yukon: Resolving Cretaceous tectonism

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The 190-180 Ma Aishihik batholith is the largest within the main belt of late Jurassic plutons in the northern Cordillera, and is thought to stitch assemblages of the Yukon-Tanana terrane with the Stikine terrane. Assessing the thermal history via zircon (ZHe) and apatite (AHe) (U-Th)/He thermochronology of samples from the Aishihik batholith against those of Paleozoic to Mesozoic host rocks can provide insight into the low-temperature (>200°C) window of Jurassic-Cretaceous tectonism and crustal exhumation. In particular, we are interested in the northwest margin of the batholith which has been purported to be a tectonic contact. We analyzed sixteen plutonic samples that possess a single population of zircon and apatite grains (demonstrated by typical igneous zoning and lacking metamorphic overgrowths). Single crystal zircon dates from individual samples show age dispersion by 200 m.y. with a positive to negative correlation as effective uranium (eU) concentration increases, as predicted by diffusion theory. Samples are grouped into three categories based on geographic location and rock type, and each set illustrates a differing thermal history. Within the first group, numerical modeling of the He data in the southeast portion of the study area, within the Aishihik batholith, suggests relatively rapid (~10°C/m.y.) cooling immediately after emplacement of the batholith. Majority of the batholith cooled by the Late Cretaceous, coinciding with the Carmacks unconformity, however some data suggests that the centre of the batholith cooled earlier (Early Cretaceous), which overlaps with the Mount Nansen unconformity. Comparatively, adjacent Yukon-Tanana terrane rocks exhibits slower (~2°C/m.y.) cooling from the Permian to the Early Cretaceous followed by very rapid (~15°C/m.y.) cooling in the Late Cretaceous. The second group in the central area displays steady cooling (~5°C/m.y.) until the Early Cretaceous then slower cooling (~2°C/m.y.) until it reaches the surface in the Late Cretaceous. The third group in the northwest exhibits slow (~2°C/m.y.) cooling until the Early Cretaceous proceeded by rapid (~15°C/m.y.) cooling in the Late Cretaceous. Recent mapping suggests that the northwestern margin of the Aishihik batholith is an intrusive contact, which has implications for the level of crust that is preserved from Jurassic time. This research adds to the network of thermochronologic data in exploring Cretaceous crustal exhumation and tectonism of the Yukon Cordillera compared to the Alaskan and British Columbia Cordillera, which recorded Eocene exhumation signatures. Increased understanding of low-temperature tectonothermal history can allow for better understanding of shallow crustal processes and their relationships to adjacent metal-bearing regions.

3D regional geological modelling in structurally complex and data sparse environments: Benefits, challenges and strategies from the northern Labrador Trough, Kuujjuaq, Quebec

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Characterization of deformation and visualization of regional geologic architecture is crucial to understanding a region's tectonic history. This is best accomplished by creating three-dimensional (3D) models of significant regional features where data can be visualized and geological theories can be tested in a 3D framework. Additionally, 3D models serve as expedient communication tools which make complex geology accessible to laypersons, managers or investors. The challenge is correctly representing geological features using available data and technology. This study focuses on developing a 3D regional model, constrained by data and interpretive points, in the northern Labrador Trough near Kuujjuaq, Québec while highlighting the benefits, challenges and strategies of creating regional-scale 3D models in structurally complex terrains with sparse 3D data. The most significant challenge is sparse data at depth. This is a common issue for regional studies as drill core and geophysical methods may not detect crustal-scale features. With minimal depth constraints, 3D modelling becomes an exercise in interpretation, interpolation and extension, applying similar practices used in making 2D maps. Another challenge inherent to any modelling effort is complexity; as complexity increases, the resolution of the model must increase to accurately sample the feature. Uncertainty estimation is also an area of concern since it is difficult to quantify while integrating multiple data sources and geological interpretations. Moving forward, uncertainty estimation techniques will become important for evaluating model accuracy. Finally, the time-consuming nature of modelling impedes the creation of multiple model solutions, limiting theory development and testing. Often there are several solutions that fit the data and all should be considered. Without the ability to compare each solution side-by-side, confidence in the final model is diminished.

Innovative approaches to leveraging public geospatial datasets will be needed to enhance regional exploration strategies and improve geological insight, especially for regional studies where private exploration would be prohibitively expensive. Developing models in complex areas such as the northern Labrador Trough is an essential step in the process of better defining future workflow requirements, algorithm enhancements and knowledge integration that will be needed to achieve a geologically reasonable modelling standard in both simple and complexly deformed regions.

Reconstruction of the metamorphic P-T-t path of garnet-bearing rocks from the Snowcap Assemblage in the Stewart River area, west-central Yukon

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The Snowcap Assemblage is the basement unit of the Yukon-Tanana terrane and has experienced diachronous metamorphism from the Permo-Triassic to the mid-Cretaceous. We investigate the metamorphic conditions experienced by amphibolite-grade garnet-biotite-ilmenite metapelitic schists from the Snowcap Assemblage in the Stewart River area using the compositional zoning of garnet for metamorphic P-T-t path reconstructions.

There is textural evidence for three phases of deformation and up to two phases of metamorphism experienced by the rocks. S(M) forms a mica foliation that wraps around garnet porphyroblasts. S(M-1) forms a crenulation cleavage, and S(M-2) forms a previous mineral foliation, with both being only observed as inclusion trails and patterns within garnet porphyroblasts. Two distinct growth zones of garnet observed in one sample are evidence for at least two phases of metamorphism. A first garnet generation forms the cores of garnet porphyroblasts in this rock and is separated from the rim-forming second generation by a microstructural discontinuity.

Selected samples were further examined using X-ray micro-computed tomography in order to quantify the 3D size and shape distribution of garnet in the rocks investigated. Compositional profiles of garnet were then obtained across the centers of the largest crystals in each sample. Garnet crystallization modeling applied to a key sample using the THERIA_G software indicates a P-T-t path of garnet crystallization with a varying heating rate and peak metamorphic conditions of 667°C and 6.8 kbar. The proposed heating rate is 20°C/My from 500°C to 650°C, followed by a slower heating rate of 0.85°C/My from 650°C to 667°C. This heating rate is necessary for the simulation to account for significant amounts of intracrystalline diffusion in garnet required to reproduce the observed garnet compositional zoning. Crystallization of garnet in this rock occurred during or after the S(M-2) and S(M-1) deformation events, but prior to the formation of the S(M) foliation. The sample used for P-T-t path modelling does not contain polyphase garnet crystals. Preliminary analysis of the polyphase garnet-bearing sample suggests that it followed a similar P-T-t path as suggested above for the growth of the first garnet generation, followed by a separate metamorphic event for the second garnet growth phase.

Past Great Lakes water level fluctuations elucidated by the sediments of the Ipperwash strandplain, southern Lake Huron

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The Laurentian Great Lakes are the largest system of surface freshwater on Earth and home to over thirty million people. People living in and around the Great Lakes rely on consistent or at least predictable lake levels. However, lake levels fluctuate on various time scales and magnitudes potentially changing the coastal zone into a more erosional or depositional system, influencing local communities. Investigating natural drivers of lake level change such as climate, glacial isostatic adjustment, and lake outlets are important to provide the context for present conditions and to develop future realistic scenarios. Strandplains record past lake levels in a lateral chronosequence of beach ridges and allow for the development of a site-specific paleohydrograph. This study examined the Ipperwash strandplain, southern Lake Huron, which mimics lake conditions experienced at the outlet because Ipperwash is the closest, most detailed strandplain to the Port Huron/Sarnia outlet. Lake level fluctuations over the past 3500 years were reconstructed to create an outlet referenced paleohydrograph. This unique outlet referenced Ipperwash paleohydrograph is essential to reconstruct lake levels for the entire Lake Huron basin. Forty vibracores were collected from individual beach ridges in the Ipperwash strandplain. Cores were visually described, photographed, sampled and preserved to define shoreface, foreshore and dune facies. Foreshore deposits are typically composed of very fine to medium sand with horizontal to lakeward dipping laminae and abundant medium to coarse grain mineralogic and shell fragments. The depth to the shoreface-foreshore contact is calculated and used as a proxy for lake level when that specific beach ridge formed. A total station was used to determine the elevation of the ground surface at the core location so an elevation of the ancient lake level could be calculated relative to the International Great Lakes Datum 1985. Soils pits were dug on every third to fifth beach ridge to collect sediment samples for optically stimulated luminescence (OSL) dating. An age model was developed to estimate the age of beach ridges in the Ipperwash strandplain. Results show beach ridges formed, on average approximately every 58 years with the oldest ridge dated to approximately 3500 years old. With measured elevations from vibracores and modeled OSL ages, a paleohydrograph for the Ipperwash strandplain was created. This new paleohydrograph is the most detailed record of conditions experienced at the outlet for modern Lake Huron and past lakes occupying the upper Great Lakes (Superior, Michigan, Huron) basins over the past several millennia.

The Zircon and Accessory Phase Laboratory (ZAPLab); A Canadian advance in nano- to atom-scale geochronology applied to resource and planetary evolution

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The Renaissance scientist Niels Steensen (Steno) deduced relative geologic time from crystal forms and positional relationships of mineral surfaces, fossils and strata. This ‘spatial’ geochronology was complemented more than two centuries later with the advent of the atomic age, radiometric dating and eventually U-Pb isotope geochronology; a field advanced greatly by Canadian university and GSC scientists. Key to the accurate interpretation of all radiometric measurements is the knowledge of the open vs. closed nature of the system and of any history of diffusive loss or gain of parent or daughter isotopes. For U-Pb geochronology, such evaluations must take place at the scale of a single crystal and sometimes crystal lattice. This has now become possible through recent developments in materials science instrumentation enabling nano-scale to atom-scale imaging of the deformation microstructure and trace element distributions in minerals. The Zircon and Accessory Phase laboratory was conceived and developed in Canada to integrate such spatial and radiometric geochronology information and apply nanoscience methodology to the Canadian Shield, its ore deposits, impact crater sites, and meteoritic material from other bodies in the Solar System (e.g. Tagish Lake). Electron nanobeam techniques such as electron backscatter diffraction (EBSD) and multi-spectral cathodoluminescence (CL) have proven particularly useful along with novel instrumentation such as laser-assisted atom probe tomography (APT). The marriage of these nanoscience techniques with measurements at partner facilities in Canada (e.g. ROM, GSC, University of Alberta, CCEM McMaster University) and internationally (e.g. UCLA, University of Portsmouth) has produced important gains in geochronology information. These include the age of resource formation events such as ore-modifying shear zones in the Sudbury impact structure, iron ore enrichment in the Baffinlands camp, and the crystallization history of Superior Province gold grains. Advances in planetary evolution include the impact history of young martian (0.2 Ga) to ancient (>4.4.Ga) lunar, martian and asteroidal crusts. Configurations of U and Pb atoms, ‘chronostructures’, have recently been discovered and enumerated in Earth’s oldest zircons, and in baddeleyite crystals exposed to intense shock metamorphism in some of Earth’s largest craters in both Canada and South Africa. These and other case studies will be presented as part of an overview of new Canadian facilities, methodologies and the growing opportunities for nanoscience applications to resource and planetary evolution.

Mountain lakes: Eyes on global environmental change

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Mountain lakes are often situated in wilderness areas with high intrinsic value, are important water resources for adjacent lowlands, and provide oases to harbour biodiversity. But equally important, these lakes are sentinels of global environmental change. Despite variations in latitude, mountain lakes are comparable across continents, potentially allowing for a global assessment of environmental issues. Usually remote, mountain lakes have been, until recently, considered pristine and relatively untouched by human activities. A growing body of research, however, is showing that remote mountain lakes are recording the effects of humans on Earth's environments at global to regional scales. Some of the environmental changes recorded include changes in dust composition and deposition, climate warming, atmospheric fertilization, and changing biogeochemical cycles. These factors, however, do not necessarily act independently, and a greater understanding of the climate interactions on biogeochemical processes can be gained from the growing number of proxies available. Paleolimnological research at a suite of lakes in a spatial network could also increase our knowledge of such interactions. For example, steep climate (temperature and sometimes effective moisture) gradients in mountain regions provide the unique opportunity to determine the effects of environmental change on lakes at varying climate starting points across short geographical distances. These studies can further benefit from pairing with other data sets, such as continuous, high frequency limnological measurements that track present changes, and provide a basis for interpretation of proxy data. Challenges now will be to amalgamate and synthesize diverse regional mountain data sets to create a global data base for contributing to global environmental issues. Mountain lakes provide a unique opportunity for global scale assessments of processes that are key to protecting biodiversity, water resources and our last wilderness areas.

Revisiting the role of shear heating in Himalayan inverted metamorphism using thermo-mechanical models

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Whether shear heating can rise temperature significantly in ductile- and brittle shear zones have been worked out. Recent works on whether shear heating can produce inverted metamorphism in different tectonic settings is contradictory. The classic channel flow model presumes a single thermal conductivity magnitude of 2 W m^{-1} K^{-1} for the entire Greater Himalayan Crystallines (GHC). However, zooming in, along few river sections in India and Nepal, the GHC can be divided into a southern schistose/non-migmatitic and a northern migmatitic/granitic melt unit. The southern unit especially contains other rock varieties, either as consistent layers or as inclusions. This work utilizes these lithological heterogeneities of the GHC as much as possible and produces shear heat models for ductile shear, based on our previous works. These models follow the first order tectonic constraints of the GHC and presume a Newtonian rheology. The input parameters are: (I) thicknesses of the entire GHC/individual layers, (II) pressure gradient for Poiseuille flow through inclined channel, (III) density, (IV) dynamic viscosity and (V) thermal conductivity of rocks. Parameters III to V have some overlap in range of magnitudes for individual rock types. The thermal profiles show where in channel maximum heating takes place, and that location is compared with the prototype GHC. The models also demonstrate how much thermal/shear heat profiles vary by modifying the magnitudes of parameters I-V corresponding to varieties of lithologies within the prototype GHC. Refining shear heat models in other collisional terrains would also be interesting to work out.

Drumlinized tunnel valleys in Simcoe County, southern Ontario

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A network of valleys deeply incise thick successions (up to 200 m) of Quaternary sediment across south-central Ontario. The valleys have previously been interpreted as an integrated network of tunnel channels recording catastrophic releases of subglacial meltwater across the former bed of the Laurentide Ice Sheet. Recent groundwater mapping investigations in the southwestern parts of the valley network integrate surficial sediment and morphological data, continuously-cored borehole data (penetrating the entire Quaternary sediment succession in valleys as well as intervening uplands), and marine- and ground-based geophysical data that provide new insights and a possible reinterpretation of the timing, genesis, and paleoglaciological significance of these valleys.

Valleys within the study area are some of the largest observed within the regional network – up to 30 km long, 9 km wide and >175 m deep. They are oriented north-south or in a radial pattern, varying from NE-SW in the southern part of the study area, to ESE-WNW in the north. An undulating Late Wisconsin till sheet (Newmarket Till) caps the regional uplands, and is commonly observed along the flanks and within the valley floors – all of which show evidence of contemporaneous drumlinization. The valleys display cross-cutting relationships, with abrupt valley heads and locally perched downflow ends. Radiocarbon age determinations of organic material from below and above the Newmarket Till constrain the timing of valley excavation to after 28.05 and before 12.81 14C kyr BP. Borehole and outcrop data indicate that Newmarket Till within the valley floors is commonly underlain by deformed substrates. The till is incised in parts of some valleys and they are infilled locally with coarse-grained gravels that pass upwards into sands and thick successions of glaciolacustrine sediments.

Valley development likely spanned much of the Late Wisconsin in the study area. Meltwater surpluses would have been generated at the ice-bed interface due to a low-transmissivity substrate, with flows preferentially routed into lows on the bed. Downward incision into confined and pressurized subglacial aquifers likely initiated rapid headward erosion, enhanced by piping. Waning meltwater flow velocities/discharges allowed ice creep to re-fill newly-formed valleys, permitting renewed till deposition and subsequent drumlinization of the valleys. Valleys also provided efficient routing for meltwater draining the retreating ice marginal zone during deglaciation, and allowed localized sand and gravel deposition as eskers and ice-proximal fans in proglacial lakes. This integrated dataset represents one of the most complete characterizations of subglacial valleys in a terrestrial setting in North America.

New insights on ice dynamics in central and eastern Ontario from the spatial arrangement and morphology of glacial landforms

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Regional-scale, high-resolution (5 and 2 m cell size) terrain data sets provide an opportunity to study late glacial ice dynamics through remote terrain analysis across a large area of south-central Ontario where the bed of the former Laurentide Ice Sheet is well-exposed. Mega-scale glacial lineations (MSGL) and mega grooves are eroded into Precambrian bedrock and patches of streamlined till in the Algonquin highlands. Long axis orientations of MSGL on shield terrain are NNE-SSW in central areas, and display a curvilinear track in the east, along the axes of the Ottawa and St. Lawrence River valleys. Downflow, MSGL pass into juxtaposed rock and drift drumlins on Paleozoic bedrock terrain. The Lake Simcoe Moraine(s) can now be traced more than 80 km across the Peterborough drumlin field (PDF) and marks a significant change in properties of streamlined bedforms in the PDF. South and west of the moraine system, drumlins are generally large and broad, showing no indication of subsequent reworking by the ice. North and east of the moraines, streamlined features show a higher degree of complexity in bedform pattern and morphology – discrete flow sets terminate at subtle till-cored moraine ridges, indicating multiple phases of ice flow with strong local topographic steering. Near the Lake Ontario basin in the south and east, more regional-scale flow switching is evident as NW oriented flutings and grooves modify drumlins south of the ORM, and radial flow sets emanate from the St. Lawrence valley.

These high-resolution terrain data provide an unprecedented look at the morphology and patterns of glacial landforms in southern Ontario. Landform relationships suggest significant reorganization of ice sheet/stream dynamics towards the end of the Late Wisconsin Episode. Most of the drumlins formed during an early, regional drumlinization phase of NE-SW flow that followed the deposition of a thick regional till sheet. These large, broad drumlins were subsequently modified by multiple younger, local-scale, topographically-controlled flow sets that terminate at till-cored moraines, providing conclusive evidence that the superimposed bedforms were eroded into the older drumlins by active ice advances throughout deglaciation.

A tectonic history of the Meliadine Gold Trend, Nunavut from aeromagnetic data modelling and interpretation

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The Meliadine Gold Trend is a series of iron-formation hosted orogenic gold deposits in the Kivalliq region of Nunavut. Gold mineralization is spatially associated with the 80km long Pyke Fault. Multiple deformation events have been recognized at Meliadine with D_1 to D_3 being related to events of gold mineralization and remobilization whereas D_4 has been recognized as not being related to gold mineralization. Outcrops in the Meliadine area are scarce, so interpretations of structure and lithology have predominantly been made from geophysical surveys and extensive drilling.

In 2009, an aeromagnetic survey was conducted by EON Geoscience Inc. over the Chesterfield block on behalf of Natural Resources Canada. Block C of this survey covers the Meliadine Gold Trend and consists of over 28,000 line-kilometers that were flown with a 400m line spacing. Total magnetic intensity and other interpretation grids were generated at 100m cell size with various filters and transformations which were then used to interpret structure and lithology of the area. The interpretation included determining the relative age and order of all structural features from cross cutting relations. This allowed for the construction of several cross sections in 2.5D, with dip directions being obtained from modelling the magnetic data. The cross section lines were carefully selected with the intention of integration into a final pseudo-3D model. This model provides insight into the contributions of different generations of faulting and folding present in the Meliadine area in a way that can help understand the tectonic history of the area for regional studies as well as mineral exploration.

Keynote (40 min): The LIP record on the rifted margins of the Superior Craton

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The Superior craton existed as a continent apparently entirely surrounded by passive margins for an extended period during the Paleoproterozoic. It is commonly supposed that rifting of continents is driven by mantle plume activity that generates large igneous provinces expressed as combinations of dike swarms, sill-sediment complexes, layered intrusions and flood basalts. Apart from voluminous bimodal intrusive and extrusive activity in the Sudbury region, most of the perimeter of the Superior craton formed in the absence of underlying mantle with anomalously high potential temperature, leading to the development of classic non-volcanic rifted margins. These margins are associated with relatively minor dike swarms whose relationships with the rifting events remain unclear because it is not known exactly when rifting occurred. After the accumulation of thick clastic sequences there were at least four major episodes of mafic to ultramafic magmatism, each of which was felt at widely spaced points lining much or all of the margin of the continent. The first occurred ca 2170 Ma and is expressed as gabbroic sills in the southern Labrador Trough (2169 Ma Cramolet sills) and the Otish basin (2169 Ma Otish gabbro) that correlate with the major intracratonic Biscotasing and Payne River dike swarms. At 2142 to 2038 Ma mafic sills were emplaced in the Cape Smith belt while komatiite, basalt, and rhyolite were erupted in the Labrador Trough. These latter were largely removed by erosion before deposition of the dolomitic Denault Fm in the Labrador Trough. The Povungnituk Group basalts were erupted ca 1991 to 1970 Ma in the Cape Smith Belt. Shortly prior to closure of the ocean a major plume event ca 1880 Ma caused the intrusion and eruption of picritic magmas around the entire western, northern, and eastern margins of the craton. Members of this LIP include the Thompson Nickel Belt, Fox River Sill, Belcher Islands volcanics, Chukotat Group and related feeder dikes in the Cape Smith Belt, ultramafic sills and komatiitic to basaltic lavas of the Roberts Lake Syncline, and the Hellancourt basalts and Montagnais sills of the Labrador Trough. This latter LIP spawned magmatic sulfide deposits throughout its length, of which the Thompson Nickel Belt, Raglan, and Expo suites have been mined. Most magmatism along the Superior passive margin sequence was related to spreading of mantle plume heads under thinned marginal lithosphere long after the initial non-volcanic rifting event was complete.

Late-tectonic magmatic-hydrothermal systems of Abitibi: Contribution of regional-scale fluid reservoirs to the Duquesne, Dolodau, Lac Shortt and Canadian Malartic gold deposits

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The Archean Eon was the most important period for the genesis of gold deposits, with approximately 60% of the world's gold depositing before 2500 Ma. Although orogenic gold is the most common type of Archean gold deposit, accounting for 18% of the world gold production, 40% of the gold deposits located within the Abitibi greenstone belt of the Superior Province, Canada, are spatially associated with felsic to intermediate intrusions, and a significant part of these deposits was previously demonstrated to be genetically associated with late-tectonic calc-alkaline to alkaline, monzonitic to syenitic intrusions. In the Superior Province, there is a frequent association between gold deposits, late-tectonic syenites and lamprophyres. Interestingly, some of these syenites were interpreted to have evolved from lamprophyric magmas, and lamprophyres, like syenites, commonly host hydrothermal carbonates. Duquesne and Canadian Malartic gold mines are used here as examples of intrusion-related gold deposits associated with syenites and lamprophyres. Furthermore, syenites are commonly found in association with carbonatites, and the association is known to host significant concentrations of gold at Lac Shortt and Dolodau gold deposits, Canada, which are here taken as examples of intrusion-related gold deposits associated with carbonatites and syenites. This study reports new trace elements concentrations, $\delta^{13}C$, $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ for hydrothermal and magmatic carbonates from carbonatites, lamprophyres, syenites and ores from the four intrusion-related gold deposits. These results show that the carbonates Sr/Ba and Sr/Mn trends correspond to their $^{87}Sr/^{86}Sr$ values, suggesting that the Archean depleted metasomatized mantle was the host of a regional-scale, high Sr/Ba – Sr/Mn fluid reservoir, and that the Archean metasomatized lower- and upper-continental crust hosted similar-sized fluid reservoirs of medium and low Sr/Ba – Sr/Mn ratios. Carbonatite-syenite-related Lac Shortt and Dolodau gold deposits have high Sr/Ba – Sr/Mn, depleted mantle-like $^{87}Sr/^{86}Sr$ and high Ba-Sr-REE carbonates, suggesting that the magmatic-hydrothermal systems were rooted in a carbonated-, metasomatized-, sub-continental depleted mantle. By contrast, syenite-lamprophyre-, and non-carbonatite-related Duquesne and Canadian Malartic gold deposits hosted medium- to low Sr/Ba – Sr/Mn carbonates, pointing toward the contribution of lower- and upper crustal fluids. Finally, the results show that ore-related carbonates from the four intrusion-related gold deposits plot within a limited intrusion-related gold deposit $\delta^{13}C$ – $\delta^{18}O$ box which should impact the prospectivity of Archean gold deposits.

The ins and outs of Ediacaran discs

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Abundant discoid fossils referable to Aspidella and rarer specimens of Eoporpita and Hiemalora occur in the Ediacaran "June beds" deposits of the Mackenzie Mountains, Northwest Territories, Canada. These specimens uniquely allow for careful observation of highly detailed fossil discs, including cross- and thin-sections to observe features of the preserving sedimentary beds. Among them are specimens that preserve partial stem imprints, supporting recent interpretations of Ediacaran discs relatable to Aspidella as the basal holdfast structures of fronds. The range and morphological transitions among the June beds specimens accounted for by taphonomy have implications for our recognition and classification of Ediacaran discoidal fossils. Details of the structure and fill of Ediacaran discs in the June beds of NW Canada are not consistent with the prevailing interpretation that Ediacaran discs functioned solely for attachment of fronds to the sea bottom, and instead imply that these discs served multiple biological functions essential to the growth of their attached fronds.

Celebrating geoheritage: Canada's newest UNESCO World Heritage Site, Mistaken Point, NL

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Mistaken Point is a globally significant fossil site in SE Newfoundland that was inscribed on the UNESCO World Heritage List in July of 2016. Mistaken Point represents Canada's newest UNESCO World Heritage Site, and additionally is the first Precambrian fossil site anywhere in the world to achieve UNESCO World Heritage status. Mistaken Point fossils mark a critical milestone "when life got big" 570 million years ago after three billion years of mostly microbial evolution. Mistaken Point organisms lived on the deep-sea floor, and were killed and preserved in exceptional detail when they were catastrophically covered by beds of volcanic ash. Each layer of ash created an "Ediacaran Pompeii" of literally thousands of Ediacaran fossils that are easily visible and available for study on the tops of the mudstone beds. Looking down on a Mistaken Point fossil surface is like snorkeling over a 570 million-year-old sea bottom. Mistaken Point fossils range up to nearly two meters long and contains the world's oldest-known examples of large, architecturally complex organisms. Most of the fossils are rangeomorphs, an extinct group of fractal organisms that dominated the world's oceans before the beginning of the Cambrian. These soft-bodied creatures died where they lived when they were buried by ash, thus preserving their community structure and permitting use of modern methods in ecological analysis on fossils more than half a billion years old. Other attributes of Mistaken Point's Outstanding Universal Value include exceptional potential for radiometric dating of the assemblages and evidence for the role of ancient oxygen levels in the regional and global appearance of complex multicellular life. Achievement of UNESCO World Heritage status took twelve years from its inclusion on the Canadian Tentative List for World Heritage in 2004 until its ratification by UNESCO in 2016. Ecotourism at Mistaken Point has been an important part of the local economy of the communities that border on Mistaken Point, and this is expected to increase significantly with its recognition as a UNESCO World Heritage Site.

External controls on the evolution of stratal architecture in the transition from basin floor to slope, Neoproterozoic Windermere turbidite system, southeastern Canadian Cordillera

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Deep-water strata in the southern Canadian Cordillera preserve a conformable succession from sheetlike basin-floor (Upper Kaza Group) to slope channel deposits (Isaac Formation). At the large scale (i.e. several 100s m thick, >1-10s km laterally), abrupt changes in grain size, volume and/or mineralogy, stacking patterns and architectural styles are interpreted to reflect changes in sediment supply linked to long-term (3^{rd}-order) changes of relative sea level (RSL).

The lower part of the succession is mostly siliciclastic and composed of three stacked channel-lobe systems (CLS) formed in the basin-to-slope transition. The lowermost CLS is detached, with a well-developed transition zone separating downdip lobes from updip feeder channels. It consists of large amalgamated and small isolated scours, fine-grained deposits and less common distributary channel-dominated lobes, and coincided with a coarsening of sediment supply caused by a fall of RSL. The overlying middle CLS is attached, comprising small isolated scours that locally incise distributary channels, fine-grained deposits and uncommon splays, and is capped by an anomalously-coarser leveed-slope channel complex with well-developed lateral accretion deposits. The dramatic change in grain size and stratal architecture is a consequence of transgression and the selective landward transport of sand leaving a residuum of coarse mixed with easily transported fine sediment. The uppermost CLS is detached and includes small and large isolated scours and distributary channels filled with calcareous sandstone. Significantly, the occurrence of detrital carbonate indicates the activation of a mixed siliciclastic-carbonate system during continued rise of RSL and the eventual onset of highstand conditions.

The middle part of the succession is mainly siliciclastic and dominated by mass-transport deposits (MTDs) overlain by fine-grained deposits and local channel deposits. These MTDs indicate an episode of enhanced slope instability followed by more stable slope conditions, and respectively, falling followed by lowstand conditions.

The upper part of the succession is represented by the first Isaac carbonate or FIC, a regional marker horizon composed of thick fine-grained calciturbidite units, commonly intercalated with siliciclastic-rich fine-grained strata, recording episodes of voluminous production and export of carbonate sediment onto an otherwise siliciclastic-dominated slope during long-term rising RSL. Superimposed on this trend are short-term episodes of lowered RSL marked by slope channels filled with carbonate-cemented coarse-grained siliciclastic strata mixed with common to abundant carbonate fragments. The FIC is then erosively overlain by a siliciclastic-filled channel complex denoting the termination of carbonate production and reinitiation of long-term coarse-grained siliciclastic delivery to the basin during a major lowstand.

Automated optical gold grain counting: A quantum leap

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Counting gold grains in glacial drift is a well proven exploration technique. However, it is limited by the size of grains that can be recovered and observed, experiencing a recuperation collapse below 50 µm. Compilation of hundred of ore petrography studies indicates that gold grains smaller than 50 µm represent in excess of 90% of the grains in rocks. Therefore, concentrating observation on the smaller fractions will improve accordingly the efficiency of the method. A dependable counting of very small particle is beyond the realm of human skill and requires automation. An automated SEM based routine has recently been developed, and the effectiveness of which has been demonstrated by recent exploration success. However, the method requires long scanning time with the SEM, which limits throughput. To circumvent this limitation, a recognition technique was developed based on image processing and interoperability between optical microscope and SEM. Gold has a quite distinctive reflectance spectrum, with an abrupt drop at wavelength below 500 nm, which has been measured as constant despite surface texture and not sensitive to silver content. First, fine <-50 µm concentrate are dusted on custom built sample holder. The concentrate is scanned with an apochromatic binocular microscope equipped with motorized stage and RGB high resolution camera. Gold grains are identified down to about 10 µm, with about 95% success, and 60% false positive. Scanning is performed in about 20 minutes. Sample holder is then transferred to a petrographic microscope equipped with a video stream multispectral camera based on 11 spectral pass bands from 475 nm to 650 nm (blue through red) and a motorized stage. The application software is applied to each grain, a multispectral image is acquired and the presence (or absence) of gold is then confirmed. The system produces five interpreted frames per second. The total scanning time depends on the number of grains identified in the previous step but typically lasts a few minutes. More than 95% of the gold grains are correctly identified. Identification errors occur if gold grains are coated by iron oxide or other coating material. High magnification images are concomitantly acquired for reporting purposes. The sample holder is then transferred to an automated SEM, where grains are relocated, analyzed with EDS-SDD and high magnification image acquired.

Geochemical controls on vanadium mobility in oil sands fluid petroleum coke deposits

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Bitumen upgrading in the Athabasca oil sands region (AOSR) of northern Alberta, Canada generates large volumes of petroleum coke. This carbonaceous upgrading by-product contains elevated concentrations of S and a host of minor and trace elements. Consequently, there is a limited market for oil sands petroleum coke and it is stockpiled in large deposits at mines in the AOSR. These stockpiles will eventually be integrated into mine closure landscapes; therefore, the mobility of minor and trace elements is an active research topic. This study examined geochemical controls on V mobility in two fluid petroleum coke deposits at an oil sands mine in the AOSR. Continuous core samples were collected at several locations within both active and reclaimed fluid petroleum coke deposits. Corresponding multi-level monitoring wells were installed adjacent to most coring locations. Overall, the sampling locations encompassed a range of redox conditions within both active and reclaimed coke. Bulk elemental analyses revealed that coke solids were dominated by C (84.2 ± 2.3 wt%) and S (6.99 ± 0.26 wt%). Elevated concentrations of Si (9210 ± 3000 mg/kg), Al (5980 ± 1200 mg/kg), Fe (4760 ± 1200 mg/kg), and Ti (1380 ± 430 mg/kg) were also observed. Vanadium (1280 ± 120 mg/kg) concentrations were highest among potentially-hazardous minor and trace elements. Pore-water V concentrations were highest – up to 3.0 mg/L – immediately below the water table, but decreased rapidly with increasing depth. These decreases corresponded to a transition from slightly acidic (pH 6−7) oxic conditions to more alkaline (pH 7−8.5) anoxic conditions. Vanadium mobility was generally greatest under oxic conditions and diminished under anoxic conditions. However, V concentrations were also very low at pH < 7 under oxic conditions. Scanning electron microscopy (SEM), electron microprobe analysis (EMPA), and micro-X-ray fluorescence (µXRF) mapping revealed the presence of successive concentric layers within coke particles. The inner regions of each layer were dominated by C and S, and micro-X-ray absorption near-edge structure (µXANES) spectroscopy revealed that organic porphyrinic V(IV) dominated V speciation. The outer margins of each layer were instead characterized by elevated concentrations of V, Si, Al, and Fe, indicating the presence of inorganic phases. Inorganic octahedrally-coordinated V(III) was more prevalent within these outer margins. A minor to trace V(V) component was also detected throughout the coke particles. Vanadium (IV) porphyrins are expected to be stable; therefore, V(III) oxidation and V(V) leaching are likely sources of dissolved V.

Regulatory research on coupled Thermal-Hydrological-Mechanical Chemical processes in natural and engineered barriers for geological disposal of radioactive wastes

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Since 1978, the Canadian Nuclear Safety Commission (CNSC), the Canadian nuclear regulator, has been involved in independent and internationally collaborative research focusing on long-term safety issues related to the geological disposal of radioactive waste. Geological repositories rely on multiple barriers (for example, the waste form, container, engineered seals, and host rock) for the long-term containment and isolation of radioactive waste. Therefore, the CNSC's research program looks at the performance of those barriers. The barriers' performance in turn are dictated by perturbations induced by the excavation and construction of the repository, the thermal load generated from the wastes, and future geological events such as continental glaciation. Those perturbations result in coupled Thermal-Hydraulic-Mechanical-Chemical (THMC) processes that need to be understood in order to assess with confidence the long-term evolution of the engineered and geological barriers. The CNSC has been actively involved in research on THMC processes. That research includes an experimental component and a theoretical component. For the experimental component, the CNSC collaborates with Canadian and international partners to obtain data from small–scale experiments performed in conventional surface laboratories, larger scale experiments from underground research laboratories, and geological scale data from paleohydrogeological information. The theoretical component consists of the development of a mathematical framework, based on an extension of Biot's theory of poromechanics to simulate the coupled processes that prevail in the above experiments.

In this paper, we describe the mathematical framework for coupled THMC processes and show how that general mathematical framework was adapted and applied to simulate:

- water and gas injection in an argillaceous formation
- THM processes in a heater experiment at an underground research laboratory
- the effects of nine glacial cycles in a sedimentary rock formation

The results of the regulatory research on THMC processes has contributed in building independent expertise, allowing CNSC staff to provide authorative and credible review of key safety aspects of applicant proposals for geological disposal in Canada.

Pearce element ratio diagrams and cumulate rocks

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Pearce element ratios have found service in deciphering the magmatic histories of volcanic rock suites but they can also enhance our understanding of the nature of cumulate rocks. Designed to model processes of fractionation and accumulation in igneous systems, Pearce element ratios have found most use with analyses of rocks dominated by melts produced by fractionation – volcanic suites. Rock bodies dominated by the sorted crystals – the cumulate rocks – have received practically no attention. Given the standard paradigm for the formation of cumulate rocks, which is based on studies of the Skaergaard Intrusion, one expects data points on a Pearce element ratio diagram to display a predictable pattern. Points derived from the mean compositions of the units in the cumulate body should fall up-slope from the point representing the initial melt composition on a diagram that accounts for the cumulate assemblage. Points derived from the compositions of the inferred residual melts present at the beginning of crystallization of a unit in the rock body should fall down-slope from the point representing the initial magma. The distance between a point on the line of a Pearce element ratio diagram and the point representing the initial magma composition depends on (1) the size of the aliquot that crystallized to form the rock unit and (2) the ratio of crystals to melt in the mush that solidified to form the rock unit. Patterns extracted from computer simulations compared to analogous data points from units of the Skaergaard Intrusion indicate that the crystal mushes that formed the units of the Marginal Border Series had a smaller ratio of trapped melt to crystals than did coeval mushes forming the Upper Border Series. Simulation patterns further indicate that the LZa and UZa units of the Layered Series formed with larger ratios of melt to crystals than did the respective coeval units, LZa* and UZa*, of the Marginal Border Series.

Clearing the muddy waters: A detailed sedimentological analysis of matrix-rich sandstones in the Windermere turbidite system and comparison with equivalent deposits

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The description, classification, and origin of deep-marine matrix-rich sandstones (i.e. sandstone with significant (> 10%) mud matrix) have been debated since the 18th century when the term greywacke was introduced in the geological literature. Sedimentologists have generally attempted to either define them based on their texture and/or composition or origin of their matrix (detrital vs. diagenetic). However, in the last decade, it has been increasingly recognized that there exists a variety of matrix-rich strata that are unlike classical turbidites or debrites and should be examined and interpreted based on their formative mechanisms and associated depositional environments. Currently, deep-water matrix-rich beds are generally categorized as slurry beds or linked debrites/hybrid-event beds deposits. Slurry beds are typically a few cm to over 30m thick with a distinctive intercalation of finer- and coarser-grained sediment layers. Matrix ranges from 10-35% matrix and syndepositional fluid expulsion features are common. Linked debrites/hybrid event bedsets are typically several dm thick with a basal matrix-poor turbidite (fine- to medium-grained) overlain sharply by a matrix-rich (~20%) debrite (very fine- to fine-grained) with abundant clasts of various sizes and lithologies, and common liquefaction-related structures and sand injection. Both types of matrix-rich beds are interpreted to be deposited by flows that underwent a longitudinal change to a more cohesive behaviour and form deposits that extend over few km's to 100's km in the medial to distal parts of submarine fans.

In the Neoproterozoic Windermere Supergroup, matrix-rich sandstones are characteristically flat-based, a few cm- to several dm-thick, fine- to medium-grained, with matrix content ranging from 10 to 70%, although typically 30-50%. Significantly, beds lack a basal clean sandstone or evidence of dewatering, and locally contain few cm-long mudstone clasts oriented parallel to bedding. Moreover, beds extend for only a few to several 100s m laterally and in slope to medial basin floor settings, and are interpreted to represent the initiation of the local sedimentary system in response to a local upflow avulsion.

The discrepancy between matrix-rich sandstones from the Windermere turbidite system compared to other deep-marine matrix-rich sandy strata is striking. The objective of this study, therefore, is to more fully document matrix-rich sandstones in the Windermere Supergroup, and then develop a comprehensive list of criteria to help discriminate the spectrum of matrix-rich sandstone facies, their physical origin, and ultimately their interpretative significance.

Keynote (30 min): Cascading, compound, multi-fault ruptures: A new class of earthquake

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Reliable earthquake forecasting hinges upon anticipating the likely length of seismic rupture, and thus, upon recognizing the role of fault segment boundaries in arresting slip. Past rupture forecast models have generally presumed that segment boundaries of a few (~5) kilometres are sufficient to halt any earthquake rupture. However this inference, which is based upon compilations of historical surface rupture maps, has recently been challenged by new observations of earthquakes that bridge fault gaps or segment boundaries that are tens of kilometres wide, near-instantaneously. Here, I use the 27th February 1997 Harnai, Pakistan (Mw 7.1) earthquake – probably the earliest well-documented example of this new class of compound rupture – to illustrate. In this instance, dynamic stresses generated by seismic waves from the first fault rupture are the probable cause of slip initiation on the second fault, ~50 km distant. Other recent notable examples include the 14th November 2016 Kaikoura, New Zealand (Mw 7.8), 16th April 2016 Kumamoto, Japan (Mw 7.0), 7th December 2012 Sanriku-Oki, Japan (Mw 7.3), 11th April 2012 Indian Ocean (Mw 8.6), 2nd January 2011 Araucania, Chile (Mw 7.1), 29th September 2009 Samoa-Tonga (Mw 8.1), and 17th June 2000 Reykjanes, Iceland (Ms 6.6) earthquakes. This rapidly growing list – which now includes subduction zone, fore-arc, ocean transform, continental, and intraplate examples – implies that cascading multi-fault earthquakes are a common and global phenomenon whose recent discovery merely reflects advances in earthquake rupture imaging. These events expose a serious flaw in forecast models that disregard cascading, multiple-fault ruptures of this type.

Litho-, δ^{13}C, and ash-bed (Millbrig) stratigraphies redefine the foreland Blackriveran-Trentonian boundary succession, Ottawa Embayment: Significance for extrabasinal correlation

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Historically, application of lower Trentonian stratigraphy (= Rockland, Hull formations) defined in the Ottawa Embayment (OE) to other regions in North America proved unsatisfactory, eventually resulting in creation of the extrabasinal Selby (Blackriveran) and Napanee (Trentonian) formations of southern Ontario, forming part of the standard Mohawkian section. We present new litho-, δ^{13}C-, and volcanic ash-bed stratigraphies that reveal that this discordance is allied to significant differential intrabasinal subsidence in the OE compared to the record displayed by the standard section. Most of the Blackriveran lithostratigraphy (Pamelia, Lowville and Chaumont or Watertown formations) and faunal (macro, conodont) associations defined from upstate New York are applicable to the embayment. However, the Watertown thickness dramatically increases eastward over 170 km along the embayment's axis, from ~3 m west of Ottawa (as also found in southern Ontario) to 11+ m at L'Orignal. δ^{13}C profiles and lithostratigraphy help characterize the Blackriveran- Trentonian (BR-T) boundary. Most significantly, lithic attributes of the overlying Trentonian Rockland Formation at its type section (i.e., thick-bedded limestone (90%) with minor shale) are restricted paleogeographically to the central portion of the embayment's outcrop belt. Elsewhere, the Watertown is overlain by a thin (~2-3 m) succession of shale and packstone representing, in part, an equivalent facies to the extrabasinal Selby Formation. At the Rockland type section, overlying shallow-water encrinites of the Hull Formation do not occur ubiquitously along the embayment; instead, a 19- to 30-m-thick bryozoan-crinoidal grainstone/shale succession forms an additional deep-water shelf facies, not previously recognized, that separates the Selby-equivalent unit (which disappears westward) and the typical shallow-water Hull facies. At L'Orignal, a 10-cm-thick altered volcanic ash bed marks the base of this deeper facies succession: biotite geochemistry identifies a Calc-alkaline subduction source, and zircons yield a U-Pb CA-ID-TIMS date of 453.36 ± 0.38 Ma (2σ, N=6, MSWD = 0.52). The paleo-ash bed is the local expression of the widespread Millbrig event in eastern Laurentia, and demarcates locally a significant vertical deepening across the BR-T boundary. In contrast, the type Rockland Formation records a coeval low-energy shallow carbonate bank episodically flooded. The variety of spatial and temporal patterns of intrabasinal subsidence through the BR-T boundary succession in the OE is pronounced compared to southern Ontario. Likely, this reflects a greater sensitivity to distal tectonic forces of an inherited weakened basement (= the paleoaxis of an intracratonic Precambrian aborted rift) that lay beneath this part of the developing regional foreland.

A regional groundwater model based on the location of diabase dykes and Landsat imagery in Ngamiland, Botswana

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The intermittent pattern of wet and dry seasons has been exacerbated due to climate change. Unfortunately, it is no longer abnormal to experience much longer droughts in areas with two seasons. Diabase dykes can be useful geological features during droughts as they are known to act as barriers to groundwater discharge. Consequently, favourable supplies of water can be found on the side of a dyke that faces the direction of regional water flow. This knowledge, used in combination with remote sensing and geophysical techniques, can help select areas with sustainable water supply in Ngamiland, Botswana.

Botswana experiences a wet season from November to March. The landscape changes drastically between the two seasons, with large amounts of vegetation disappearing during the dry season and returning during the wet season. An exception of this is the Okavango Delta located in North-West District of Botswana, which provides water to the area all year round. The area around the delta includes part of the Okavango dyke swarm. The dyke swarm extends for approximately 1500km and is made up of multiple mafic dykes striking N110°E. The impermeable characteristic of diabase dykes allows them to act as groundwater barriers. The resulting accumulation of groundwater allows for vegetation to grow on the side of the dyke perpendicular to groundwater flow. The opposing side of the dyke is deprived of groundwater and is left with little to no vegetation growth. This pattern of a strip of vegetation beside a barren strip of land can be indicative of a dyke.

An airborne magnetic survey was flown in Botswana in January of 2016. The resulting data was reduced to the pole and the first derivative used to visually observe dykes within the surveyed area. The dykes were marked and sorted by relative age. Using Landsat 8 data collected in consecutive dry and wet seasons, a normalized difference vegetation index (NDVI) was created displaying the vegetation health of the study area. The images of the two seasons were then compared with the magnetic data to identify patterns of vegetation growth along known dykes, therefore, identifying areas for sustainable agriculture or human occupation.

Integrated groundwater system modelling: Characterizing geosphere stability and resilience in crystalline rock settings

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Integrated groundwater system models are used to illustrate the impact of geosphere processes and their parameters on the long-term stability of groundwater systems at potential repository depths, including the impact of future glacial advances and retreats, and permafrost. The behaviour and stability of a hypothetical crystalline rock geosphere is illustrated through the use of representative reference case and sensitivity case analyses. A methodology, directly traceable to field data, and linked to paleoclimate models is presented. Through the use of performance measures such as Mean Life Expectancy (MLE), deep groundwater systems can be, subject to site-specific conditions, shown to remain stable and resilient to change. The fractured crystalline rock domain covers an area of approximately 150 sq. km, bounded by surface water divides. A discrete fracture zone network model, generated using MoFrac and delineated from surface features, was superimposed onto a three-dimensional mesh. Orthogonal fracture faces (between adjacent finite element grid blocks) were used to best represent the irregular discrete fracture zone network. The numerical groundwater modelling was performed using the discrete fracture dual continuum computational model HydroGeoSphere.

In the sensitivity cases, key geosphere parameters, such as hydraulic conductivities, are varied to illustrate the role they play in influencing groundwater system stability at depth. The connectivity and high hydraulic conductivity of the fracture zone network have a significant influence on the deep groundwater system. Paleohydrogeological simulations that include the impact of hydro-mechanical coupling are used to illustrate the long-term evolution and stability of the geosphere to external perturbations. In particular, the simulations explore transient hydraulic gradients, groundwater velocities, and the depth of penetration by glacial recharge, which are relevant to illustrating long-term repository safety. The distribution and duration of permafrost at the repository location play a role in governing the depth to which meltwater penetrates. However, the glacial perturbations did not materially affect mass transport rates at repository depth within areas of the rock mass not impacted by fractures, where low rates of mass transport are expected.

Integration of textural, mineralogical and geochemical characterization of refractory Carlin-type gold ore: Application to ore processing

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Increasing exploitation of refractory gold ore, where gold is hosted mainly in sulfides, requires a better understanding of the distribution of gold and other metals in the sulfide structure, the mineralogy and textural relationships, and the overall whole rock geochemistry of the ore. Carlin-type deposits are hosted in hydrothermally altered impure carbonate rocks where gold is structurally bound or occurs as submicron inclusions in pyrite (refractory, locked gold ore). At Betze-Post Carlin-type deposit in Northern Nevada, USA, auriferous pyrite is found in two main types of ore: Type 1 ore, which is the most common, is highly silicified (>45 wt. % hydrothermal silica) and contain lower organic C amounts (< 5 wt. %); and Type 2 ore is less silicified (< 45% hydrothermal silica) but has higher organic C content (5 to 18 wt. %: double-refractory). The auriferous pyrite is characterized mainly by 1-3 micron thick zones that overgrowth barren diagenetic or early hydrothermal pyrites and by disseminated grains (2-10 microns in diameter) associated with microcrystalline quartz +/- clays filling dissolution zones in the impure carbonate rocks (mainly in the Type 1 ore). Due to the fine-grained nature of the auriferous pyrite, its composition was determined using microprobe and synchrotron X-ray fluorescence techniques. Arsenic, Cu, Sb, Ni, Se, Hg, Tl, Ti, Zn, Ag, Co, Pb, and W were found in the auriferous pyrite in variable concentrations and spatial distribution. Gold concentrations in pyrite increase with As, for Au up to an optimal 3,700 ppm (0.08 at %) and 5 wt. % As (3 at %). At As contents higher than 6 wt. % (3.6 at %), gold concentrations decrease with increasing As. The distributions of other trace elements show a similar pattern to Au, with the highest gold concentrations in grains with a maximum of 2 wt. % (~ 1 at %) total trace elements. Textural evidence indicate that, in general, the auriferous pyrite is not encapsulated in silica in both ore types. However, high organic C amounts, typical of Type 2 ore, can be detrimental to the leaching of auriferous pyrite, as the carbonaceous matter tend to adsorb gold from the leaching solutions, thereby reducing recoveries. Pre-treatment to liberate gold from pyrite is therefore required, including roasting (conventional or microwave), pressure oxidation, chlorination and/or bio-oxidation. Furthermore, waste rocks, tailings and mine effluents must be closely monitored for trace elements commonly enriched in Carlin-type ores.

Integrating sustainable energy sources into a semi-autogenous grinding mill: A simulated case study accounting for spatial variability of ore grindability

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Mining activity faces an increase in energy consumption, which is related to the lower ore grades, the increase in rock hardness and deeper mines. In order to make mining more sustainable, the integration of renewable energies is desirable. This work explores, through simulation, the integration of a solar photovoltaic system (PV) and a battery energy storage system (BESS) –as a buffer for the variations in energy (solar) production and consumption-, with grid backup, to operate a semi-autogenous grinding mill (SAG). We explore the effect of the spatial variability of the ore grindability, specifically, the SAG Power Index (SPI), on the energy required by the system to operate a SAG in a medium size mine. The spatial distribution of geometallurgical units defined in terms of grindability is simulated with geostatistical methods, as well as the distribution of SPI within these units. The spatial distribution is then converted into a time series that represents the truckloads of ore that are sent to the processing plant. This time series is translated into energy requirements of the SAG mill, and feeds a technical-economical optimization model that decides the operational balance between renewable energy and energy from the grid. The aim is to minimize energy imports from the grid and smoothening the power consumption (the ore hardness variability could result in exceeding the contracted power); thus, reducing the total cost of the energy consumed, and adding sustainability to the operation. The results show that the size of the PV-BESS system depends on the spatial variability of the rock hardness, and that having more than one stockpile may be beneficial for the SAG-PV-BESS system. This suggests that the integration of renewable energies into mining may need adapting the operation to new requirements. The geometallurgical modeling appears as a key tool to optimize the design of this integration.

A new tablet App for 2D and 3D mapping, sampling and data analysis

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For centuries, field geologists have used sketches in a field notebook to capture a record of the terrain and sites of interest, later augmented by slide and film photography and, more recently, digital photography. While technology has advanced, today's field geologists may carry a diverse collection of data collection and sampling devices that often do not communicate with each other. When they exit the field and return to their labs, a time consuming and human error prone process begins to determine what data element residing on which device (each having their own storage standards) were collected and about what sample. This data is only loosely coupled to actual samples through field notes that aim to identify the relationships between the peripheral data and the sample itself. The advent and use of tablet PCs and PDAs equipped with GPS and mapping software, has resulted in improvements in efficiency and a limited increase in situational awareness. However, uptake has been extremely limited. The cost of conducting surveys – both in terms of hardware and person time – and the significant training required to learn software are the major obstacles.

In this contribution, we report on the development of a new digital field data management system. A tablet or smartphone acts as the central data collector and organizer. The ability to capture 2D images, take notes, both written and as audio, and the ability to overlay sketches in real time offer fundamental improvements over current best practices. The testing of 3D scanning systems that plug in to the iPad are currently being tested. A critical advance is that samples are tagged with physical chips that encode a reference to all associated data. The time savings as well as the reduction in error and frustration from the field workers and analysis team is a unique benefit of this system. In addition, archiving data in a standardized and reproducible way is enforced by having a syncing system in place with an architecturally immutable database residing in the cloud. Further, the extensible suite of post-processing analytical software services and tools that our web portal provides gives the end user a powerful toolbox to create new ways of visualizing, analyzing and interacting with data. The App will be demonstrated during this presentation and we welcome input, feedback, and persons willing to test the App in the field in summer 2017.

Exploring the Planets – A new blended and online approach to geoscience teaching

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Planetary science and space exploration, like perhaps no other discipline, can ignite interest and motivate young minds to pursue education and careers in the sciences. The Department of Earth Sciences, in collaboration with the Centre for Planetary Science and Exploration at Western University, has recently developed a new Minor in Planetary Science and Space Exploration that seeks to capture this excitement and capitalize on the enormous future potential of Space. A major goal of this new Minor is to attract students to geoscience from other disciplines, thereby boosting the numbers of students enrolled in Earth Sciences modules.

The foundation course for this new Minor is ES 2232 – Exploring the Planets. This new course was developed from scratch and is offered in both a blended (online and in person) and fully online format. This course features the following innovative features:

- A combination of pre-recorded and live lectures;
- The use of Twitter, a widely used social media platform, to foster student interaction and build a sense of community in the online classroom;
- Fully online laboratories utilizing software such as JMARS, to enable mapping exercises of the Moon and Mars, and a Virtual Microscope, to provide a virtual hands on investigation of rocks and minerals;
- A collaborative online group project, "Mission to Mars", where student teams work together to develop a concept for a Mars mission.

The centerpiece of this course is the collaborative group project. Students build upon the lectures and laboratory sessions and begin to evaluate and synthesize course material to decide the scientific objectives for their mission. Students have to decide upon what type of platform (rover versus satellite) and what instruments to put on their spacecraft, and, finally, where to land on the Red Planet. As with an actual mission they will face hard caps on mass, power, and cost. The framework for this group project is provided through a website that provides all the background materials for this group project. The site allows the students to actually build their rover using a 3D graphical interface where they can drag and drop different instruments, monitoring power, mass and other constraints. The culmination for this course is a poster presentation where the student teams present their mission concepts to a Mission Review Panel.

Impact cratering: An important driver of near-surface hydrothermal processes

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The kinetic energy transferred to a planet during a meteorite impact can generate intense shock pressures and temperatures capable not only of melting and vapourizing target rock but of inducing a hydrothermal system. Indeed, there is evidence for hydrothermal activity in approximately half of the 190 impact craters on Earth; however, only a handful of craters have been studied in detail so the presence of hydrothermal alteration products is likely underreported. In this contribution, the results of ongoing studies of several impact craters (Chicxulub, Mexico; East Clearwater Lake, QC, Canada Haughton, NU, Canada; Ries, Germany; Rochechouart, France; Sudbury, ON, Canada; West Clearwater Lake, QC, Canada) are presented. These observations are summarized as follows: 1) hydrothermal activity is initiated immediately following the impact event; 2) there are six main locations within and around impact craters where impact-generated hydrothermal deposits can form (crater-fill impact melt rocks and melt-bearing breccias; interior of central uplifts; outer margin of central uplifts; ejecta deposits; crater rim region; post-impact crater lake sediments); 3) the composition of the target rocks is the primary driver for alteration mineral assemblages; 4) fluids are predominantly meteoric in origin; 5) the presence of an overlying crater lake in continental settings, or ocean water for marine impacts, results in more pervasive hydrothermal alteration. The similarities and differences between endogenic and impact-generated hydrothermal systems will be discussed. It is clear that on early Earth, when the impact rate was substantially higher than today, impact events would have been a major driver of hydrothermal processes within the near-surface crust. This has important implications not only for the evolution of the lithosphere and hydrosphere, but for the biosphere, whereby impact craters would have provided suitable habitats for the origin and evolution of life.

Upper mantle and lower crustal xenoliths from southeast Yukon Territory

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Xenoliths of spinel-bearing lherzolite and granulite facies paragneiss were recovered from basaltic dykes that intrude Neoproterozoic-Palaeozoic metasedimentary rocks in the upper Hyland River region of southeast Yukon Territory. The dykes are typically 1-5 metres in diameter and commonly exhibit columnar jointing along their margins. The age of the dykes is poorly constrained, but they post-date Early Cretaceous regional metamorphism and deformation. Whole rock geochemical data indicates the dykes are nepheline-normative alkali basalts, and they plot within the basanite field on a TAS diagram. The xenoliths occur as discrete subrounded to subangular fragments up to 8 cm in maximum dimension. The lherzolite samples, which consist of equidimensional crystals of olivine, orthopyroxene, clinopyroxene, brown spinel, and Fe-Ni sulphide, exhibit smoothly curved grain boundaries. Orthopyroxene locally contains fine exsolution lamellae. Preliminary results from analyses of 18 mineral pairs using the Fe-Mg olivine-spinel thermometer provide temperatures of 807 ± 65℃ (2), 819 ± 65℃ (2), and 832 ± 66℃ (2) at pressures of 10, 15, and 20 kbar, respectively. Granulite facies paragneiss samples contain K-feldspar, quartz, sillimanite, graphite, and 1-8 mm rounded domains that consist of patchy, symplectic intergrowths of feldspar and orthopyroxene. These domains are interpreted as pseudomorphs (after Grt?) and may record post-peak metamorphic decompression. The aim of this project is to provide an estimate of pressure and temperature conditions of the xenoliths, which may help inform our understanding of the nature of the upper mantle and lower crust in this region of the northern Canadian Cordillera.

Structural evolution of the Caledonian Highlands, New Brunswick: Timing and deformation history in part of Avalonia

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The Caledonian Highlands of southern New Brunswick form part of Avalonia in the northern Appalachian orogen. The highlands consist mainly of two Ediacaran volcanic-sedimentary units – the older Broad River Group intruded by a suite of 630-615 Ma plutons and the younger Coldbrook Group intruded by a suite of 560-550 Ma plutons. A major high-strain zone transects the highlands from NE to SW with related deformation that affected the older plutons prior to Coldbrook Group deposition. Later deformation involved both the Coldbrook Group and early Paleozoic cover rocks of the Saint John Group. The style of structures varies systematically from NE to SW reflecting varying depths of dissection. In the NE no Saint John Group has been identified, and Broad River and Coldbrook Group rocks are involved in thrust slices expelled to the south. In the central segment isoclinal folds involving Ediacaran and Saint John Group rocks face and verge to the south, rooting in the high-strain zone. In the SW segment, where the highest level structures are seen, the most complete Saint John Group sequence is preserved in asymmetric folds facing and verging south before the entire structure disappears beneath Carboniferous cover. These structures also relate to the high-strain zone. North of this zone Saint John Group is unconformable on Coldbrook Group, and south of the Baxter Mountain Fault, deformation is minimal (e.g., in the type Hanford Brook section). North of this fault, slaty cleavage and folding are pronounced in Cambrian-Ordovician rocks, with asymmetric structures facing and verging to the north. Kinematic features in the main high-strain zone suggest right-lateral motion, and the same is inferred for the Baxter Mountain Fault. These structures juxtapose domains with contrasting basement-cover relationships implying considerable translation. All of these structures pass beneath the basal Carboniferous unconformity giving a timing somewhere between late Ordovician and late Devonian for the deformation affecting the Saint John Group. $^{40}Ar/^{39}Ar$ ages on muscovite from the main high-strain zone imply cooling during the mid-Devonian, suggesting a Neo-Acadian age for the latest deformation in a long history going back into the Ediacaran.

SW of Saint John, late Pennsylvanian thrusts place Cambrian-Ordovician Saint John Group over Lancaster Formation (Langsettian). Timing of the latest deformation suggests that it was broadly related to docking of the Meguma terrane, although not likely the part now adjacent. The earliest deformation relates to the pre-accretionary history of Avalonia itself.

Simultaneous simulation of engineered and natural barriers for the disposal of spent nuclear fuel/vitrified nuclear waste in underground repositories with HydroGeoSphere

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In a geologic repository, engineered and natural barriers work together to isolate spent nuclear fuel / vitrified nuclear waste from the biosphere. Traditionally, various numerical models are used to simulate transport along each of these barriers. However, various simplifications are necessary in order to make the computations possible. Moreover, the engineered and geologic barrier systems have rarely been analyzed simultaneously, thus, linking a series of the models often requires simplifying assumptions for safety assessments of geologic repository systems, despite the immense advancement in numerical modelling techniques over the last several decades.

This study attempts to simultaneously simulate transport processes along engineered and geological barriers within a single modelling framework. The ConnectFlow (NAMMU/NAPSAC) model is used to generate multiple statistically-equivalent DFN realizations and to upscale flow and transport properties, while the HydroGeoSphere model is used to simulate flow and transport through discretely fractured porous media. Transport processes considered include; (1) dissolution of vitrified waste and potential precipitation of radionuclides of a decay chain, (2) diffusion-sorption-decay along the clay backfill, (3) advective-dispersive transport along random discrete fracture networks (DFNs), and (4) diffusive imbibition of radionuclides into matrix with sorption and decay. Simulation capability of the model for radionuclide migration was first verified separately for transport along each of engineered and geologic barrier systems by comparing the simulation results to analytic and other simplistic models. The model was then applied to radionuclide migration in a 3D domain, which was designed to include an access tunnel, 10 pits with 10 containers, excavation disturbed zones (EDZs) around the tunnel and pits, and host rock with a stochastic DFN. The model was tested for the host rock containing a DFN from both representative crystalline and sedimentary formations in Japan.

Key findings from the study were: 1) diffusive transport along the engineered barrier required the highest spatial resolution along both radial and axial directions; 2) mass release from the engineered barrier was strongly influenced by ambient groundwater flow, thus radial symmetry for diffusion results in over-simplification; 3) radionuclide transport was significantly different in crystalline and sedimentary host rocks due to the difference in matrix storage capacity; 4) using a single 1D fracture as a simplified representation of a multi-fracture pathway can be misleading; and 5) the computational cost for simultaneous transport simulations of engineered and geologic barriers is now possible using modern multicore personal computers.

Geochemical and structural analysis of Slide Mountain Terrane in south-central Yukon: Insights into the early development of the NW Cordilleran orogen

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Accretionary orogens such as the NW Cordillera are often long lived and represent a collage of terranes amalgamated through multiple phases of deformation. In order to understand the early development of these orogens, key crustal components present during these early stages must be identified and studied in detail to unravel present day structural relationships and reveal past orogenic events. In the NW Cordillera, the oceanic Slide Mountain Terrane (SMT) formed between Phanerozoic arcs and the North American continent (NAC) during Devonian-Permian times. Subsequent to its formation, the SMT recorded multiple deformation events during ocean closure and arc accretion. Thus, due to its age and structural position, the SMT provides an excellent target for investigating the early development of the NW Cordilleran orogen. We present geochemical and structural data from the Dunite Peak area of the Big Salmon Range, south-central Yukon; an area in which klippen of mafic-ultramafic rocks belonging to SMT structurally overlie rocks that are interpreted as basement of the Yukon Tanana Terrane (YTT). Our results indicate that in this region, the SMT comprises a range of geochemical assemblages indicative of a lower lithospheric portion of a suprasubduction zone ophiolite. Below these ophiolites lies a mylonitised and thrust imbricated stack of lower amphibolite facies island arc tholeiites of unknown origin. These are tectonically emplaced on a basement of basinal metasedimentary rocks, at the base of which lies garnet-kyanite-schists, amphibolite and eclogite that are interpreted as part of YTT. We propose that this stack of metamorphosed rocks overlain by SMT ophiolitic assemblages may represent a fossil subduction zone in which SMT formed the upper plate to eastward subducting YTT in the lower plate during the Permian. In this situation, SMT represents a back-arc to an as yet unnamed oceanic island arc between YTT and NAC. The highly deformed island arc tholeiites identified between SMT and YTT in this region may represent the remnants of this arc and the suture between upper and lower plates. This hypothesis is differs significantly to current popular models for the NW Cordillera and has important implications for the timing of accretion of outboard terranes to the NAC. Future PTtD studies will be carried out to test this hypothesis further.

Stratigraphy of the Paleoproterozoic Karrat Group, Greenland: Defining sedimentary-tectonic cycles on the "far east" Rae craton

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The connection between Rae supracrustal cover sequences in eastern arctic Canada and west Greenland has been hypothesized since the late 1970's, but detailed geoscientific data have been insufficient to confirm these ideas. A recent reinvigoration of geological interest in the far North of both Canada and Greenland has led to new insights into the tectonic setting of sedimentary basins along the Rae craton margin and their possible correlation prior to ~1.9 to 1.8 Ga orogenic events. Expeditions in west Greenland, in collaboration with the Geological Survey of Denmark and Greenland and Ministry of Mineral Resources, have allowed for stratigraphic investigations of the Paleoproterozoic Karrat Group, which spans several hundred kilometres from north to south along coastal west Greenland (~71° to 75°N). These studies have economic importance, since the Marmorilik Formation hosts significant Pb-Zn mineralization at the well-known Black Angel Mine, in addition to Pb-Zn potential in the nearby Qaarsukassak Formation. New field observations have led to division of the Karrat Group into at least two depositional stages, separated by a regional unconformity. The Qeqertarssuaq Formation comprises the lower Karrat Group, whereas the Kangilleq, Mârmorilik, Qaarsukassak, and Nûkavsak formations comprise the upper Karrat Group. Marked lateral variations in stratigraphy suggest the possibility of coeval deposition of upper Karrat Group units within sub-basins, complicating their interpretation. Regardless, several important observations have allowed for preliminary stratigraphic correlations within the Karrat Group, which can be established based on unconformity surfaces. In this scenario, the unconformity surface beneath the Kangilleq-Nukavsak formations would correlate with that found beneath the Qaarsukassak and Mârmorilik formations, which were deposited directly on Archean basement rocks. Sedimentary structures are not ubiquitously preserved, but are present in most units of the upper Karrat Group, making reconstruction of paleoenvironments possible. Conversely, the Qeqertarssuaq Formation is deformed, metamorphosed, and infolded with Archean rocks, making stratigraphic studies challenging. The recently defined Qaarsukassak Formation (upper Karrat Group) has some similarities to the Mârmorilik Formation to the south, in that its stratigraphy includes carbonate rocks and hosts Zn-Pb mineralization, but the stratigraphic thickness and facies of their lowermost siliciclastic units differ (fluvial vs. shallow marine). Ongoing definition of the stratigraphic architecture and intrabasinal correlation of the Karrat Group, especially in relation to tectonic events responsible for successive sedimentary cycles, provides insights into metallotects in space and time, and also serves to highlight similarities and differences between the Karrat Group and Paleoproterozoic successions in eastern arctic Canada.

Kinetic controls on staurolite-Al_2SiO_5 mineral assemblages, with implications for Barrovian and Buchan metamorphism

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Staurolite-Al_2SiO_5 mineral assemblages are of key importance to the interpretation of the P-T conditions of Barrovian and Buchan metamorphic terrains. Increasing evidence points to petrologically-significant kinetic control on their development. Barrovian terrains are characterized by mineral assemblages containing kyanite, or co-existing staurolite and kyanite. When interpreted in current equilibrium phase diagrams, they imply surprisingly restricted and rather high-pressure conditions of formation (>6 kbar = >20 km depth) in which, for any reasonable P-T path, kyanite is predicted to form upgrade, and at the expense, of staurolite. Whereas rarely there is evidence of kyanite having formed from reaction of staurolite, more commonly there is no evidence of such a reaction relationship; rather, the two minerals appear to coexist stably, or to be intergrown. For these, an alternative interpretation is that both minerals crystallized in response to chlorite breakdown reactions. This possibility is favoured by the similarity of the two minerals' crystallographic structures, the similar P-T conditions of the St- and (metastable) Ky-producing, Chl-consuming reactions (<10 °C separation), and the slightly larger entropy change of the Ky-producing reaction that allows it to approach and then overtake the St-producing reaction in terms of reaction affinity as overstepping increases. If so, considerably lower pressures (as low as ~5 kbar) may be possible for the formation of St-Ky assemblages than assuming equilibrium. In the Nelson aureole, BC, staurolite and andalusite have been shown to co-crystallize in response to chlorite-consuming reactions in the range 3-4 kbar. Taken together, the pressure difference between Barrovian (St-Ky) and Buchan (St-And) sequences may be less than widely assumed. This interpretation would solve the present conundrum, assuming equilibrium, of the rarity of prograde sequences in which staurolite yields upgrade to sillimanite with neither kyanite nor andalusite in the sequence. If these interpretations are correct, they demonstrate the need to consider kinetically-controlled processes in the interpretation of mineral assemblages and microtextures in regional as well as contact metamorphic settings.

The Strange Lake dispersal train: A product of a hard-bedded ice stream

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The Strange Lake glacial dispersal train, in northern Quebec and Labrador, is a remarkably linear, ribbon-like geochemical dispersal pattern trending >40 km down ice (northeast) from a mineralized rare earth element (REE) peralkaline intrusion. Recent mapping of Laurentide Ice Sheet streams by Margold and others in 2015, places the Strange Lake train directly within the trunk of the Kogaluk River ice stream (IS #187), one of a number of ice streams that operated near the center of the Labrador dome and drained into the Atlantic Ocean. In soft-bedded areas, subglacial landforms can be used to map the spatial extent of ice stream tracks (e.g., mega-scale glacial lineations, ice stream shear margin moraines). Over hard-bedded, higher relief areas, the geomorphic imprint of ice streams tends to be less obvious, and sometimes features, such as shear margin moraines, can be completely absent. Despite the relatively thin till cover in the Strange Lake area, fast-flowing ice formed spectacular crag-and-tail landforms down ice of bedrock outcrops (up to 5 km long, with length:width ratios exceeding 12 and higher) within the dispersal train.

Airborne gamma-ray spectrometry surveys conducted in the Lac Brisson region in the 1980s show a subdued signal over part of the Strange Lake deposit and a long equivalent thorium (eTh) ribbon that extends more than 60 km to the northeast, well beyond the till geochemistry train. Deposition of REE-sediment was also controlled, in part, by the local rugged bedrock topography. Sediment dispersal trains, coupled with erosive corridors of streamlined terrain, provide a potentially powerful means of identifying 'hard-bedded' ice streams elsewhere in northern Canada.

Mineralogical signature of the St. Lawrence Columbium Mine at Oka, Québec

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Global demand for modern technology has increased the requirement for critical metals including REEs, PGEs, Nb, Ta, In and W. These elements are used in high-tech devices, and in development of green and defence technologies. In Canada, the supply of these elements is limited to a few deposits that are currently being mined (Niobec (Nb), St. Honoré, QC) or under development (e.g., Aley (Nb) in BC; Nechalacho-Thor Lake (Nb, Ta, HREE) in NT; Hoidas Lake (Nd) in SK; Eldor (Nb, Ta, REE), Kipawa (HREE), Montviel (REE), and Strange Lake (HREE) in QC). These deposits commonly occur in carbonatite or peralkaline granite rocks, have complex mineralogy, and are associated with the radioactive U, Th and their daughter products.

The abandoned St. Lawrence Columbium Mine in Oka, QC, formerly one of the largest Nb producers in the world, afforded a good proxy to examine long-term environmental effects. This open pit and underground mine operated between 1961 and 1977 and produced 3,536,200 tonnes of Nb-bearing ore (average grade 0.51% Nb_2O_5) and 3,857,350 t of waste material in the first decade. This mine is hosted by a carbonatite and alkaline rock complex contemporaneous with the Monteregion Hills. Over 70 minerals have been identified and is the type locality for two Nb minerals (niocalite and latrappite). The complex is formed largely of silica-undersaturated rocks of the melilitite and nephelinite series. Niobium occurs mainly in pyrochlore group minerals in calcite- carbonatite.

This study focusses on the geochemical and mineralogical controls of metal mobility. To this end, representative rock samples, tailings, slags, and waters from the open pits, tailings, decant pond and local creeks are being analysed. Preliminary mineralogical analyses by XRD show tailings are rich in calcite (~90 wt%) with minor to trace amounts of apatite, niocalite, perovskite and pyrochlore. Rock samples contain abundant calcite with variable amounts of gypsum, apatite, mica (biotite/phlogopite), chlorite, amphibole, garnet, pyroxene and zeolite group minerals. Smelter slag left over from the on-site production of ferroniobium is dominated by high-temperature hibonite and grossite along with vesuvianite, as well as minor amounts of augelite, bredigite, cristobalite, perovskite, thorite and uraninite (not in order of abundance) interspersed in a glass matrix. The main environmental concern at this site is the radioactivity of thorium and uranium and their possible mobility along with other critical metals. The mineralogical footprint of this Nb deposit is complex and its characterization will aid in determining the mobility and long-term fate of contaminants in the mine wastes. Lessons from Oka will be applicable to Nb- and REE-deposits currently under development.

Detrital U-Pb and $^{40}Ar/^{39}Ar$ geochronology of Silurian-Devonian sedimentary rocks of the Connecticut Valley-Gaspe trough: Tectonic implications for the southern Quebec and northern Vermont Appalachians

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The paleogeographical setting of the Northern Appalachians during the Silurian still remains debated. Among key elements, the nature of erosional sources that contributed to the infilling of Silurian-Devonian sedimentary basins has to be investigated. A detrital U/Pb and $^{40}Ar/^{39}Ar$ geochronology study has therefore been performed in Quebec and Vermont in order to constrain sediment provenances and ages of deposition. In the Québec-northern New England Appalachians, the Connecticut Valley-Gaspé trough (CVGT) is host to the sedimentary rocks of the Gaspé belt in Québec and correlative rocks of the Connecticut Valley Sequence in Vermont. The CVGT is a major Upper Ordovician-Devonian post-Taconian sedimentary basin which extends for more than 1000 kilometers from New England to Gaspé peninsula. In the southern Québec Appalachians, the deposition of the Gaspé belt is attributed to the formation of the CVGT sedimentary trough during a late-Silurian to Early Devonian crustal extension event, known as the Salinic disturbance in Gaspé peninsula, which has been almost coeval to, or immediately followed, the Salinic collisional orogeny. The CVGT was regionally-deformed and metamorphosed at variable intensities during the Middle Devonian Acadian orogeny, marking the final accretion of the peri-Gondwanan Avalon terrane.

Detrital zircon and muscovite detrital ages are reported from the base to the top of the Gaspé Belt sequence, from Silurian-Devonian stratigraphic units known as the Ayer's Cliff and Compton formations in southern Quebec, which correlate, in Vermont and Massachusetts, with the Waits River and Gile Mountain formations, respectively. Detrital U-Pb zircon results suggest that most of the «proximal», early Silurian to Devonian sources were likely immerged at the onset of sedimentation of the Gaspé Belt in that area, which is consistent with the interpretation of a major marine transgression at the base of the sequence, marked by the Ayer's Cliff-Waits River formations. The absence of Ediacaran ages in the Ayers Cliff Formation zircons in Québec, in contrast to samples of the Waits River Formation in Vermont, support a diachronic timing for the deposition of both units or that along-strike erosional sources were not the same. A good correlation between zircons age populations from samples of the Compton and Gile Mountain formations suggest, however, the homogenization of erosional sources with time, presumably due to the approaching Avalon terrane towards the beginning of the Devonian. Detrital $^{40}Ar/^{39}Ar$ results highlight the contribution of erosional sources that record Llandoverian metamorphic ages, suggesting the contribution of crustal sources having experienced Salinian metamorphism.

A wish for wings that work: The use of aerodynamic modelling to unravel the origins of avian flight

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Powered flight is a major locomotor novelty that has only occurred three times in the 500+ million-year history of vertebrates: in birds, bats and the extinct pterosaurs. Of these, birds are unique in having a geologically extensive and rich fossil record documenting the series of morphological changes that characterize the transition for terrestrial based theropod dinosaur to volant birds. Recently a series of taxa bridging this transition have been discovered possessing long feathers not only on their forelimbs but on their hindlimbs as well. This has been taken by some researcher to denote the presence of a "four-winged" gliding stage in the origin of flight, but this interpretation is contradicted by several lines of anatomical evidence which suggest that flight first appeared in a ground based ancestor and that gliding was not possible in non-avian theropod taxa. This latter interpretation raises question on the origin and function, if any at all, of the "hind wing". Here we present work seeking to test the aerodynamic implications of having a set of feathers on the hindlimb to better understand how flight first appeared in the ancestors of modern birds. 3-D printed models were created for several key taxa (Anchiornis, Microraptor and Archaeopteryx) along this transition and incorporating mechanisms to permit a flapping flight stroke mimic that seen in these organisms. These were then run in Queen's Optical Towing Tank to examine the effects of drag and vortex shedding in our models based on the addition and variation in dimensions of the hindlimb feathers. These results were then incorporated into mathematical models for takeoff potential to see how much, if any, locomotory benefit long leg feathers gave to non-avian dinosaurs and early birds. This work is a major step forward in testing our hypothesis about the adaptive nature of this unique feature and helps us better understand how and when flight first arose in the lineage leading to modern birds.

The source and paleofluid evolution of secondary minerals in low-permeability Ordovician limestones of the Michigan Basin

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Secondary vein minerals in low-permeability sedimentary rocks provide a unique opportunity to understand solute transport mechanisms associated with the migration of deep basin fluids. In this study we report on the source and evolution of fluids associated with secondary minerals from veins and vugs in low-permeability Ordovician limestones and siliciclastic Cambrian units in the Michigan Basin. Samples of mm-scale veins and cm-scale vugs were obtained from argillaceous limestones of the Upper Ordovician Trenton and Black River groups, which respectively represent aquiclude (Kh = 10^{-16} to 10^{-12} m s^{-1}) and aquitard (Kh = 10^{-12} to 10^{-10} m s^{-1}) units, and from Cambrian sandstones which represent a deep confined aquifer (Kh = 10^{-6} m s^{-1}).

Petrography and microthermometric measurements on fluid inclusions are used to identify three main stages of fluid migration responsible for secondary mineral formation. Primary fluid inclusions from these stages have T_{trap} values of 88–128 °C (stage I – dolomite) and 54–78 °C (stage II and III – calcite and anhydrite/celestite, respectively), and salinities that indicate formation from halite-saturated brines (31 to 37 wt.%). Previous U-Pb model ages of 434 ± 5 Ma (LA-ICP-MS) and 451 ± 38 Ma (TIMS) on calcite provide constraints on the absolute timing of stage II fluid influx. Secondary stage IV fluid inclusions have minimum T_{trap} values of 57–106 °C and are interpreted to reflect fluid migration during a regional heating event.

Secondary minerals from the Cambrian and the overlying Upper Ordovician Shadow Lake Formation have $\delta^{13}C$ values of –6.1 to –2.5‰ (VPDB), $\delta^{18}O$ values of +14.6 to +24.2‰ (VSMOW) and $^{87}Sr/^{86}Sr$ of 0.70975 to 0.71043. With increasing distance upward into the Black River and Trenton groups the isotope profiles display positive shifts in $\delta^{13}C$ (–1.0 to +1.9‰) and $\delta^{18}O$ (+18.9 to +28.1‰) and decreases in $^{87}Sr/^{86}Sr$ (0.70790 to 0.70990). The isotope data are interpreted to reflect mixing between connate sedimentary porewater and ascending hydrothermal fluids with a geochemical signature inherited from interaction with the underlying Precambrian shield, or shield-derived minerals in the Cambrian aquifer. Relatively uniform isotopic compositions in vein minerals from the Trenton Group suggest formation from either connate-dominated fluids, or hydrothermal fluids that experienced high degrees of fluid-rock interaction during transit through the underlying Black River Group.

Complex fault reactivation history and style of the East Irish Sea Basin, offshore UK

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The stacked components of the East Irish Sea Basin (EISB) record a long and complex evolution, the geological history of the UK in microcosm. The heterogeneous basin substrate comprises crust accreted during Neoproterozoic to early Palaeozoic orogenic events. This is exposed around the margins of the basin, in Anglesey, North Wales, the Lake District and Southern Uplands, and bears the 'usual' SW-NE Caledonide structural grain. Reflective zones seismically mapped at the pre-Devonian level are correlated with major structures recognised onshore.

Devono-Carboniferous basins formed in a N-S oriented extensional regime, but were strongly influenced by the SW-NE Caledonide grain. The Eubonia-Lagman Fault System, at the SE edge of the Manx Ridge, controlled the northern limit of a major half-graben complex. Two generations of inversion structures are recognised in the foreland region of the Variscan Orogen. The first, trending SW-NE, formed by compressional reactivation of the basement thrusts, is represented onshore by the Ribblesdale Fold-Fault Belt of the Craven Basin. Second phase structures have a N-S trend, and are correlated with late deformation in the Ural Orogen, in latest Carboniferous-early Permian time. A major N-S fault, ancestral to the Keys Fault, partitioned the EISB into two parts; the eastern part underwent significant regional uplift and erosion of Pennsylvanian Coal Measures strata. Inversion anticlines developed adjacent to the Keys Fault and elsewhere, resulting in severe local excision of Carboniferous strata.

In late Permian time, the newly created supercontinent of Pangaea was subjected to extensional stress resulting from the opening of the Tethys Ocean. A major rift system extended en-echelon NW-SE through western Britain, with thick clastic and evaporite-bearing sequences. Propagation of the rift through the eastern Irish Sea was facilitated by the presence of the previously established N-S trending structures. Further extension in Triassic time on the N-S trending rift marginal fault systems led to rapid subsidence, thick clastic rift-fill and halokinetic activity.

Jurassic and Cretaceous sequences were entirely removed by Alpine inversion, starting in latest Cretaceous time and culminating in the Miocene. These events coincided with lithospheric doming and magmatic intrusion associated with the Scottish Tertiary Igneous Province, consequent on the opening of the Atlantic Ocean east of Greenland, in Palaeogene time. Alpine inversion was focussed on all the major extensional faults of the Permo-Triassic rift system; further growth of Variscan anticlines deformed their cover; salt movement enhanced the N-S structural trends; thrusts developed in zones buttressed by regional highs.

Heterogeneous stress distributions within shallow subduction mélanges: Do they control the distribution of seismic features?

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Within the shallow portion of subduction zones, tectonic mélanges are produced by distributed shear within downgoing sediments above the oceanic plate. Basaltic slabs (incorporated into the sediments through plucking and underplating) and sandstone layers form boudins within a shale dominated matrix due to strength contrasts within this zone of distributed shear. These tectonic mélanges are the host rocks of seismicity in subduction zones at shallow depths. Fluidized granular flows and pseudotachylytes are evidence for paleo-seismicity within exposures of mélanges, and occur preferentially along the contacts of shale matrix mélange and sandstone or basaltic layers. Detailed mapping within the Mugi Mélange, Japan has revealed basalt and sandstone boudins surrounded by cataclasites derived from comminution along the boundaries of the boudins. We model the stress concentrations around the strong basalt and sandstone boudins using the Power-Law Creep (PLC) toolbox developed at the University of Maine, which uses Asymptotic Expansion Homogenization (AEH) over a finite element mesh to determine the instantaneous stress distributions in a multiphase system. We model the shale matrix mélange to be deforming through a modified flow law for viscous creep, where at a strain rate of 10^{-10} s^{-1} the flow stress is ~10 MPa under the pressure and temperature conditions during deformation, and describe the behaviour of the basaltic and sandstone blocks using experimentally-derived power law flow laws. The results show that differential stresses high enough to cause comminution of the basalts (~300 MPa) correspond strongly to areas around the blocks with basalt derived cataclasites. We compare the microstructures of these natural cataclasites with those formed from other workers' constant stress experiments. In these experiments, conducted at a differential stress below the short term strength of the sample (determined in constant strain rate experiments), slow brittle creep occurs due to distributed cracking and cataclastic flow, followed by failure induced by chemical weakening along cracks. These long duration (minutes to days) failure events may be a geologic explanation of slow slip events in the shallow portion of subduction zones. Around the margins of the sandstone boudins, we observe thick dark seams of phyllosilicates, presumably due to increased efficiency of pressure solution in areas of high differential stress. These seams may be preferentially exploited during seismic slip. Pseudotachylyte along the upper margin of the Mugi mélange has a matrix composed of illite, and contains survivor grains of Fe and Ti oxides, quartz, and plagioclase. This is consistent with preferential melting of a phyllosilicate seam rich in Fe and Ti along the shale-sandstone interface. We hypothesize that the heterogeneous stress distributions within subduction mélanges controls the distribution of seismic features seen in the field.

Relative timing between the Canadian Malartic footprint and the regional metamorphism of the northeastern Pontiac Subprovince, Abitibi, Québec

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The Pontiac Subprovince is located south of the Cadillac Larder Lake Fault Zone in the Superior Province. Whilst most gold deposits in the Abitibi Subprovince occur north of or straddle this deformation zone, Canadian Malartic Gold is the only known deposit where the main body is hosted within the Pontiac Subprovince.

The Canadian Malartic deposit is spatially associated with intermediate intrusive rocks, but shares many common genetic attributes with neighboring Au deposits mainly hosted by volcanic rocks. Characterizing the relative timing between the mineralization and regional metamorphism is key to understanding the hydrothermal alteration footprint that surrounds the deposit. In the vicinity of the Canadian Malartic deposit, the regional metamorphism is characterized, from North to South, by biotite, garnet and staurolite metamorphic zones. The regional fabric is defined by an E-W, NW-SE lepidoblastic ductile foliation in which garnet and staurolite porphyroblasts are interpreted to be syn- to late-kinematic. The Au mineralization of the Canadian Malartic deposit is located in the biotite zone at the greenschist metamorphic grade, where the absence of porphyroblasts hampers interpretations of the textural relationship between the mineralization, hydrothermal and metamorphic minerals. Nonetheless, macroscopic and thin section observations suggest that the main mineralizing event is associated with the main deformation event, which suggests that it was coeval or preceded porphyroblast growth during peak metamorphism.

Lu-Hf dating of garnet from three outcrops south of the towns of Malartic and Val-d'Or yielded a consistent age of ~2657 +/- 7 Ma that is inferred to represent the growth of garnet on a prograde path close to metamorphic peak conditions. This age, compared to a previously published Re-Os age of ca. 2664 Ma on molybdenite hosted with mineralization in the main fabric is consistent with our interpretation that the bulk of the mineralization is coeval with or preceded regional metamorphism.

This contribution has a significant impact on our understanding of the Canadian Malartic deposit. (1) Regional metamorphism has likely overprinted the early hydrothermal halo, which is an important factor for the interpretation the mineralogical footprint of this deposit. (2) Its relative timing with regional metamorphism is significantly different than for late-metamorphic orogenic Au deposits hosted in rocks at green schists metamorphic grade.

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A tale of two lakes: Algal palynomorphs record the history of Walden Pond and Sluice Pond since the Pilgrims landed in eastern Massachusetts

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Anthropogenic impact is a major environmental concern, but it must be distinguished from natural stressors. Two small lakes in NE Massachusetts, Sluice and Walden Pond, are similar in size but experienced dissimilar histories over the past 400 years. Palynological analysis of sediment cores from the deep basins of both lakes allows pre-disturbance conditions to be reconstructed, and comparison with historic records allows assessment of ecosystem response to human activity in their respective watersheds. Pollen records vegetation and algal palynomorphs (e.g., dinoflagellate cysts, chlorococcalean green algae and desmid half-cells) record conditions in the water column and on the lakebed. Cysts of the dinoflagellates Peridinium willei and P. volzii dominated algal palynomorph assemblages below the Ambrosia rise, recording oligotrophic – mesotrophic conditions in Walden and Sluice Pond prior to European land clearing. A sharp increase in the cyanobacterium Microcystis marks the Ambrosia rise in cores from both lakes. The geochemistry and physical properties in both cores record an influx of terrigenous sediments and nutrients (nitrogen, phosphorus) from human waste and agricultural runoff. Marked differences in algal palynomorph assemblages in the Ambrosia zone record the different degree and type of anthropogenic impact on both lakes. Concord was settled in the 17th century but impact peaked when an amusement park was built on the eastern shore of Walden Pond in the early 20th century; the lake is now in a park under control of the Department of Conservation and Recreation (DCR). Abundant half-cells of benthic desmids (Cosmarium spp. including C. formosulum) in the upper part of the core record good light penetration in the mesotrophic Walden Pond, attributed to conservation efforts. In contrast, abundant planktonic chlorococcalean green algae (e.g., Pediastrum, Scenedesmus, and Coelastrum reticulum) in Ambrosia-rich sediments from Sluice Pond reflect turbid, hypereutrophic conditions resulting from urban runoff and industrial pollution by heavy metals; Sluice Pond is in a residential neighbourhood of Lynn (settled in AD 1629) that hosted thriving leather tanning industry during the 19th to mid- 20th centuries. Increased turbidity and toxic levels of heavy metal concentrations such as lead and zinc in the eutrophic Sluice Pond has negatively impacted some fresh water algae. Although there is evidence of positive effects of recent conservation efforts in both ponds, neither ecosystem has returned to pre-impact conditions.

Petrographic, geochemical, and isotopic fingerprint and economic potential of the ca. 780 Ma Gunbarrel LIP

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The ca. 780 Ma Gunbarrel Large Igneous Province (LIP) consists of spatially discrete suites of sills, dykes and minor volcanic packages distributed over a vast area in western and northwestern Laurentia, extending from Montana, Wyoming, and Idaho, USA in the south, to the Wopmay Orogen and the Mackenzie Mountains of Northwest Canada. Thick (≤100 m) sills and dykes at all localities are moderately evolved, augite + oligoclase–labradorite + ilmenite–magnetite gabbros and amygdaloidal basalts. Mineral chemical data for plagioclase and clinopyroxene in chill margin samples from a Hottah sheet in the Wopmay orogen indicates rapid and repeated turbulent mixing of geochemically and thermally similar magmas. The entire LIP shares a remarkably similar petrographic, geochemical, and isotopic fingerprint. All rocks preserve petrochemical evidence of an enriched MORB-like mantle source, but a small lithospheric component in the primary magmas resulted in elevated LILE, minor negative HFSE anomalies, and sub-depleted mantle but supra-bulk earth εNd values. The lithospheric component was slightly older, modestly fractionated, Sr-depleted, garnet-free (pyroxenitic?) lower crust or, similar material that was previously recycled into the lithospheric mantle. These data indicate that Gunbarrel magmas were generated by partial melting of an enriched MORB-like source in the spinel stability field and experienced interaction and mixing of multiple components (N-MORB, E-MORB, enriched lithospheric mantle?) in a periodically replenished and tapped magma chamber(s). The data support a model of a common, well-homogenized magmatic source derived from large, lower-most crust(?) magma chambers centred over an asthenospheric thermo-chemical anomaly (mantle plume) thought to lie to the west of present-day North America. These magmas were then rapidly emplaced across western Laurentia through a giant radiating dyke swarm with separate subswarms having slight systematic petrographic differences.

Gunbarrel magmas consist of both chalcophile-element depleted and undepleted magmas which suggests S-saturation and possible sulphide immiscibility, thus indicating Ni-Cu-PGE mineralization potential. However, no significant mineralization has yet been noted in Gunbarrel rocks. In the Mackenzie Mountains significant accumulations of redbed copper immediately follow Gunbarrel volcanism (Little Dal basalts). The slightly younger (ca. 700 Ma) Rapitan iron formation may have received some contribution of iron from continental weathering of the 725-715 Ma Franklin and 780 Ma Gunbarrel LIPs.

Structural and petrological constraints on the metamorphic evolution of the foreland-hinterland transition in the northern New Quebec Orogen, Nunavik

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The New Quebec Orogen (NQO) is a Paleoproterozoic orogenic belt located in the southeastern Churchill Province of northern Quebec, resulting from the protracted collision of the Superior Craton and the Archean Core Zone during formation of the supercontinent Nuna. The NQO is divided into a western foreland referred to as the Kaniapiskau Supergroup (KS), and an eastern hinterland which is composed of the Rachel-Laporte (RLZ) and Kuujjuaq zones. The Kuujjuaq Zone represents remobilized Archean basement. The KS and the RLZ represent metamorphosed and deformed supracrustal rocks and are the focus of this study. Several deformation events relating to the NQO, including two early compressional events (D_1 and D_2) and a late oblique compressional event (D_3), have been identified and analyzed with respect to relative timing of metamorphism and mineral growth.

Samples were collected across a 40 km transect across the foreland-hinterland transition with the emphasis of the study on the mineralogy and thermobarometry of sub-aluminous meta-sedimentary samples. Metamorphic grade generally increases from west to east with greenschist facies metamorphism recognized in the KS, and up to upper amphibolite facies metamorphism in the RLZ. Greenschist facies rocks from the KS typically contain a matrix of chlorite, muscovite, biotite, quartz, accessory epidote and titanite and, as metamorphic grade increases structurally upwards towards the greenschist-amphibolite transition, biotite and locally, garnet porphyroblasts. Amphibolite facies samples in the RLZ are typically composed of a matrix of muscovite, biotite, quartz, ±calcite, with abundant biotite, and garnet, and locally titanite, as well as plagioclase and microcline porphyroblasts in samples of intermediate meta-volcanic composition. Several aluminum-rich samples in the far eastern segment of the transect contain staurolite and garnet.

The western foreland attained peak greenschist facies metamorphism (D_1-M_1) during the initial accretion or collision between the Superior Craton and the Core Zone. Amphibolite-facies metamorphism (D_2-M_2) overprinted earlier M_1, however was only experienced in the hinterland samples. This was observed in garnet porphyroblasts with rotated S_1 inclusion trails. Retrograde metamorphism, M_3 syn-tectonic with D_3, was experienced across the entire orogen and resulted in abundant chlorite overgrowth, the replacement of biotite, the breakdown of garnet, biotite and staurolite porphyroblasts and new S_3 biotite and muscovite foliation growth.

We present quantitative thermobarometry using Theriak-Domino and in-situ U-Pb dating of metamorphic titanite, that will allow for constraints on a PTt path of both metamorphic and deformation events experienced across the northern NQO.

Holocene record of climate and marine primary productivity change in the Santa Barbara Basin, southern California

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High-resolution sedimentary records of dinoflagellate cysts and other marine palynomorphs from the Santa Barbara Basin (Ocean Drilling Program Hole 893A) demonstrate large variability of primary productivity during the Holocene, as the California Current System responded to climate change. Throughout the sequence, dinoflagellate cyst assemblages are characterized by the dominance of cysts produced by heterotrophic dinoflagellates, and particularly by Brigantedinium, accompanied by other upwelling-related taxa such as Echinidinium and cysts of Protoperidinium americanum. During the early Holocene (~12-7 ka), the species richness is relatively low (16 taxa) and genius Brigantedinium reaches the highest relative abundance, thus indicating nutrient-rich and highly productive waters. The middle Holocene (~7–3.5 ka) is characterized by relatively constant cyst concentrations, and dinoflagellate cyst assemblages are indicative of a slight decrease in sea-surface temperature. A noticeable increase and greater range of fluctuations in the cyst concentrations during the late Holocene (~3.5-1 ka) indicate enhanced marine primary productivity and increased climatic variability, most likely related to the intensification of El Niño-like conditions.

Identifying the hanging wall of the West Cycladic Detachment System, Aegean region, Greece

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The Cyclades (Aegean, Greece) formed during Miocene back-arc extension, which has led to the formation of several Cordilleran-type metamorphic core complexes, which exhumed along at least three low-angle normal fault systems. The timing, location, orientation and kinematics of the low-angle normal faults has been a matter of debate mainly because the detachments arch over the islands and only remnants of the fault systems and small klippen of hanging wall rocks are preserved. The small (4 km^2) island of Aghios Georgios, 20 km south of the Attica Peninsula, resides to the south-west of the crustal scale, low angle normal fault system, the West Cycladic Detachment System (WCDS). The Western Cyclades of Makronisos, Kea, Kythnos and Serifos below the WCDS contain relict Oligocene-Eocene blueschist facies footwall rocks recording pervasive Miocene greenschist facies deformation. Published zircon (U-Th)/He dates from the Western Cyclades record cooling at 14-9 Ma. Strongly altered hanging wall rocks are only rarely preserved within the system. The rocks on Ag. Georgios consists of meta-sedimentary to meta-igneous rocks consisting of greenschist metamorphic minerals Ms+Chl+Ep+Clz+Ab±Amp. Dynamically recrystallized feldspar suggest earlier upper greenschist to amphibolite facies conditions. Petrographically, the muscovite is in bundles that define an anastomosing foliation, and is locally sericitized. The granitoid sample show the bundled muscovite surrounding pre-kinematic subhedral epidote. Elemental maps of the muscovite from most of the rocks illustrate rims of elevated Fe and Mg, which corresponds to fine grained, deformed chlorite. New Ar-Ar geochronology on the muscovite yields c. 60 Ma dates, markedly older than the middle Miocene Ar-Ar ages from the footwall. Moreover, new (U-Th)/He zircon dates from the small island indicates cooling at ca. 21 Ma. The older ZHe and Ar-Ar dates compared to the footwall rocks support the model that Ag. Georgios represent the hanging wall rocks of the WCDS. Additional geochronology on the synkinematic mica will further evaluate the timing of deformation along the structurally higher crustal block.

Diagenesis in the Mg-carbonate system: Implications for carbon sequestration

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Mineral carbonation, a process for sequestering anthropogenic carbon dioxide (CO_2), aims to enhance the natural rate of silicate weathering to produce silica and Mg-carbonate phases, the latter acting as long-term sinks for CO_2. Hydromagnesite-magnesite playas near Atlin, British Columba, Canada formed from weathering of ultramafic rocks and are a natural analogue for carbon storage. The playas host a complex assemblage of hydrated and anhydrous Mg-carbonate minerals that undergo diagenetic transformations at Earth's surface conditions. A systematic experimental study of Mg-carbonate mineral precipitation and diagenesis showed that hydrated Mg-carbonate minerals including those present in the playas decompose via the Ostwald rule of phases to form less hydrated, more stable phases under humid, but nominally dry conditions. These phase transitions (lansfordite nesquehonite dypingite hydromagnesite) occur via coupled dissolution–precipitation reactions within interfacial water layers on mineral surfaces. In addition to direct precipitation from porewaters, magnesite in the playas forms through diagentic reactions with very high Mg:Ca (~100 to 1000:1) groundwaters that cause dolomitization of Ca-carbonate followed by magnesitization. These diagenetic reactions within the Mg-carbonate system result in greater phase stability, which is required for long-term carbon storage in minerals. Conversely, experiments that incorporated both hygroscopic Mg-carbonate minerals and silica demonstrated that these two products of mineral carbonation react to produce the smectite mineral, stevensite, when stored together at high relative humidity (e.g., Eq. 1).

$$3MgCO_3{\cdot}3H_2O + 4SiO_2 = Mg_3Si_4O_{10}(OH)_2{\cdot}nH_2O + (8\text{–}n)H_2O + 3CO_2 \text{ (released)} \qquad \text{(Eq. 1)}$$

This reaction goes to completion within 7–18 months of storage at ~100% relative humidity and temperatures relevant to Earth's surface environments (23–75 °C). These reactions can occur in the absence of observable liquid water and proceed via reaction of either hydrated Mg-carbonate or magnesite with amorphous silica, cristobalite or to a lesser extent quartz. This finding has major implications for mineral carbonation processes such as the reaction of Mg-silicates (e.g., forsterite) with CO_2 to form Mg-carbonate and silica because the sequestered CO_2 may be released if these minerals are stored together. Diagenetic reactions, either favourable or unfavourable, must be considered in the design of mineral carbonation strategies.

Transformation of the Geological Survey of Canada and Canadian Geoscience during the second half of the Twentieth Century --- A personal perspective

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In the second half of the 20th century, in the wake of World War II, during "the Cold War" and "the Space Race", while the human population increased from 2.5 billion to 6.0 billion, and the per capita consumption of energy and other earth resources increased at about the same rate, the geosciences (and the GSC) were transformed by innovative new technologies and scientific concepts, and by increasing concerns about earth resources.

As packhorses and canoes were replaced by helicopters, and notebooks, printed air photos and maps, by tablet computers, GPS, and digital images, there was a dramatic increase in the rate and precision of GSC geological mapping of Canada; and the GSC introduced new geophysical and geochemical maps and mineral exploration technologies.

On a global scale, as new technologies unveiled the geology of the 70% of Planet Earth's surface that was hidden below oceans, an ingenious new Earth-system conceptual model emerged:

Planet Earth is a dynamic, evolving system of inter-active concentric terrestrial spheres (solid inner core, molten outer core, mantle, lithosphere, hydrosphere, atmosphere and biosphere). Gravity and variations in internal and/or solar heating drive flow within (and between) the terrestrial spheres.

New ocean-floor lithosphere, created continuously by buoyant upwelling and symmetrical 'seafloor spreading' of hot mantle beneath intra-ocean ridges, cools and thickens while advancing along Earth's spherical surface. Eventually, it becomes negatively buoyant and is consumed by sinking asymmetrically (edgewise) back into the mantle beneath deep ocean trenches and associated volcanic arcs. Continental crust is created by 'mountain building' in the zone of convergence above the sinking oceanic lithosphere.

GSC geological mapping changed with the realization that deformation in Canada's Phanerozoic and Proterozoic "geosynclinal" orogenic belts included foreign 'terranes' that were accreted by subduction-consumption of intervening oceanic lithosphere.

The interdisciplinary and international collaboration that is implicit in the Earth-system concept was promoted and nurtured within Canada by the GSC. The GSC provided support and leadership for: the GSA's Decade of North American Geology Project; the establishment of Canada's world-renown Lithoprobe Project; Canada's participation on the International Upper Mantle Project, the International Geodynamics Program, and the International Lithosphere Program, and the International Geological Correlation Program; and also in securing Canadian membership in the International Ocean Drilling Program. The GSC also provided part-time employment and invaluable fieldwork or laboratory experience to legions of future geologists geochemists and geophysicists for Canadian industry, academia, and government. (I was one of them.)

Keynote (40 min): Giant economic iron formation and phosphorite deposits: Applied sedimentology of ancient upwelling systems

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Giant iron formation and phosphorite deposits are bioelemental sedimentary rocks commonly associated with coastal upwelling. Bioelemental sediments are composed of the nutrient elements Fe and P, which are concentrated in iron formation and phosphorite, respectively. These bioessential elements are necessary for numerous life processes that ultimately lead to their precipitation as stable minerals. Fe is an important micronutrient required for photosynthesis and integral to numerous proteins. P is a component of many skeletal systems, a building block of DNA, essential for cellular energy transfer, and limits biologic productivity over geological timescales. Economically, Fe is required for steel manufacture, and P is the critical ingredient in fertilizer that allows modern agriculture to feed the world's burgeoning population.

Because the deposition of iron formation and phosphorite is so closely linked to biology, periods of enhanced accumulation generally correspond to pronounced changes in the biogeochemical cycling of Fe and P through time. These globally recognized episodes possess an intelligible record of the Earth system feedbacks that regulated ocean-atmosphere composition, climate, and biologic evolution. The largest economically important iron formations formed in the Paleoproterzoic (ca. 2.5 to 1.8 Ga) when upwelling of anoxic, ferruginous seawater promoted the widespread precipitation of Fe-rich minerals on continental shelves. Although the earliest P-rich deposits are also Paleoproterozoic in age, upwelling-related phosphatic ore bodies did not develop until the Late Neoproterozoic. The deposition of these giant epeiric sea phosphorites began in the Ediacaran and persisted into the Devonian (ca. 635 to 410 Ma). Except for much smaller localized ironstones, the accumulation of upwelling-related Fe deposits ceased in the Phanerozoic because a well-ventilated water column precluded the transport of Fe. Instead, coastal upwelling produced peaks in phosphorite during the Carboniferous to Permian (ca. 305 to 252 Ma) and the Jurassic to Miocene (ca. 200 to 10 Ma). The latter contains the single largest accumulation of phosphorite on Earth, the Cretaceous-Eocene South Tethyan Phosphogenic Province.

The fact that giant iron formations are Precambrian, and economic phosphorites are generally a Phanerozoic phenomenon provides the initial starting point for greenfield exploration. Critical to the generation of exploration targets is the recognition that regardless of deposit type, all upwelling systems have a similar sequence stratigraphic architecture. This predictability provides a framework for delineating high-grade, synsedimentary ore zones such as the "taconite window" in iron formation, or condensed surfaces with thick, amalgamated beds of economic phosphorite that characterize phosphogenic systems.

A new map database of glacial geomorphological landforms in Finland

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The ever-increasing use of airborne LiDAR (Light Detection And Ranging) technology has revolutionized the mapping and documentation of geological and geomorphological characteristics. Geological Survey of Finland (GTK) has initiated the development of a new national geologic database in order to combine and store pre-existing data of surficial Quaternary deposits and landforms (Glacier Dynamic database or GDdatabase). The definition combines various Quaternary geological map databases between 1:20 000 and 1: 200 000 and other geological data. The main sources for GDdatabase polygons and lines are: 1. LiDAR-DEM data provided by National Land Survey of Finland, 2. GTK's Quaternary geological maps and data from aggregate, engineering geological and groundwater aquifer investigations. Simultaneously a multi-year mapping project has been set up to produce a cost-effective remote sensing high-resolution glacial dynamic characteristics for entire Finland with minimal fieldwork. The various themes combine both the main geological unit information and the new glacial geomorphological data.

The glaciodynamic themes included in the GDdatabase are: 1. Mega-scale glacial lineations (MSGL) drumlins, rockdrumlins, megaflutings reflects the variations in glacier-bed continuum under the fast ice flow velocities and various classes of hummocky and ribbed moraines that are referred to much slower or sluggish ice flow velocities. 2. Large ice marginal complexes and smaller zones of end moraine ridges or De Geer moraines are also included in the classification. 3. Glacial melt stream landforms, like eskers, interlobate eskers, deltas, sandurs and various types of glaciofluvial hummocky terrains are related to later stages of the deglaciation.

This new map database will be significant contribution to the applied geoscience, including aspects such as mineral exploration, groundwater studies and land use assessment in Finland. In the future, the GDdatabase will be linked to a nationwide stratigraphical unit classification (Finstrati) and extended to the national subsurface 3D geodatabases.

Fate of adsorbed molybdate during reductive transformation of iron(III) (hydr)oxides under advective flow conditions

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Elevated concentrations of Mo in groundwater are a growing concern in mining environments worldwide. Molybdenite [MoS_2] is a principal source of Mo in ore deposits; however, association with U, Cu, V, and As in other minerals is common. Consequently, elevated Mo concentrations are often observed in waste deposits produced at mines exploiting porphyry-type Cu deposits, unconformity-type U deposits, oil sands bitumen deposits, and other ore systems. Biogeochemical weathering of minerals within wastes generated and release, transport, and attenuation of Mo remains a significant challenge. Adsorption onto Fe(III) (hydr)oxide phases is an important mechanism of Mo attenuation in mine wastes and groundwater systems. Ferrihydrite [$Fe_2O_3 \cdot nH_2O$] and goethite [α-FeO(OH)], which are common in mine wastes, soils, sediments and aquifers, are likely important for Mo attenuation. However, Fe(III) (hydr)oxides can undergo reductive transformation or dissolution under anoxic conditions, which may lead to Mo release or re-partitioning. Laboratory column experiments were conducted to examine the fate of adsorbed molybdate (MoO_4^{2-}) during Fe(II)-induced transformation of ferrihydrite and goethite. Columns were packed with ferrihydrite- or goethite-coated sand and approximately 120 pore volumes of 0.1 mM molybdate solution buffered to pH 6.5 were pumped through each column over roughly 100 days. Approximately 70 pore volumes of solutions containing 0.2 mM Fe(II) or 2.0 mM Fe(II) without molybdate were then pumped through the columns to promote reductive transformation of the Fe(III) (hydr)oxides. Raman spectroscopy and scanning electron microscopy – energy dispersive X-ray spectroscopy (SEM-EDX) revealed that lepidocrocite [γ-FeOOH] was the major transformation product in the both goethite and stored at these mines can result in elevated Mo concentrations in associated surface and groundwater systems. Information on geochemical controls on Mo mobility within mining environments is limited. Consequently, predicting the ferrihydrite columns. Despite this transformation, 70 to 97 % of Mo was retained within the columns. Molybenum retention was generally greater with the 2.0 mM Fe(II) input solution and for ferrihydrite compared to goethite columns. X-ray absorption spectroscopy (XAS) indicated that the Mo coordination environment changed from tetrahedral to octahedral during transformation, suggesting Mo may be incorporated into the transformed Fe phases with a distorted structure. Overall, this research suggests reductive transformation of Fe(III) (hydr)oxides may not promote extensive mobilization of adsorbed molybdate.

Keynote (30 min): Athabasca Basin diagenesis and diagenetic-hydrothermal alteration: What it is and how it was characterized

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The diagenesis and clay mineralogy of the Athabasca Basin (northern Saskatchewan, Alberta), and the superimposed diagenetic-hydrothermal clay alteration associated with unconformity-type uranium mineralization, have been well-studied. Historically, methodologies for examination of the diagenetic and metallogenetic histories included optical microscopy, XRD, and lithogeochemistry, with restricted SEM and EMP. With technological improvements, SWIR spectroscopy replaced XRD and use of stable isotope geochemistry has become routine. Hyperspectral core mapping is being introduced at the expense of SWIR.

The present Athabasca Basin fill comprises Paleo- to Mesoproterozoic, dominantly fluvial, red-bed sandstone, ~2 kilometres thick, nearly flat-lying, unmetamorphosed, and mostly undeformed. Pore space was initially filled with detrital kaolinite, Fe-oxyhydroxides, and trace amounts of heavy minerals (zircon, tourmaline, Fe-Ti oxides, monazite). The basin fill developed from greenish, non-hematitic, early-diagenetic framboidal pyrite-bearing, detrital quartz-dominant orthoquartzite, to non-pyritic oxidized strata, with quartz grains having a thin hematitic dust rim beneath quartz overgrowths and local hematite in pores. Burial compaction produced concavo-convex grain boundaries and local stylolitization.

The basin-scale pre-mineralization diagenetic mineralogy is consistent, with three forms of superimposed clay mineral alteration. The pores are typically filled with variably recrystallized/transformed detrital kaolin and prograde diagenetic 1Mc illite, local hematite, and trace amounts of diagenetic APS minerals (svanbergite-goyazite) and tourmaline overgrowths. Kaolin morphology varies from detrital (sub-)vermicular kaolinite to dominant coarse-grained subhedral diagenetic dickite, with incomplete transformation of kaolinite to dickite. Diagenetic 1Mc illite formed through replacement of kaolin, also with incomplete alteration of kaolin to illite. Di,trioctahedral Al-Mg sudoite is only locally present.

Superimposed on the regional clay mineral background are sub-basin-scale linear regions (10s of km) containing anomalously-high 1Mc illite proportions. Some also contain sub-parallel zones of anomalous sudoite and dravite.

Subsequently, the structurally-focused unconformity-type uranium deposits, with associated diagenetic-hydrothermal clay alteration, were formed. The Mesoproterozoic high-grade egress-style polymetallic mineralization, associated with fault zones that offset the unconformity, comprises veins and lenses of semi-massive uraninite/arsenide/sulphide mineralization. Host-rock alteration includes redox bleaching/hematitization, desilicification, and clay mineral alteration forming a mineralogically-zoned envelope of strongly-altered dequartzified rock containing illite ± sudoite after kaolin and a secondary hematite shell. Sudoite occurs toward the centre of the alteration halo, with trioctahedral Mg chlorites locally at the core. Enrichments in alkali-deficient dravite, APS minerals (florencite), pyrite, and siderite are commonly present. Contrasting with diagenetic background, the characteristic illite polytype is 1Mt and the APS mineral is florencite.

Late-diagenetic, fault-related, low-temperature retrograde diagenetic alteration includes leaching of pore illite and formation of poorly-crystalline kaolinite.

Lead isotopes in exploration for basement-hosted uranium deposits at Kiggavik, Nunavut

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Lead isotopes have been proposed as indicators of the fluid evolution of sedimentary basins and as guides for exploration of unconformity-type uranium deposits. In uranium exploration, the Pb isotope ratios provide information on timing of mineralization and element remobilization, and presence and timing of U and Pb migration on a regional basis and at drill hole scale. In sandstone, samples distal to known uranium mineralization dominantly show non-radiogenic Pb isotope ratios using Weak Acid Leach (WAL) ICP-MS data, while samples proximal to mineralization often display radiogenic Pb isotope ratios unsupported by the amount of U in the sandstone. However, the Mesoproterozoic Kiggavik uranium deposits of the NE Thelon region, Nunavut, are all basement-hosted, within a completely different lithological environment: the metamorphic basement; typically the Neoarchean metasedimentary rocks of the Pipedream assemblage (Woodburn Lake group) and epiclastics of the ~2.6 Ga Snow Island Suite, but also in Hudson granite and presumed Archean granitic gneiss. Many of the structurally-controlled deposits and mineralization are encompassed by clay mineral host-rock alteration haloes and contain several generations of pitchblende hosted by fault-related fracture systems and foliation-parallel veinlets.

Partial-digestion (reverse AR) ICP-MS geochemical data, including Pb isotopes, are typically obtained in exploration for unconformity-type uranium deposits, however, WAL Pb isotopes data are not, due to extra cost and lengthy preparation time. The Kiggavik samples were analysed for Pb isotopes by both partial-digestion and WAL at the Saskatchewan Research Council Geoanalytical Laboratory. Overall, the partial-digestion results are similar to WAL results, indicating that interpretation of the Pb isotope signatures can be successfully carried out from partial-digestion isotope data if WAL data are not available.

Plots using the $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$, and $^{207}Pb/^{206}Pb$ ratios for the basement rocks at Kiggavik show systematic trends useful for exploration vectoring. 206Pb/204Pb downhole plots, adjusted for U content, highlight those isotopic values that are unsupported by the amount of U in the rock, as do $^{206}Pb/^{204}Pb$ ‘excess lead’ plots. $^{207}Pb/^{206}Pb$ and $^{207}Pb/^{204}Pb$ ratios also show complementary trends downhole relative to location of uranium mineralization. U-Pb isotopic data suggest that many samples from the deposit areas display unsupported excess Pb (eg. Contact, Bong, End).

The Pb isotope distributions in the Kiggavik basement lithologies, not in a sandstone environment, show that Pb isotopes can be useful for indicating elevated potential for presence of uranium mineralization and can provide vectoring information useful for uranium exploration within the Kiggavik region.

Effects of marine inundation on till composition in permafrost terrain South of Wager Bay, central Mainland Nunavut

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In northern Canada, systematic till sampling in frost boils is an exploration technique commonly used to find commodities of economic value. Post-depositional alteration by various processes can modify the first order sediment, resulting in a less suitable deposit for drift prospecting. Below the limit of the post-glacial marine inundation, reworking and winnowing processes by waves and currents may remove the fine fraction of till, whereas the incorporation of fine-grained marine sediments may dilute the signature from local bedrock, leaving a different material from till collected above the marine limit. A detailed study to evaluate the effects of the post-glacial marine processes on till texture and geochemical composition was initiated in the summer of 2016 at two separate sites in central mainland Nunavut (NTS 56B and NTS 56C) where paired frost boils located on either side of the well-defined local marine limit were collected. The sampling sites were chosen using airphoto interpretation and ground truthing observations, concentrating on the presence of thick till above and below the marine trimline, and continuous bedrock units along the trimline. The first site is characterized by intensely wave-washed surfaces surrounded by bouldery beaches forming a distinct trimline with unmodified till-covered surfaces above; the second site forms a clear trimline around a small topographic high forming wave-cut notches between intact till above and reworked till below the marine limit. For each site, two frost boils were sampled; one was located immediately below the marine limit and the other directly above. Several samples (~3 kg each) were collected from each frost boil along a vertical profile at 10-15 cm intervals, down to 95 cm maximum depth. Five small field duplicate samples were also collected near each frost boil at approximately 40 cm depth to measure the local variability. A total of 54 samples were collected for this study. Geochemical and textural analyses were performed on the samples to evaluate variations with depth and between sites. Analyses are currently underway and the results that will be presented should help assessing the impact of marine inundation on till composition in soils affected by cryoturbation.

Glacial dynamics of the Quebec-Labrador sector of the Laurentide Ice Sheet in northcentral Quebec/Labrador

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Throughout the Wisconsin glaciation, an ice dome developed in the eastern sector of the Laurentide Ice Sheet covering northern Quebec and Labrador. The complex geomorphological record created by the Quebec-Labrador ice dome, indicates that it was a mobile dome throughout the Wisconsin. Previous reconstructions of ice-divide migration through time, the reported effect of this migration on sediment dispersal, and the reconstructions of the regional deglacial history are based upon limited data that have led to a number of conflicting interpretations. This quandary has implications for our understanding of large ice sheet dynamics as well as a number of other applications, such as drift prospecting in glaciated terrain. Till analysis for clast provenance, indicator mineral content, and matrix geochemistry are examined to establish dispersal patterns and are combined with outcrop scale glacial flow indicators to establish and ice-flow chronology of a vast region, east of Schefferville, Quebec. Analysis of cosmogenic (^{10}Be) inventory in bedrock surfaces and till is used to constrain the erosion and subglacial thermal regime interpretation. Dating of erratics, through cosmically produced ^{10}Be, and dating of proglacial littoral sediments through optically stimulated luminescence are used to better constrain ice-marginal retreat. Field observations document a glacial erosion history of four ice flow phases in the region: 1) an early northeastern flow across the entire region, likely from ice buildup in the Quebec Highlands; 2) a radial ice flow phase from near DePas batholith highland, once the Quebec-Labrador ice dome was fully established; 3) a younger phase of radial flow from a readjusted dispersal center which had shifted to the west, and 4) a deglacial ice flow phases associated with the downwasting of the ice sheet. Esker systems mapped in the region generally align with these later deglacial flows. This research will further our understanding of past glacial regimes, sediment dispersal patterns, and surficial geology related to large ice dome migrations.

Rocks are Us – 175 years of the Geological Survey of Canada

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Twenty-five years before Confederation, the Geological Survey of Canada (GSC) was established under William Logan to discover, map, and tell Canadians about the natural resources of the land around them. As Canada expanded, the GSC led the way in recording the shape of the landscape, the resources to be found and the people, animals and plants that lived here. Its exploration, maps, images and specimens became part of the national and international "vision" of Canada. It affected our history, politics, art and public imagination.

Out of the GSC grew the National Museums of History, Nature, and Science and Technology. Over the years it also gave birth to the federal agencies that mapped our topography, and guided and stimulated the development of our resources. Although the Provinces and Territories now have similar agencies and have taken over some of its activities, the GSC remains the one federal agency and centre of expertise that is responsible for assessing and documenting the geology and resources of the whole Canadian landmass and offshore areas.

Gravitationally-driven extensional collapse of a large hot orogen: Evidence from the western Grenville Province

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As observed in the Himalaya-Tibet Orogen, and modelled so successfully by Rebecca Jamieson and colleagues, the hinterland of a large hot collisional orogen is the site of an orogenic plateau underlain by crust of approximately double normal thickness. Perhaps less widely recognized, however, is that gravitationally-driven extensional collapse (aka orogenic collapse) of such large regions of thick elevated crust is inevitable ─ a result of the relationship that the scale of gravitational forcing is proportional to the volume of elevated crust and therefore an order of magnitude larger than the surface forces responsible for crustal shortening. Moreover, the gravitational forces are acting on profoundly weakened deep crust due to its prolonged burial at upper mantle depth and temperature. This presentation builds on Jamieson et al.'s interpretation that the Grenville Province is a remnant of a large hot orogen by focussing on empirical evidence for its subsequent extensional collapse across a range of scales, and concludes that it is one of the best preserved Precambrian examples of a collapsed large hot orogen.

First-order, orogen-scale evidence for collapse of the Grenvillian hinterland comes from the post-peak extensional juxtaposition of gneissic 'belts' up to hundreds of km in length defined by contrasting peak-Ottawan metamorphic pressures ranging from ≥1.1 to ≤0.6 GPa (orogenic infrastructure), including an 'orogenic lid' (composed of remnants of the orogenic superstructure) that lacks evidence for Ottawan metamorphism and ductile deformation. Second-order regional scale evidence is centred on the deduction that the infrastructure and superstructure define the core and cover of large extensional metamorphic core complexes, which is supported by third-order outcrop observations that much of the structural and metamorphic character of the gneissic infrastructure developed after the Ottawan metamorphic peak during exhumation and retrogression. We use the Ottawa River Gneiss Complex in the western Grenville Province of Ontario and western Quebec to illustrate these developments in understanding of the scale and style of orogenic collapse in the Grenville Province and conclude that it is the regional scale of the process, which greatly exceeds the purview of most structural-metamorphic studies, that has led to its role being under-appreciated until recently.

Constraining the thermal evolution of the UG2 reef, Bushveld Complex, South Africa

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The Bushveld Igneous Complex in South Africa is the largest known layered mafic intrusion and is host to extensive chromium and platinum group element (PGE) reserves. Its characterization typically follows, as a first approximation, a simple model of a fractionating magma chamber where the deposition of increasingly fractionated layers produces a stratigraphically distinct structure. Genetic models may be adjusted to included episodes of magma replenishment and differentiation in an attempt to constrain the petrogenesis of layers. Implicit in this model is a requirement for the units to follow a typical younging-up sequence. Recent U-Pb dates suggest the emplacement of the ultramafic layers of the Upper Critical Zone occurred after the emplacement of the mafic hanging-wall and foot-wall lithologies as a series of discrete sills. Discontinuous anorthosites flanking both the upper and lower contacts of the UG2 pyroxenite-chromitite unit resemble restites and have been interpreted to have formed by the partial melting of norite and gabbronorite host rocks. Physical evidence for out-of-sequence sill emplacement relies upon the observation of textural and composition changes occurring symmetrically about the mineralized ultramafic unit. Norites outside regions of significant interpreted thermal influence have a larger modal abundance of quartz and alkali-feldspar in the solid interstitial phase assemblage. Plagioclase crystals within marginal anorthosites close to the ultramafic layers display larger degrees of annealing to an adcumulate texture whereas the increase in intercumulus liquid in the rocks farther from the intrusion more closely resemble that of an orthocumulate or mesocumulate texture. Simultaneous increases in the extent of zoning within plagioclase crystals are observed closer to the contact of the UG2, within the adcumulus zone. The observed occurrence of loss of intercumulus material coupled with preservation of zoning in plagioclase in the marginal anorthosites is consistent with the hypothesis that the anorthosites formed as a result of partial melting both above and below the UG2 macrolayer, followed by rapid cooling that preserved the zoning in plagioclase. Here we model the duration and extent of thermal influence caused by the injection of a hot UG2 magma constrained by the time-integrated history of compositional equilibration of zoned plagioclase crystals. This suggests a major difference in the cooling rate of the rocks directly opposed to the UG2 from those outside its zone of thermal influence due to the imposition of a late high temperature overprint on an older record of slow cooling of the mafic host rocks.

Subglacial landscape zones and their glacial dynamics based on surficial geology, till geochemistry, and detrital ^{10}Be: Hall Peninsula, southeastern Baffin Island

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Relict non-glacial surfaces occur on several high plateaus of the Canadian Arctic. These surfaces are commonly surrounded by a zone of areal scouring, which is in turn crosscut and dissected by linear glacial troughs leading into coastal fjords. It has been demonstrated that chemical weathering and cosmogenic inheritance from pre-Late Pleistocene exposure to atmosphere is high across relict surfaces and is lacking in glacial troughs. However, the predicted gradual decrease of inheritance across the areal scouring zone due to subglacial transport and sediment mixing (dilution) is seldom documented. The details of this predicted continuum, however, not only depend on subglacial thermal regime, but also on sedimentary processes that are modulated by variations in bedrock lithology, as well as by ice flow shifts. In order to capture the net effect of all these factors, we analyzed the glacial geomorphology and geology of Hall Peninsula, southeastern Baffin Island, by integrating recent mapping, a large industry till geochemical database, as well as 18 ^{10}Be results from till matrix from contrasting landscape zones. Glacial landscapes are analyzed using a GIS-based index that uses bedrock-controlled lake density and subglacial landform metrics. Dispersal patterns were mapped using multivariate statistical approaches and the Random Forest algorithm, an innovative 'machine learning' technique. Relationships are identified between bedrock geology, ice flow indicators, dispersal patterns, and cosmogenic (^{10}Be) inheritance in till. Dispersal patterns starting along the outer edge of relict surfaces are longer where abundant evidence of glacial erosion exists in the areal scouring transition zone. Their shape also seems to capture the ice flow phases identified through remote sensing and field mapping. Cosmogenic (detrital ^{10}Be) results are also spatially consistent with the other observations, providing additional constraints to the overall subglacial process reconstruction. The integration of glacial geology and bedrock maps with large till geochemical datasets supplemented with targeted cosmogenic isotope results, shows great potential for advancing our understanding of subglacial processes and related sediment-landsystems.

Using susceptibility modelling to determine terrain sensitive to subsurface water pressurization in permafrost landscapes

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Warming temperatures in Arctic regions has resulted in changes to the thermal, hydrological and geotechnical properties of the active layer and the uppermost permafrost leading to increased permafrost degradation and disturbance. Slope failures such as active layer detachments (ALDs) and mud ejection features (ME), two forms of permafrost disturbance, are both surface expressions of high pore-water pressure (PWP). High pore-water pressures generated at the thawing front and from deep active layer thaw causes slope instability and can lead to potentially hazardous forms of permafrost disturbance. While both ALDs and MEs have similar processes of formation, they are morphologically different and found largely, in discrete areas. In order to effectively assess and mitigate permafrost disturbance, it is important to understand how pore-water pressurization occurs across the landscape. To predict areas that have the potential for subsurface pressurization, statistical susceptibility models of ALDs and MEs were used to identify key landscape variables contributing to their occurrence and areas of overlap were compared to examine how high PWP are distributed spatially.

Active layer detachments and MEs, both formed by high PWP at the Cape Bounty Arctic Watershed Observatory located on Melville Island, NU, were used as response variables in the generalized additive models. These models were fit with disturbed and undisturbed locations using spatially derived geomorphological predictor variables (i.e., slope, potential incoming solar radiation, elevation etc.) and spatially interpolated to the landscape producing disturbance susceptibility maps. Results show a strong mutual exclusivity in space between ALDs and MEs that suggest differential responses to pressurization across different terrain factors within relatively short distances. This highlights the complexity of the distribution of PWP and landscape response to changing hydroclimatic conditions. The susceptibility models demonstrate that ALDs are most probable on concave hillslopes with gradual to steep slope angles and relatively low incoming solar radiation, whereas MEs are associated with higher elevation areas, low angled slopes and in areas relatively far from water (drier).

While field measurements are necessary to further explain these patterns, these results reflect controls over how pressurization affects landscapes and the terrain types most susceptible to high PWP. Knowledge of the fundamental processes behind the initiation of disturbance improves our understanding of geomorphic sensitivity to permafrost degradation and is highly relevant for developing permafrost mitigation strategies.

Rivers Mile 183.6: A deep seated landslide in the clay-shale of the Riding Mountain Formation

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The Rivers Subdivision is CN's mainline railway linking Eastern and Western Canada. The Rivers Subdivision runs down the Assiniboine valley walls, across the Assiniboine River and up to the Qu'appelle Rivers Valley wall near St. Lazare, Manitoba. The valley walls are prone to movements ranging from shallow sloughing to deep seated landslides which frequently affect the railway, resulting in regular track maintenances, patrols and reduction in train speeds. The geology of the valleys generally consists in sand and clay-till layers overlying clay-shale of the Riding Mountain formation. Shale from this cretaceous formation typically possesses bentonitic seams and pre-sheared zones near surface that make them prone to landslides. Residual angle of shearing resistance can be as low as 6°. Water from the upper plains area infiltrates and travels through aquifers within the sand and till layers and on top of the clay-shale. Water is the primary driving force behind both types of landslides. An increase in the rate and number of instabilities was observed following heavy rainfall events of 2011 and 2014 in this area. There is a large active landside at Mile 183.6 Rivers Subdivision. The slide has been active since the realignment of the line in 1967 however the rate of movement has accelerated in the past 3 years. Site investigations indicate a deep seated landslide located within the clay-shale at a depth of 20 m below track level. In the past 3 years, slide movements have been in the order of 0.3 mm per day during the winter up to approximately 1.0mm per day in the summer. The slide involves a moving mass of approximately 550,000 cubic meters. Main remediation options under investigation are the construction of a large granular shear key or the installation of an extensive sub-drains system to lower the water table through the slide mass.

A 3-D framework of surficial geology for Canada

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As part of an initiative of the Canadian National Geological Survey Committee a 3D geological model for Canada is being developed by the GSC in collaboration with provincial and territorial partners. The current model consists of three layers, surficial geology, bedrock geology and mantle, with a focus on developing bounding surfaces and incorporating key existing regional models. This abstract reports on the development of a depth to bedrock surface that will provide a first iteration model of surficial sediment thickness for Canada. This national scale surface will be in-filled with local, higher resolution, and multilayer models. To facilitate progress on a national model, the Canadian geological landscape has been partitioned into distinct geological domains, (e.g. Precambrian Shield, Phanerozoic basins, orogenic belts) to permit both prioritization and employment of different approaches to the modelling of surficial geological thickness. A workflow is reviewed for 3D mapping with two different approaches to model development based on i) stratigraphic complexity, ii) sediment thickness, and iii) availability of subsurface data. Each of the areas is also prioritized so that a forward-looking plan can be developed for the country. For areas of Phanerozoic basins with thick surficial sediment cover and abundant data support, a data driven approach is employed. For large areas of the Canadian Shield and orogenic belts that have limited subsurface data, a knowledge driven approach relying primarily on landforms and surficial mapping is employed. For the Great Lakes and Canadian offshore, different approaches for data capture and level of data support available will be reviewed. To support modelling, there is a need for a common data framework, including a data model covering the breadth of input data and output models, a well-structured science language aligned with national and international standards, development of an appropriate metadata structure, and the capture of key stratigraphic and ancillary legacy data. In parallel with this 3D development, 2D provincial surficial geological compilations have been integrated into a single entity without interprovincial boundary reconciliation and themed to a single national legend to provide an enhanced surficial geological mapping coverage of Canada. The existing national compilation, similarly themed, is used for areas lacking compilation coverage. For Prince Edward Island existing provincial map coverage has been digitized from a previously published GSC map. This initial depth-to-bedrock 3D surface and nationally themed 2D surficial geology map constitute inaugural work to develop the surficial geology layer for the 3D geological model of Canada.

Communicating 3D geological models to a broader audience: A case study from southern Ontario

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With advances in computer hardware and software and availability of digital well and drillhole databases it is now possible to model and visualize subsurface geological relationships in 3D at regional scales. This is a valuable new tool for geologists in interpreting and understanding the geology and geological history of an area, and for communication of geological concepts to non-geologists.

A preliminary 3D model of the Paleozoic bedrock geology of southern Ontario has been constructed using Leapfrog implicit modelling software, subsurface geological data and expert knowledge. The model covers an area of 110,000 km2 representing the stratigraphic and structural relationships of 58 Paleozoic sedimentary bedrock formations, with an aggregate thickness of up to 1400 metres, plus the Precambrian basement and overlying Pleistocene sediments. Little of the Paleozoic succession crops out at the surface and thus requires synthesis and interpretation to understand.

In the virtual visualization environment, the geology can be examined from a number of perspectives interactively. The stratigraphic succession and boundary geometry can be identified from either unroofing of the units or cross-section slicing. In the southern Ontario model features that can be viewed and studied include depositional and erosional limits, reefs, faults, salt dissolution and collapse structures, regional dips, arches, depositional and structural basins, oil and gas traps, and regional aquifers. To increase the communication potential of the model to a broader audience an animation has been developed that provides a systematic progression through the model units, provides regional context, an overview to the data support, and illustration and explanation of geological features. Selected geological features are presented and highlighted through graphic techniques supported by embedded imagery, annotations, animations and maps.

Modelling the MOHO for the Canada3D initiative: An integrated approach using refraction seismic, teleseismic and gravity data

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The crust-mantle interface, in geophysics defined by the Mohorovièiæ discontinuity (MOHO), corresponds to the transition in P-wave seismic velocity from 6-7 km/s to 8 km/s. Although the MOHO is discontinuous across plate boundaries and can be offset by deep-seated fault zones and sutures, a national scale continuous 3D surface of the MOHO is included in the Canada3D initiative, to provide a first-order characterization of crustal thickness variations underneath Canada's landmass and offshore domains. Traditionally, MOHO depth estimates are derived from seismic refraction profiles, while in the last two decades teleseismic data are increasingly being used for this purpose. Gravity surveys, in addition, provide a third geophysical data source that is relevant for modelling the MOHO, as inversion algorithms based on simple layered Earth models are sensitive to the overall 0.3-0.5 g/cm^3 increase in density across the crust-mantle boundary. Because in Canada the spatial distribution of teleseismic stations and refraction transects is sparse, the MOHO surface can in practice only be compiled on a national scale when depth estimates from both methods are combined. The interpolation of 1235 MOHO depth estimates from both seismic datasets using kriging yields a reasonable first-order representation of MOHO topography across Canada displaying crustal thickness variation between the main tectonic domains, including the Archean cratons of the Canadian Shield, superimposed Proterozoic orogenic belts, younger Phanerozoic orogens and sedimentary basins. In addition to this seismic MOHO model, a higher spatial resolution model was generated by including MOHO depth estimates from gravity data inversion as a secondary variable using co-kriging. This model displays, in addition to the elements of the seismic MOHO model, structural details of individual orogenic belts, such as the Grenville orogen in Atlantic Canada, Cordillera, and Cape Smith Belt of northern Quebec. Integrating the three different data sources in modelling MOHO depth, however, is not straightforward. The mutual relationships between MOHO depth estimates from the different data sources are only moderately correlated due to inherent limitations in resolution, modelling assumptions, non-uniqueness in inversion and interpretation bias in each of the three individual MOHO depth variables. Nevertheless, exploiting the complementary value of MOHO depth variables, by using multivariate interpolation methods, such as co-kriging, results in crustal thickness models of higher spatial resolution that display enhanced structural detail. Future Canada3D research initiatives directed toward interpreting MOHO topography will include previously acquired seismic reflection profiles and magnetotelluric surveys to further enhance structural details with particular emphasis on MOHO discontinuities.

Mineral surface coatings in contaminated soils: Records of environmental processes and sinks of metal(loid)-bearing incidental nanoparticles

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Mineral surface coatings (MSC) preserve products of past (a)biotic soil processes and can sequester contaminants in soils and sediments. The coatings can contain complex mineral and organic components and their formation, composition and morphology are dependent on the mineralogical and chemical composition of the underlying grain and local biogeochemical conditions. In this contribution, we will show that mineral surface coatings can effectively sequester incidental nanoparticles (NP) which form in highly disturbed environments and can either structurally incorporate or adsorb contaminants from their immediate environment and transport them over longer distances by alluvial processes. NP play thus a significant role in dictating the transport, distribution, bioavailability and toxicity of contaminants in the environment. Soil samples are collected from Pb-Zn-Sb-As contaminated soils in Trail, British Columbia, Canada. MSC and mineralized organic matter (MOM) are examined with a combination of scanning electron microscopy, focused ion beam technology and transmission electron microscopy. The latter examinations show that sequestration of Pb-Zn-Sb-As bearing NP in MSC and MOM is controlled by their coalescence and crystal growth by particle attachment. NP of anglesite, Fe-As-phosphate and franklinite occur in matrices of amorphous silica and kintoreite (Pb-Fe-As-phosphate of the alunite group), which retain different stages of their coalescence and aggregation. A complex mineralogy of Pb-Zn-As-Sb bearing nano-size phases in MSC and MOM indicates that these phases control the mobility of metal(loid)s in the local soils as they are their sinks and their sources during weathering and alluvial transportation processes.

The solid-phase speciation and post-depositional mobility of arsenic in lake sediments impacted by ore roasting at Giant Mine, Yellowknife, NT, Canada

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Arsenic (As) concentrations in lake sediments in the Yellowknife area may be elevated as a result of the natural weathering of mineralized bedrock or as a result of the roasting of gold-bearing arsenopyrite (FeAsS) ore at Giant Mine, which resulted in the release of more than 20,000 tonnes of arsenic trioxide (As_2O_3) to the atmosphere as stack emissions. Arsenic trioxide, which is more bioaccessible than naturally occurring arsenopyrite, has potentially accumulated in the sediments of surrounding lakes, some of which are used for swimming and recreation by Yellowknife residents. Therefore, understanding the solid-phase speciation and post-depositional mobility of As in Yellowknife lake sediments is important and will provide valuable information to support risk assessment.

Long Lake is located approximately 5 km downwind of Giant Mine. Sediment cores were collected from shallow- and deep-water sites to understand how solid-phase concentrations of As vary with depth in the sediment column. Arsenic-rich sediment samples were analyzed using scanning electron microscopy coupled with mineral liberation analysis (SEM-MLA), electron microprobe analysis (EMPA), and synchrotron-based microanalyses to characterize As-hosting solid phases. The deep-water core was age-dated using ^{210}Pb methods. At the shallow-water site, sediment porewaters were sampled using dialysis arrays (peepers). The post-depositional mobility of As, including the direction and magnitude of diffusive transport across the sediment-water interface (SWI), was determined using dissolved As concentrations.

In the shallow-water core, the maximum sediment As concentration (90 mg/kg) occurs directly beneath the SWI, where the dominant host of As is authigenic Fe-oxyhydroxide (mean As content of 4 wt.%). Congruent porewater profiles for As and Fe indicate that the post-depositional mobilization of As is governed by the reductive dissolution of As-bearing Fe-oxyhydroxide. At this site, dissolved As is upwardly mobile and diffusing across the SWI; diffusive efflux accounts for approximately 90% of the As concentration in the overlying water column. In the deep-water core, the maximum sediment As concentration (1500 mg/kg) occurs 17.5 cm below the SWI. The sediments from this interval are enriched in As_2O_3 (as identified by SEM-MLA) likely originating from stack emissions; ^{210}Pb dating indicates that this horizon is coincident with the period of maximum emissions from the Giant Mine roaster. Authigenic As-bearing sulfides are the predominant host of As in this interval, however, indicating that the partial dissolution of As_2O_3 leads to the formation of less bioaccessible phases where reduced sulfur is available.

Large-area SEM imaging in geosciences: Bringing the world of multiscale and multi-source correlative microscopy to classrooms as a tool for teaching and learning

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In geoscience, it is very important to be able to investigate and understand mineralogical, textural, and structural relationships of entire samples that are commonly prepared as petrographic thin sections, epoxy mounts, or polished hand specimens. With conventional SEM imaging, the operator examines specific regions of interest preselected through tedious screening using transmitted or reflected light microscopy. This process is time consuming if the goal is the thorough understanding of the mineral associations and textures across the entire sample. Simultaneously displaying acquired light microscopy, SEM, and chemical data to a large audience poses additional challenges. Here we present a novel approach to imaging, analyzing, evaluating, displaying, and sharing large-area SEM image mosaics of entire samples. Automated high-resolution, large-area SEM imaging enabled by the ZEISS Atlas 5 software affords a comprehensive, fast, and user- friendly means of defining, acquiring, observing, and manipulating image mosaics of large areas up to one terabyte in size on ZEISS SEM systems. Atlas 5 allows the user to acquire simultaneously imaged mosaics from two detector signals (e.g. BSE-CL; BSE-SE). Background images and overlay images from other sources can be aligned with the SEM image mosaics, allowing for the correlation between all data layers (e.g. light microscopy, element maps, automated mineralogy data). These datasets can be exported together into a Browser-Based Viewer (BBV) format that can be stored on a server and shared on the internet. Light-microscopy data or mineral distribution maps are displayed side by side, together with SEM image mosaics. Navigation through the image mosaics is controlled with a computer mouse and akin to using Google Maps©. Any additional information (e.g. high-resolution subregions, chemical information, movie clips) can be linked. The BBV format allows the data to be made publicly available for easy use (see www.petapixelproject.com) in universities, high schools, geological surveys, and museums around the world. Large screen touch-table installations in museums allow visitors to navigate hands-on through image mosaics. Datasets of samples can be projected in auditoriums or on screens and be used for a wide range of teaching tasks in geology and mineralogy classes. Similarly, large-area image mosaics of rare samples (e.g. meteorites, lunar rocks, microfossils) can be acquired, archived, and made publicly accessible for teaching and research over the internet. We will demonstrate these capabilities using select datasets of particularly interesting geological samples comprised of large-area petrographic light-microscopy image mosaics, dual-signal SEM image mosaics, element maps, and FIB-SEM nanotomography movies.

Silicocarbonatite melt inclusions in fluorapatite from Otter Lake (Quebec): Evidence of carbonate melts in the Central Metasedimentary Belt of the Grenville Province

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Occurrences of "skarn zones" are common in the Central Metasedimentary Belt of western Quebec and eastern Ontario, in a corridor running from Mont-Laurier, Quebec, southeast to the Bancroft area, in Ontario. The best known of these is the Otter Lake occurrence and the associated Yates uranium prospect in the western Grenville Province of Quebec, located in the Marble Domain of the Mont Laurier terrane. The Otter Lake location is known for its well-formed doubly terminated fluorapatite crystals that occur in a matrix of orange calcite and may reach a length of 30 cm and several cm across. The calcite matrix also contains impressive crystals of diopside, titanite, meionite, phlogopite, allanite-(Ce), fluorite, thorite, and thorianite. The apatite crystals commonly contain peculiar millimetric to centimetric inclusions of orange calcite. We investigated the nature of the macroscopic orange calcite inclusions and the micro-inclusions that occur in the fluorapatite crystals. This was accomplished with high-resolution large-area SEM imaging capabilities provided by the Zeiss Atlas 5 software. Overview-image mosaics of the entire samples were acquired on a Zeiss EVO SEM using the backscattered electron (BSE) detector. The acquired BSE image mosaics were combined with light-microscopy image mosaics in the Atlas 5 correlative workspace followed by chemical analyses (EMPA, EDS) of regions of interest. The results revealed that the large macroscopic inclusions of orange calcite are merely "the tip of the iceberg". In fact, the fluorapatite itself contains a bewildering array of various micro-inclusions. The latter have a globular shape, range from <1 μm to 700 μm in size, and are polymineralic in nature. They may contain all or just a few of the following mineral phases: quartz, fluorite, calcite, hematite, julgoldite-(Fe^{3+}), diopside, allanite-(Ce), thorite, cerite-(Ce), parisite-(Ce) and synchysite-(Ce), baryte, and anhydrite. SEM analyses reveal that the macroscopic orange calcite globules are in fact the largest component of polymineralic inclusions that also contain fluorite, allanite-(Ce), thorite, cerite-(Ce), and quartz. The orange calcite globules themselves also contain polymineralic and monomineralic inclusions. The polymineralic inclusions contain quartz, apatite, hematite, baryte, and xenotime-(Y). Anhydrite primarily occurs as monomineralic inclusions, but was also observed together with cerite-(Ce).

We contend that the macroscopic and microscopic inclusions, polymineralic or monomineralic in nature, crystallized from a fluxed silicocarbonatite melt. Droplets of this melt, which also forms the orange calcite matrix surrounding the fluorapatite crystals, were trapped during the growth of the apatite and crystallized to the observed assemblage of mineral inclusions.

Tectonic significance of late-orogenic cross-folds in a high-grade gneiss terrane - formation during transtensional collapse

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The NE-striking Ontario segment of the Grenville Front Tectonic Zone is overlain by polydefomed assemblages of high-grade parautochthonous and allochthonous gneisses separated by a major zone of ductile décollement containing the Allochthon Boundary (AB). The structurally lower, parautochthonous gneisses of metaplutonic and meta-sedimentary origin have yielded Archean and Paleoproterozoic model ages suggesting they represent redeformed parts of internal Proterozoic Laurentia, whereas the overlying allochthonous gneisses have Mesoproterozoic model ages and comprise a 1090-1050 Ma (early Ottawan) thrust-sheet stack derived from its complex southeast margin. Thrust-sheet stacking and high-grade metamorphism were followed by gravitationally-driven extensional collapse during the late-Ottawan (~1050-1020 Ma). At an early stage of this process, the gneisses were thrown into trains of N- to NW- to W-trending, upright to inclined, markedly noncylindrical, multi-order buckle cross-folds, yielding structural interference patterns geometrically similar to types 1-2 of J.G. Ramsay. The axial traces of some km-scale (first-order) cross-folds pass from the Ottawan allochthon into the parautochthon, giving rise to the wavy trace of the intervening AB surface. Km- and m-scale cross-folds in these orthogneisses deform the regional foliation and contain S>>L shape fabrics in their limbs and L>>S shape fabrics in their hinge zones, some of which are defined by distorted plagioclase-rich pseudomorphs after garnet porphyroblasts, indicating formation after the metamorphic peak during retrogression and high-temperature decompression. Based on published results of kinematic and dynamic numerical modelling of single-layer and multi-layer buckle folds, we interpret the L-S shape-fabric pattern in cross-folded gneisses to result from late-orogenic regional buckling with hinge-parallel constrictional strain in a structural regime of heterogeneous, extension-dominated, ductile transtension.

Several large, gneissic granitoid bodies, including the Bonfield, Cosby, Mulock and Powassan 'batholiths' with emplacement ages of ~1.26 Ga, are delineated from the surrounding heterogeneous gneisses on regional maps by S.B. Lumbers published by the Ontario Geological Survey. High-order (m-scale) cross-folds in these bodies are also characterized by prominent L-S mineral-aggregate shape fabrics defined by deformed, variably recrystallized, igneous megacrysts and strained amphibolite-facies mafic clots after granulite-facies precursors. Moreover, like the heterogeneous enveloping gneisses, these 'batholiths' (actually approximately tabular concordant sheets) also exhibit map patterns resembling fold interference structures, collectively supporting the interpretation that they were deformed after the metamorphic peak in a regime of multi-order cross-folding during regional late-Ottawan ductile transtension.

The Muskox intrusion and the connection between LIPs and layered intrusions

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The Muskox intrusion is one of the archetype mafic layered intrusions yet its emplacement sequence and role as a sub-volcanic magma reservoir to flood basalts of the 1269 Ma Mackenzie large igneous province (LIP), including the coeval Coppermine River basalts and Mackenzie dike swarm, have until recently been relatively poorly constrained. Discovered in 1956, the Muskox intrusion (Nunavut, Canada) was the target of a scientific drilling program in 1963 by the Geological Survey of Canada that yielded an unprecedented composite section (3050 m) of a layered intrusion. The intrusion, which is funnel-shaped in cross-section and forms a shallowly northward-plunging elongate body, is composed of a keel dike, marginal zone, layered series, and roof zone. The 150-500 m-wide gabbronoritic keel dike constitutes the earliest injections of crystal-rich, contaminated magmas that crystallized at high levels in the crust. The 100-200 m-thick marginal zone consists of a thin interval (<10 m) of contaminated granophyre-bearing gabbronorite at the contact followed inward by uncontaminated feldspathic ol-opx cumulates and it formed incrementally during progressive inputs of magma that in turn produced the layered series. The layered series, grouped into four megacycles, contains 25 cyclic units (ol-chr, ol-cpx, ol-opx cumulates), each representing the partial crystallization sequence of a single sill-like magma injection. The heterogeneous roof zone consists of gabbro and granophyre that were produced by extensive fractionation and by partial melting of the overlying roof. Based on Nd isotopic constraints, construction of the Muskox intrusion was restricted to the early stages of emplacement of the Mackenzie LIP and it correlates only with the 1000 m-thick lower member (~30 flows) of the Copper Creek Formation, the stratigraphically lowest part of the regionally extensive 4500 m-thick Coppermine River flood basalts (~150 flows). The Muskox intrusion is interpreted as a high-level magma reservoir where crystals (mostly olivine) were deposited as crystal cargoes during transit of the earliest fractionated basalts of the Mackenzie LIP. Eruption of the subsequent upper 3500 m of Coppermine River flood basalts utilized alternate conduit systems and magma reservoirs imaged by 250 km-long aeromagnetic and gravity anomalies to the north. The presence of a large, sub-volcanic, open-system magma reservoir like the Muskox intrusion, where crystals entrained from depth are deposited and accumulate, reflects a combination of local and regional stress fields, rheological contrasts, and host rock lithology at the level of emplacement during periods of high magma volume and flux at the onset of LIP magmatism.

Till stratigraphy in the drumlinized terrain of the McArthur River uranium mine area in the eastern Athabasca Basin

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The high-grade uranium deposit at McArthur River, in northern Saskatchewan, is located at a depth of approximately 550m. Related alteration products have been dispersed along structures in the overlying sandstones up to the bedrock surface where the sandstone, and contained alteration products, were eroded and dispersed by glacial processes during the Quaternary glaciations. However, glacial sediments are variably thick (ranging 0-100m) and the surface is characterized by large drumlins, which can affect the surface expression of dispersal patterns of alteration products (e.g., clay minerals and related geochemical pathfinders) and which are used in drift prospecting. The purpose of the research was to investigate the stratigraphy of the Quaternary cover and determine whether drumlinization has eroded into the layers. One 36m till section on the flank of a large drumlin was studied in detail, 145 till samples were collected for compositional analysis, and 6 ground penetrating radar profiles were acquired. Results show that multiple contrasting till units occur in the subsurface and are also exposed at surface, possibly due to erosional processes during drumlin formation. Specifically, two end member tills are recognized: a 'local' till and a 'distal' till. The local till is characterized by high proportion of locally derived sandstone clasts, as well as by elevated values of As, B, Cr, and Cu. In contrast, the distal till has a high proportion (>50%) of basement clasts and its matrix is enriched in most metals (e.g., alkalis, alkaline earth metals, and rare earth elements) relative to the local till end-member. Additionally, a range of hybrid tills are also identified based on compositional characteristics that fall between the two end-members. Till compositional data and classified airborne radiometric data (K, eTh, eU) clearly show that most of these tills are exposed at surface across the study area. This has implications for drift prospecting because till at surface is usually mapped as one uniform till blanket unit. At McArthur River, dispersal patterns of key alteration pathfinder elements (e.g., B) may be affected by the spatial distribution of these tills at the surface. Identification of different tills and their detailed mapping can enhance drift exploration in areas of thick multi-till stratigraphy and drumlin fields.

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Hadean-Archean transition: Implications of a global continental reconstruction

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A global reconstruction that links concentric diamond-bearing lithospheric keels, greenstone belts, and Archean and Proterozoic orogenic trends into an elliptical continental mass has implications for Earth's Hadean-Archean transition. The late heavy bolide bombardment of the Earth-Moon system, which ended at ~ 3.9 Ga, opened giant craters, such as the lunar South Pole-Aitken impact basin, which, according to NASA, spans nearly a quarter of the lunar circumference. Earth likely experienced more intense bombardment than the Moon, and giant terrestrial impact basins were likely rimmed by heavily mixed aggregates of TTG crust and were likely floored by magma oceans with oscillating, plume-like central peaks.

The large terrestrial impact basins may have widened by some process akin to seafloor spreading, driven by gravitational instability of their plume-like central peaks. As the basins widened, they swept back, interleaved, and thickened ductile ribbons of their intervening TTG rims. This late Hadean/early Archean Earth may have resembled Venus, with wispy tracts of corrugated highlands rising above tessellated plains. The crater rims coalesced into an elliptical rampart as they drew back across the spherical planet. Competing processes of lithospheric thickening and uplift of the rampart vs. gravitational spreading of its weak continental crust may have driven down-slope crustal extension with emplacement of flood basalt LIPs above the TTG crust, followed by gneiss doming and greenstone belt subsidence.

The reconstruction links Archean cratons into a loosely connected ellipse having the essential geometry of an early Pangaea. The diamond-bearing lithospheric keels and Archean greenstone belts and tectonic trends are approximately concentric with the ellipse. Proterozoic accretionary orogenic belts overlap the periphery of the ellipse. A medial high-grade, 2.0-1.8 Ga metamorphic belt divides the Archean cratons into concentric outer and inner bands. Giant Proterozoic dike swarms and rifts are generally radial or concentric to the ellipse. Juvenile Neoproterozoic magmatic arcs fill the interior of the ellipse, which may represent a remnant basin.

The elliptical continent may have evolved slowly from Hadean through Archean time with accretion of various continental scraps. It was cratonized from 2.0 to 1.8 Ga, but peripheral subduction and trench roll-back may have stretched the circumference of the ellipse, leading to radial rifts and dike emplacement. The medial high-grade metamorphic belt may represent a type of core complex system extended along the crest of the rampart.

Deformation of the subduction plate interface beneath the seismogenic zone: An example from the Leech River Shear Zone

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Recent observations of episodic tremor and slow slip (ETS) in subduction zones suggest shear fracture and viscous flow occur concurrently in the transition between unstable stick-slip and stable fault creep at the down-dip limit of the seismogenic zone. Geophysical observations indicate that this transitional regime is characterized by anisotropic seismic velocities and low velocity zones, indicating foliated rocks and near-lithostatic pore fluid pressure, but there are few insights from the rock record. We investigate the Leech River Shear Zone on Vancouver Island, a paleo-plate interface where an oceanic plateau was subducted beneath an accretionary wedge unit to explore deformation processes in this transitional regime. Previous analyses of the mineral assemblage in the Leech River Schist and Metchosin Basalt report peak metamorphic conditions of 500-600˚C and temperatures exceeding 300˚C, respectively, comparable to estimated temperatures of ~525-650˚C for ETS at the present-day Cascadia margin. The plate interface is defined by a mylonitic shear zone developed across the boundary between the units. Isoclinal folding, boudinage, strong S—C fabrics, and a steeply plunging stretching lineation are consistent with sinistral-oblique subduction. Discordant quartz veins are variably sheared into sigmoidal shapes, isoclinally folded, and boudinaged, indicating synkinematic fracture and vein formation. Within the schist, interconnected, anastomosing layers of muscovite, chlorite, biotite, and graphite define the foliation, and likely deformed through kinking and dislocation glide. In the metabasalt, chlorite and amphibole form a scaly fabric, where chlorite dominates the foliation and amphibole porphyroclasts have a lenticular morphology. Amphibole porphyroclasts were deformed by rigid grain rotation and dissolution-precipitation creep. Monomineralic vein quartz varies from relatively undeformed to dynamically recrystallized by grain boundary migration. Deformation at the subduction plate interface beneath the seismogenic zone was therefore accommodated by distributed viscous shear partitioned between aligned phyllosilicates and quartz, and coeval fracture likely assisted by high pore pressure. These structures may record a similar phenomenological behavior to modern ETS.

Geochronology and genesis of the Andrew Lake uranium deposit, Thelon Basin, Nunavut, Canada

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The Thelon Basin in the western part of Nunavut, Canada is an intraplate Paleoproterozoic basin that is similar in age, size, geology, and geometry to the U-producing Athabasca Basin 600 km to the SW in Saskatchewan. The Kiggavik project area, located near the northeastern edge of the Thelon Basin, just south of the Aberdeen sub-basin, contains a series of U deposits and showings along the ~30 km long NE-SW Kiggavik-Andrew Lake structural trend. The Andrew Lake deposit is near the southern end of this trend, located near the intersection of the structural trend with the E-W Judge Sissons fault. Uranium mineralization is dominantly hosted within fine grained and finely laminated siliciclastic rocks of Neoarchean age.

A preliminary four-phase genetic model is proposed for the Andrew Lake deposit. Pre-mineralization (tentatively 1.75 Ga) is characterized by quartz ± carbonate veins that occupy fault systems later reactivated as conduits for U-mineralizing fluids. Phase 1 comprises uraninite (U1; 1031 ± 23 Ma) as vein-type mineralization that is associated with illite and hematite. Stage 1 (U1) uraninite contains variable PbO contents (0.2 to 9.5 wt.%). Phase 2 is characterized by altered uraninite (U2; with an average age of ~530 Ma) that is associated with coffinite [$(U(SiO_4)_{1-x}(OH)_{4x})$]. U2 has variable and elevated contents of SiO_2 (0.0 to 13.7 wt.%) and CaO (0.6 to 6.7 wt.%), and also contains widely variable PbO contents (0.0 to 12.3 wt.%). Altered uraninite (U3; < 1 Ma) characterizes Phase 3, and occurs as mini "roll-fronts". U3 has elevated SiO_2 contents (9.2 to 12.5 wt.%), low CaO contents (1.4 to 2.5 wt.%), and contains below detection limit amounts of Pb. In Phase 4, all three uraninite stages, as well as coffinite, show very late hydrous alteration to boltwoodite [$(K,Na)(UO_2)(HSiO_4)\bullet 0.5(H_2O)$].

Although the oldest U-Pb age obtained from uraninite is ~1030 Ma, illite associated with the U mineralization gives ^{40}Ar-^{39}Ar ages of 941 ± 31 Ma and 1330 ± 36 Ma. The younger age is similar to the age of U1, suggesting that there was a fluid event that either precipitated U1 or reset the U-Pb isotopic system at ~1000 Ma. However, the older age (1330 Ma) for illite does not correspond to Andrew Lake U-Pb uraninite ages, but is similar to ages previously reported for uraninite and clay alteration minerals elsewhere in the Kiggavik area.

A unified hydrogeological framework for southern Ontario: A progress report on surficial geological stratigraphy

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Ontario implemented the Clean Water Act in 2006 and embarked upon a ten year Source Water Protection (SWP) program that invested ~250 million dollars to establish a framework to protect municipal water supply. Groundwater studies were conducted at several scales from the well-head protection zone of a municipal well to watershed characterization reports of a source protection region. There has been little attempt; however, to integrate these results into a Southern Ontario scale geologic or hydrogeologic framework. As such, these studies can be considered to be under-utilized regional hydrogeological assets which could contribute to a broader understanding of regional hydrostratigraphy and hydrogeology. For example, relating municipal wells to a geological understanding could support improved characterization of aquifer geometry, architecture and hydrogeologic properties. More broadly, there continues to be an opportunity to integrate not only SWP information but data from Permits to Take Water and the Provincial Groundwater Monitoring Network (PGMN) into a more comprehensive, standardized, regional hydrostratigraphic framework.

This presentation is a status report on a geological co-ordination activity that will preview selected areas of the hydrostratigraphic framework. In particular, we highlight geological model development to support an improved framework and analysis of the related hydrogeological datasets. Work is advancing on the capture of high-quality control datasets such as measured field sections, borehole records and hydrostratigraphic classification. All Ontario Geological Survey 3D models have been integrated in a single model environment along with the regional Oak Ridges Moraine model. Progress has been initiated on the hydrostratigraphic classification of wells in the PGMN with an initial focus on wells screened in surficial deposits, and located in areas of controlled 3D geological models and areas with abundant high-quality datasets. Progress has also been made on mining SWP program data for municipal well fields. Current data mining is focused on relating municipal well data to defined aquifers.

Geological models that can be used to support the above hydrogeological frameworks are now available for portions of the GTA including, at variable scales, ORM, Simcoe County and the Yonge Street aquifers. We preview these steps to the eventual development of a regional conceptual 3D hydrogeological model for southern Ontario.

Timing of post-collisional Pan-African Orogeny granitic magmatism within south-central Chad

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Precambrian crust within southern Chad and eastern Cameroon preserves rocks that were remobilized and emplaced during and after the Neoproterozoic (~650 Ma to ~610 Ma) collision between the Congo, São Francisco, West African cratons and the Saharan Metacraton. The Guéra Massif of south-central Chad and granites located near Lake Fitri are inferred to be of Neoproterozoic age but there are no radio-isotopic dates available to confirm their association with the Pan-Africa Orogeny. New zircon U/Pb geochronology of granitic rocks from the Guéra Massif, Lake Fitri region and the Doba Basin of the southern Chad yielded mean $^{206}Pb/^{238}U$ ages from 595 ± 8 Ma to 545 ± 6 Ma. The oldest inherited zircons indicate that the Guéra Massif is either built upon Meso- to Paleoproterozoic (1000 Ma to 1900 Ma) continental crust or that pre-Neoproterozoic rocks were the source of the silicic Ediacaran rocks. The granites located in the Lake Fitri region likely represent a westward extension of the Guéra Massif as there are temporal and compositional similarities between the two massifs. The age of the diorite from the Doba Basin of Southern Chad is similar to rocks from the Central African Fold Belt suggesting that the southern boundary of the Saharan Metacraton may be north of the Doba Basin. Post-collisional magmatism appears to be closely linked to deformation cycles recorded in eastern Cameroon after the main continental collision episode between the Congo Craton and the Saharan Metacraton.

A geochemical explanation for the absence of environmental contamination by heavy metals in the region of the Athabasca bituminous sands

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Sphagnum moss from peat bogs surrounding open pit mines and upgraders yield concentrations of Ag, Cd, Pb, Sb and Tl which are comparable to moss from remote areas of northern Norway. Accurately and precisely dated peat cores show that concentrations and enrichment factors for these elements have been in decline for decades and now approach "background" values. Acid-insoluble ash (AIA) in moss samples nearest the open pit mines show that they are clearly impacted by dust, and the correlations between chalcophile elements (Ag, As, Cd, Cu, Pb, Sb, Tl, Zn) and lithophile elements (Al, Sc, Th, Y and the REE) show that most of the variation in element abundances is due to differences in the amount of dust on the plants. Trace metal concentrations in snow are dominated by particulate forms. In the Athabasca River, most of the elements of interest are found almost exclusively in the particulate fraction. In the dissolved fraction (<0.45 µm), metal concentrations are extremely low, and largely associated with colloidal organic matter and iron hydroxide. In summary, in all of the environmental media sampled to date, the "bioaccessible" fraction of Ag, Cd, Pb, Sb, and Tl is extremely low. The simplest explanation for these results lie in the bituminous sands themselves: extraction and digestion of the organic and mineral fractions of ABS in the metal-free, ultraclean SWAMP lab shows that only four metals are found in bitumen: V, Ni, Mo and Re; virtually every other element is found almost exclusively in the mineral fraction.

Selenium stable isotope ratio measurements as a tool for determining processes in groundwater

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Determining the in situ processes occurring in contaminant plumes and groundwater remediation systems can be difficult, particularly in regions with complex stratigraphy. When the exact flow path of a system is poorly defined, aqueous geochemical data may be insufficient to constrain estimates of the impacts of differing mechanisms on the concentrations of dissolved constituents. This study focused on the use of selenium (Se) stable isotope ratio data to assist in the determination of the predominant geochemical processes in aquifers impacted by dissolved Se and in groundwater remediation systems. Laboratory batch and column experiments were conducted using zero valent iron (ZVI) as a treatment material to determine the degree of fractionation expected under both stagnant and saturated flow conditions. Aqueous pH, cation and anion concentrations, and Se isotope ratio analyses were performed to provide a more complete understanding of the geochemical processes involved. Where possible, information about Se speciation was collected using aqueous and solid phase samples to further determine the exact mechanisms involved in Se removal. Additional information about Se isotope ratios changes under flow conditions was obtained by changing the input solution in the column experiment over time. Both batch and column experiments yielded distinct effective fractionation values that can be used to identify processes in remediating groundwater systems. The effective fractionation values derived from these experiments, and from the literature, can be used, in conjunction with Se isotope ratios measured at locations along the groundwater flow path and mixing calculations, to better understand the processes controlling Se concentrations in aquifers and in groundwater remediation systems.

REE geochemistry of cumulate clinopyroxenites, wehrlites and mantle rocks and their REE-clinopyroxene concentrations, from W. Chalkidiki ophiolites, N. Greece

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The Vavdos and Gerakini-Ormylia constitute parts of the SSZ West Chalkidiki ophiolite complex (N. Greece). Both complexes include layered dunites, which host podiform chromitites, as well as harzburgites, lherzolites, cumulate pyroxenites, wehrlites and gabbroic rocks. Wehrlites and pyroxenites host unstrained clinopyroxenes which are relatively richer in absolute REE values than the mantle harzburgites and lherzolites. Chondrite normalized patterns of wehrlites and clinopyroxenites show strong LREE depletion and enrichment in HREE, typical of cumulate rocks created in MORB settings. REE concentrations in clinopyroxenes of the four lithotypes were obtained with LA-ICP-MS. Clinopyroxene in the harzburgites and lherzolites is strongly depleted in REE, whereas that from the clinopyroxenites and wehrlites is relatively enriched. Chondrite normalized multi-elemental profiles of the analyzed clinopyroxenes from all lithotypes illustrate strong Zr negative anomalies, while those in the cumulate clinopyroxenites and wehrlites display week Ti anomalies. To sum up, we conclude that wehrlites and pyroxenites are cumulate and harzburgites and lherzolites are mantle rocks. Chondrite normalized whole rock and clinopyroxene patterns of clinopyroxenites and wehrlites follow the same trend, yet clinopyroxenes are slightly more enriched in REEs, indicating that they are the major cumulate phase among other minerals such as olivine and plagioclase.

Marine palynology of the Miocene–Pliocene Rees Borehole, Belgium: biostratigraphy and paleoenvironments at the southern margin of the North Sea

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Correlating and dating Neogene deposits along the southern margin of the North Sea Basin have historically been complicated by the fragmentary nature of the outcrops studied, the boreal aspect of the benthic foraminifera present, and scarcity of planktonic microfossils. Dinoflagellate cysts and other palynomorphs from the Rees Borehole, Campine area of northern Belgium, are therefore used to provide new insights into the paleoenvironmental history of the area. The borehole contains the Upper Miocene Diest, the Upper Miocene Kasterlee, the mid-Pliocene Poederlee, and the Pliocene Mol and Merksplas formations. For the Diest Formation, the presence of Achomosphaera andalousiensis andalousiensis, Barssidinium pliocenicum, Operculodinium? eirikianum, Operculodinium tegillatum, Selenopemphix armageddonensis, Gramocysta verricula and the acritarch Nannobarbophora walldalei are consistent with a late Late Miocene age. The dinoflagellate cyst assemblages of the Kasterlee Formation in the Rees borehole differ from those of the Kasterlee Formation in other areas, and are more similar to assemblages of the underlying Diest Formation. This could be explained by reworking of the Diest into the Kasterlee Formation. Previous studies from elsewhere in Belgium place the Kasterlee Formation in the latest Tortonian of the Upper Miocene. The Poederlee Formation assemblages compare closely with a previous study of the Poederlee Formation in the Oud-Turnhout well. The presence of Achomosphaera andalousiensis suttonensis, Invertocysta lacrymosa, Operculodinium? eirikianum and the absence of Reticulatosphaera actinocoronata, Operculodinium tegillatum and Batiacasphaera minuta/micropapilata point to a mid-Pliocene age, between 3.7 and 2.7 Ma. For the first time, dinoflagellate cysts were found in the Merksplas Formation, indicating a marine influence. High resolution sampling reveals productivity cycling over a 3-metre interval. The presence of Achomosphaera andalousiensis suttonensis, Barssidinium pliocenicum, Capisocysta lyelli, Geonettia waltonensis, and Invertocysta lacrymosa within this formation collectively point towards a Late Pliocene age. Assemblage compositions throughout the Rees Borehole reflect neritic deposition within a restricted marine basin under temperate climates. Elevated abundances of Operculodinium israelianum and Lingulodinium machaerophorum in the Kasterlee Formation suggest an estuarine influence, and abundant Heteraulacacysta sp. with common Capisocysta lyelii in the Merksplas Formation suggests warm, restricted-marine conditions. This analysis provides new information on the depositional history of the area, thereby enhancing understanding of the complex development of the North Sea Basin. In particular, paleoenvironmental reconstructions provide new insights into the response of a restricted marine basin to climate changes occurring throughout the Miocene and Pliocene.

Paleomagnetic directions from the Pretoria Group of South Africa: Hints at the position of the Kaapvaal Craton at 2.2 – 2.1 Ga

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New geochronological constraints on the Ongeluk Formation require updated correlations of the classic South African strata recording the Great Oxidation Event (GOE) at ~2.4-2.3 Ga. The associated revision of the age of the paleomagnetic pole for the Ongeluk Formation leaves a large time gap in the Kaapvaal Craton's apparent polar wander path between 2.43 Ga to 2.06 Ga. In the aftermath of the GOE, the Earth and its biogeochemical cycles underwent dynamic changes; additional constraints are needed to understand paleogeography during continental fragmentation, latitudinal extent of global glaciations, and any tectonic drivers of global perturbations in the oxygen, sulfur, and carbon cycles (e.g. the Lomagundi Event). To this end, paleomagnetic measurements are being performed on basaltic volcanic rocks of the 2.22 Ga Hekpoort Formation and the ~2.1 Ga Machadodorp Member of the Silverton Formation within the Pretoria Group of the Transvaal Basin, South Africa. Sites span an along-strike north-south swath in the Mpumalanga Province. Results from the Hekpoort Formation highlight the impact of the 2.06-2.04 Ga Bushveld Igneous Complex on the region; all samples with a high-temperature component record overprinting magnetizations matching the Bushveld direction, with three sites completely remagnetized by this magmatic event. Four sites preserve a higher-temperature component with a steep northwest up direction which does not overlap known Paleoproterozoic directions of the Kaapvaal Craton. Notably, this new paleomagnetic direction is distinct from that of the Ongeluk Formation corroborating new radiometric dates which show the volcanics of the Ongeluk and Hekpoort Formations to be temporally separated in contrast with previous interpretations. Pyroclasts of the Hekpoort Formation rarely yield stable directional data; however, three large clasts show the same direction as the basaltic flows indicating that pyroclasts were emplaced hot, pyroclasts were remagnetized immediately following deposition, or this direction is secondary. The Machadodorp Member is closer stratigraphically to the Bushveld intrusion; in-progress analyses will show if any primary signal is recorded. If primary, these new results from the Pretoria Group can help constrain geomagnetic polarity choices for all pre-2.0 Ga poles of the Kaapvaal Craton and shed light on plate reconstructions during the fragmentation of ancestral supercratons and during the rise of atmospheric oxygen on Earth.

Natural and anthropogenic controls of groundwater geochemistry on the Niagara Peninsula

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Groundwater chemistry on the Niagara Peninsula has been identified as highly mineralized in comparison to groundwaters collected from the same bedrock formations elsewhere in southern Ontario. Groundwater located along the Niagara and Onondaga Escarpments is characterized by unconfined aquifer conditions, parameters reflective of surficial contaminants, including road salt, and elevated HCO_3, DOC, NO_3^-, coliform bacteria and tritium. In contrast, in the central Niagara Peninsula low-permeability sediments and gypsiferous bedrock results in highly mineralized groundwaters with elevated S^{2-}, Ca^{2+}, Mg^{2+}, SO_4^{2-}, Cl^-, Br^-, Sr^{2+} and CH_4. Groundwater completed in the Guelph and Eramosa Formations contains the lowest electrical conductivity in the study area. Outliers exist with groundwater geochemistry that differs from the local geochemical zone and the host aquifer. These sites have elevated SO_4^{2-} (>1000 to 5200 mg/L) with depleted $\delta^{34}S_{SO4}$ (-2.2 to 14.3 ‰ VCDT) signatures that differs starkly from Devonian and Silurian evaporites (~20 to 32 ‰) in the host formations. This exogenic SO_4 was identified in a cross-formational northeast – southwest linear trend crossing three major groundwater flow systems. The lack of down-stream impact in these systems and tritium groundwater ages that are typically only decades old indicate a young, non-geological origin and implicate anthropogenic activities. Additionally, nine samples were identified with elevated methane concentrations and $\delta^{13}C_{CH4}$ signatures within the thermogenic range. As thermogenic methane is not produced within shallow aquifers and would be short-lived in the presence of the ubiquitous sulfate, these samples imply recent upward migration of methane from depth through vertical conduits. Taken together, the evidence supports large-scale upward movement of fluids in the centre of the Niagara geochemical anomaly and more sporadic upward transport of gases over a wider area of the peninsula. The most likely vector is through corroded and leaking casings or boreholes of abandoned (century) gas wells that are common across the peninsula.

Construction and destruction of some North American cratons interpreted using 3-D lithospheric models

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Construction histories of Archean cratons remain poorly understood; their destruction is even less clear because of its rarity, but metasomatic weakening is an essential precursor. By assembling geophysical and geochemical data in 3-D lithosphere models to 300-400 km depths, a clearer understanding of the geometry of major structures within the Rae, Slave and Wyoming cratons of central North America is now possible. These geological models are based on geophysical data: several types of seismic discontinuity, wave speed models and new 3-D conductivity models. Little evidence exists of subducted slab-like geometries similar to modern oceanic lithosphere in these construction histories. Underthrusting and wedging of proto-continental lithosphere is inferred from multiple dipping discontinuities, emphasizing the role of lateral accretion. Archean continental building blocks may resemble the modern lithosphere of oceanic plateau, but better match the sort of refractory crust expected to form at Archean ocean spreading centres. Radiometric dating of mantle xenoliths provides estimates of rock types and ages at depth beneath sparse kimberlite occurrences, and these ages can be correlated to surface rocks. The 3.6-2.6 Ga Rae, Slave and Wyoming cratons stabilized during a granitic bloom at 2.61-2.55 Ga. This stabilization probably represents the final differentiation of early crust into a relatively homogeneous, uniformly thin (35-42 km), tonalite-trondhjemitegranodiorite crust with pyroxenite layers near the Moho atop depleted lithospheric mantle. Peak thermo-tectonic events at 1.86-1.7 Ga broadly metasomatized, mineralized and recrystallized mantle and lower crustal rocks, apparently making mantle peridotite more 'fertile' and more conductive by introducing or concentrating sulfides or graphite throughout the lithosphere at 80-120 km depths. This metasomatism may have also weakened the lithosphere or made it more susceptible to tectonic or chemical erosion. The arrival of the subducted Shatsky Rise conjugate part of the Farallon plate at the Wyoming craton at 65-75 Ma appears to have eroded and displaced the thus weakened base of the craton below 140-160 km. This process replaced the old re-fertilized continental mantle with relatively young depleted oceanic mantle.

Exploring the origins of drumlins and megascale glacial lineations

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Current models for the origins of drumlins and mega-scale glacial lineations (MSGLs) are incapable of adequately accounting for the wide variability in shapes and compositions of glacially streamlined landforms. Many hypotheses are based off of data that is spatially limited and often incomplete, with landform populations only partially mapped in detail due to logistical difficulties. Any comprehensive hypothesis must be able to explain the presence of all drumlins and MSGLs, which can only be done by greatly expanding the datasets used for modelling. This presentation outlines techniques which aim to fill the identified data gap in glacial geomorphology studies by using high resolution elevation datasets to improve the mapping of streamlined landforms. Demonstrated techniques, such as the Curvature-Based Relief Separation (CBRS) methodology, have the potential to increase data resolution and shed new light on the relationship between subglacial processes occurring during episodes of faster ice flow, called ice streams, and the resultant postglacial geomorphology.

Direct dating of a shear fabric: An example from a Himalayan shear zone

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Dating the precise onset of deformation in shear zones is crucial to assess the time scale at which they operate and calculate accurate creep rates. Widely-used dating of pre-kinematic dykes involves interpretative uncertainties larger than analytical uncertainties because it is difficult to evaluate the time lag between the dyke intrusion and the onset of deformation. We present an alternative multi-faceted approach combining in-situ laser-ablation split-stream inductively-coupled plasma mass spectrometry monazite geochronology with monazite trace element analysis, microstructural analysis, petrography, and metamorphic phase equilibria modelling to precisely date the onset of deformation along the South Tibetan detachment in the Karnali klippe, western Nepal Himalaya. This approach is complemented by $^{40}Ar/^{39}Ar$ thermochronology to constrain the termination of shearing.

The South Tibetan detachment is an orogen-wide top-down-to-the-north shear zone that separates low metamorphic-grade supracrustal rocks in the hanging wall from high metamorphic-grade mid-crustal rocks in the footwall. It is a key structure in Himalayan tectonic models because of its important role in the exhumation of the Himalayan middle crust. A sheared garnet-muscovite-biotite schist at the base of this ~1-km-thick shear zone contains pre-kinematic garnet that grew at 575-625 °C and 900-1200 MPa between ca. 36 and 30 Ma. Garnet breakdown during decompression is inferred to start at ca. 30 Ma from the increasing Y and decreasing Gd/Yb content of monazite. Syn-kinematic asymmetric Y-rich and Gd/Yb-poor rims of monazite indicate the shear zone was active from ca. 29 to <24 Ma. Quartz crystallographic <c>-axis preferred orientations suggest a temperature of deformation of 600 °C at the base of the shear zone, higher than the isotopic closure temperature of muscovite. The minimum age of ductile deformation at the base of the shear zone is therefore constrained to 18.8 ± 0.3 Ma by the post-deformation muscovite $^{40}Ar/^{39}Ar$ cooling age. Nevertheless, a second muscovite $^{40}Ar/^{39}Ar$ age from the upper part of the shear zone, which was deformed at lower temperature (≤480 °C), is interpreted to indicate syn-kinematic recrystallization at 16 ± 2 Ma, suggesting that deformation propagated up-section in the South Tibetan detachment shear zone.

These data constrain the onset of mid-crustal tectonically-driven exhumation along the South Tibetan detachment to the early Oligocene, several m.y. before commonly reported values. The well-constrained duration of activity of the South Tibetan detachment in western Nepal (ca. 30 to <16 Ma) and published estimates of dip-slip displacement (150-200 km) together yield creep rates of 1.1 to 1.4 cm/year.

Abrupt along-strike variations in the P-T-t evolution of the Himalayan middle crust: Insights from western Nepal klippen

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The Himalayan metamorphic core, exposed between two opposite sense shear zones, is locally preserved in a series of klippen that form its foreland-most exposure. The Karnali and Jajarkot klippen in western Nepal Himalaya are investigated to decipher the tectono-metamorphic history of the apparent leading edge of the exhumed middle crust. Both klippen are east-west trending doubly-plunging synforms underlain by a folded reverse-sense shear zone. They comprise upper greenschist to amphibolite metamorphic facies rocks in contact with overlying weakly to non-metamorphosed sedimentary rocks along a folded normal-sense shear zone.

Despite similar first order structural architectures and across-strike positions of the two klippen, phase equilibria modelling combined with multi-equilibrium thermobarometry suggest a contrasting metamorphic evolution. Migmatitic schists (Ky + Grt + Bt ± Ms ± St) in the Karnali klippe are characterized by chemically homogenised garnet, yield peak metamorphic conditions of 600-750 °C at 800-1200 MPa, and show textural evidences of decompression. In contrast, Grt + Bt + Ms ± Chl schists in the Jajarkot klippe are characterized by garnet with preserved growth zoning and yield peak metamorphic conditions of 550-600 °C at 900-12000 MPa. Higher temperatures of deformation in the Karnali klippe (600-750 °C) compared to the Jajarkot klippe (500-600 °C) are also supported by quartz crystallographic <c>-axis preferred orientation fabrics.

In the Karnali klippe, protracted prograde metamorphism between ca. 45 and 30 Ma was followed by retrograde metamorphism and exhumation between ca. 30 and 20 Ma. In the Jajarkot klippe, peak metamorphic conditions were prevailing around 28-23 Ma, followed by retrograde metamorphism until 18 Ma. However, rare monazite and xenotime inclusions in garnet suggest that metamorphism may have started as early as 45 Ma.

The most striking difference between the two klippen is the absence of migmatites affected by protracted high temperature metamorphism in the Jajarkot klippe, which also contrasts with any other mid-crustal section exposed farther north. This implies that part of the middle crust was either (1) tectonically excised, or (2) pinched out southward and eastward towards the Jajarkot klippe. Partial tectonic removal of the middle crust requires unrealistic geometries of the bounding shear zones. Alternatively, partially molten mid-crustal material may not have extruded as far south as the Jajarkot klippe. Because of their marked tectono-metamorphic differences, an important structure, such as a lateral ramp in the Himalayan basal detachment possibly caused by an inherited basement cross-structure, must separate the two klippen.

Geochronology and geochemistry of calcite-filled fractures, southern Ontario: Insight into Cretaceous plate reorganization?

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Resolving the timing of brittle faulting is a challenge since the classical chronometers required for analyses are often in disequilibrium with the surrounding material or simply absent. In this study, we propose to couple LA-ICP-MS U-Pb and (U-Th)/He dating with geochemical proxies in vein calcite to tackle this dilemma. We examined intracratonic Middle Ordovician limestone bedrock that overlies Mesoproterozoic Grenvillian crystalline basement along the north shore of Lake Ontario. Both the basement and cover rock are cut by NE-trending fault zones, including the Salmon River and Picton faults, that have historic M_{4-5} earthquakes along their traces. The youngest stress recorded in the limestone bedrock is preserved as E-W to NE-SW vertical joints that hosts 1-7 mm thick calcite veins. Some calcite veins preserve sub-horizontal slickensides, µm- to mm-scale offset and extensive lamellar twinning that are often kinked and broken, suggesting some brittle deformation after vein crystallization. Calcite $\delta^{18}O$ and $\delta^{13}C$ values are analogous to the bulk composition of Middle to Late Ordovician limestones, and suggest vein formation from a source dominated by connate fluids. The calcite contains trails of fluid inclusions commonly along fractures, and $^{3}He/^{4}He$ analyses indicate a primitive, deep fluid signature (R/Ra: 0.5-2.7). Trace element geochemistry is highly variable, generally following the moderately negative REE slope of continental crust trends. Despite abundant helium concentrations, (U-Th)/He dating was unsuccessful yielding highly dispersed dates likely from excess He derived from the fluid inclusions. However, LA-ICP-MS U-Pb dating on calcite yielded model ages of 110.7 ± 6.8 Ma (MSWD: 0.53; n: 16) to 81.4 ± 8.3 Ma (MSWD: 2.6; n: 17). Since all veins are sampled from joints with the same E-W to NE-SW trend, we regressed all the calcite dates together, yielding an age of 101 ± 6 Ma (MSWD: 2.3). These veins are ~200 km to the west, and slightly younger than, the c. 140-120 Ma alkaline igneous rocks which mark the surface trace of the Great Meteor Hotspot. The period of 110-90 Ma has been identified as a time of global plate reorganization that involved tectonic and magmatic events, which may be reflected in our new calcite dates. Nonetheless, LA-ICP-MS U-Pb dating of vein calcite was successful, and coupled with other geochemical information, can yield primary information about the timing and source of fluid flow through joints and fractures, which has direct applications to reducing risk associated with characterizing hydrocarbon reservoirs and deep geological repositories for nuclear waste.

On the trail of the Great Stone Chief

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Robert Bell (1841-1917) likely explored more of Canada than any other person. Mostly as an employee of the Geological Survey of Canada, but at times on private ventures, Bell collected details on the geology, natural history, forestry, and ethnography from Newfoundland to Yukon. He was a charter member of the Royal Society of Canada, and was honoured at home and abroad. Bell's story was researched by Ian Brookes (York University, dd) based largely on Bell's correspondence with his wife. It is being rewritten as a book to be published to coincide with both the 150th anniversary of Canada and the 175th anniversary of the Geological Survey. Much of Bell's materials were saved from the debris of a house fire of his daughter in 1962, and are now housed in the National Archives.

The main focus of his mapping was the rivers draining into Hudson Bay, but he also completed comprehensive studies of the Paleozoic of Ontario, gold fields of Nova Scotia, the Appalachian thrust belt of the Gaspé, the Red River Valley of Manitoba, and routes from the Metis heartland in Saskatchewan to Great Slave Lake and an expedition to the Klondike. Bell was responsible for naming over 3000 geographic features in Canada, and his later explorations resulted in the naming of the Bell River, downstream from Matagami, Quebec, after him. Serving as geologist, botanist, naturalist, medical doctor and linguist, he pioneered canoe-based excursions of many of the large rivers entering Hudson Bay and James Bay east from Churchill, and provided both navigational and medical support in three expeditions from St. John's to Hudson Bay through Hudson Strait. He interacted with aboriginal peoples, and was given the title "Great Stone Chief" by the Inuit of the Ungava Peninsula.

In situ dating of multiple events in Neoproterozoic granulite-facies rocks of the Larsemann Hills, Prydz Bay, East Antarctica using electron microprobe analysis of monazite

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The metamorphic rocks exposed along the southeast coast of Prydz Bay were affected by several metamorphic and plutonic events associated with continental collision in the Neoproterozoic and Cambrian. Critical units exposed in the Larsemann Hills and nearby ice-free areas are (1) basement Søstrene Orthogneiss, (2) cover sequence Brattstrand Paragneiss and (3) anatectic pegmatites intrusive into the Brattstrand. Zircon U-Pb data from previous studies yielded an igneous protolith age of 1126 ± 11 Ma for the Søstrene and a maximum depositional age of 1023 ± 19 Ma for the Brattstrand, but only approximate ca. 900 Ma and ca. 530 Ma ages for two metamorphic events. In order to constrain the timing of these two events and anatexis, monazite in the three units was dated in-situ with the electron microprobe. Monazite grains were selected for dating using maps of U, Th, Y, and Pb to identify growth domains. Domains in a given sample having a similar composition are interpreted to constitute one generation, whose geologic significance is inferred from the petrologic context.

Our results confirm that the basement and cover were affected by metamorphism in the Neoproterozoic and Cambrian, i.e., respectively, 969 ± 7 Ma and 519 ± 4 Ma ages for the Søstrene (2σ uncertainties), and 911 ± 5 Ma and ca. 500-545 Ma for the Brattstrand Paragneiss. The spread in Cambrian ages for the Brattstrand is attributed to a clockwise P-T path. Monazite generations interpreted as representing near peak conditions (estimated to be 6-7 kbar and 800-850°C by previous research) gave the following ages in three samples of the Brattstrand: (1) 544 ± 3.8 Ma for grains in a phosphate segregation, (2) 532 ± 4 Ma for grains with garnet and orthopyroxene and (3) 535 ± 4 Ma for core domains of monazite included in garnet and in the matrix. Monazite in restite yielded 535 ± 9 Ma for the beginning of melting (i.e. associated with garnet growth) and 513 ± 2 Ma for garnet breakdown while melting continued. Monazite found within a quartz-hercynite symplectite, interpreted to have formed during decompression at 4.5 kbar and 750°C, yielded an age of 518.6 ± 4.4 Ma. Monazite found within a quartz-cordierite symplectite formed during further decompression yielded an age of 500 ± 16 Ma. Ages on the pegmatites range from 519 ± 2 to 506 ± 3 Ma, i.e., anataxis of the Brattstrand paragneiss is associated with the Cambrian event.

Supracrustal rocks of the Tehery-Wager area: Distinct packages and their metamorphic assemblages

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The Tehery-Wager area (western Hudson Bay, Nunavut) comprises mostly felsic to intermediate Archean orthogneiss, and Archean to Paleoproterozoic supracrustal rocks of the Rae craton. Recent geological mapping has led to the identification and division of the supracrustal rocks into two packages based on their lithological and metamorphic assemblages, relative abundances, and structural character. These rocks preserve a metamorphic gradient that ranges from lower amphibolite- to granulite-facies peak conditions from north to south, with local evidence of high-pressure metamorphism. The ultimate goal of this research is to better define the orogenic processes operating at mid-crustal levels in this portion of the Western Churchill province during the 1.92-1.80 Ga Trans-Hudson Orogen.

The Lorillard supracrustal package contains a diverse lithological assemblage intruded by boudinaged ultramafic rocks, and occurs as laterally discontinuous panels that are foliation-parallel within the basement orthogneiss. Rock types include biotite ± garnet psammite–semipelite, garnet + biotite ± sillimanite/kyanite ± cordierite pelite, quartzite, iron formation, and garnet-bearing metabasite. The proportion of mafic to aluminous units is nearly equal. This supracrustal assemblage resembles the Paliak supracrustal belt found along Wager Bay, and contains 2.70 Ga andesitic volcanic rocks.

The other package of supracrustal rocks is openly folded in synformal structures found north of a major structure (i.e., the Chesterfield fault zone). This assemblage is characterized by thick basal quartzite with sillimanite and muscovite, an abundance of biotite psammite, and lesser garnet + biotite ± sillimanite semipelite–pelite, and discrete layers of biotite + hornblende metabasite. The aluminous units are more abundant than the mafic units. This supracrustal package resembles the Paleoproterozoic Ketyet River Group documented to the west-southwest.

Ketyet-like supracrustal rocks north of the Chesterfield fault zone preserve lower amphibolite-facies assemblages with minimal retrogression. South of the Chesterfield fault zone, metamorphic assemblages within the Lorillard supracrustal package indicate upper-amphibolite peak conditions with retrogression (decompression) to lower-amphibolite conditions. The southwest corner of the Tehery-Wager area contains orthopyroxene-bearing assemblages, indicating granulite-facies metamorphism, and a pervasive amphibolite-facies overprint. Evidence of high-pressure conditions is found in aluminous supracrustal rocks along the Wager shear zone (kyanite-bearing assemblage) and a garnet + clinopyroxene + orthopyroxene mafic granulite body found near Lunan Lake. P-T and in situ monazite dating studies are currently underway to unravel the tectonometamorphic history of the supracrustal sequences within the context of the different accretion events of the Trans-Hudson Orogen.

Stable and radiogenic Sr isotope systematics of magmatic-meteoric hydrothermal systems

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Magmatic-meteoric hydrothermal systems are an important ore-forming process for a large number of economic ore deposits. Exactly how the hydrothermal fluids evolve from magmatic systems is still not entirely clear. Stable isotopes such as O and C and radiogenic isotopes such as Sr have helped characterize carbonate-dominated hydrothermal systems through analyses of the carbonate minerals. These analyses have demonstrated that the majority of carbonate-dominated magmatic hydrothermal systems such as carbonatites and carbonate-quartz veins in Precambrian basalt and granite ore systems are dominated by mantle derived C, O and Sr isotope compositions.

Research has shown that a number these carbonate-dominated hydrothermal systems have stable carbon and oxygen isotope compositions that plot outside the field of accepted mantle values and these non-mantle compositions may reflect a number of processes including sedimentary contamination, high temperature fractionation, seawater and/or meteoric water infiltration or low temperature alteration. Stable Sr isotope ratios ($^{88}Sr/^{86}Sr$) provide insight into the behavior of Sr and carbonates in hydrothermal solutions because the stable isotope ratios of Sr vary as a function of carbonate precipitation and dissolution.

Stable isotope (C, O) as well as stable and radiogenic Sr isotope analyses were obtained from a series of carbonate-dominated magmatic and hydrothermal systems with the goal of better understanding the formation and evolution of hydrothermal systems as well as the interaction between magmatic and meteoric hydrothermal systems. The resulting radiogenic Sr isotope compositions for the samples are consistent with mantle dominated fluids. However, oxygen and carbon stable isotope values range from mantle values, to values suggesting low temperature alteration and/or sedimentary contamination. The stable Sr isotope compositions range from values consistent with the silicate mantle average to values consistent with low temperature calcite precipitation. Together these results suggest that the stable isotope compositions of magmatic-meteoric hydrothermal systems may reflect, in-part, the carbonate versus silicate composition of the system.

Architecture of Upper Cretaceous faulting within the Great Plains polygonal fault system

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An extensive polygonal fault system is hosted within fine-grained Late Cretaceous sediments deposited beneath the Great Plains of the United States and Canada. Polygonal fault systems (PFSs) are layer-bound normal faults and fractures that can form in after deposition without external stresses. The initially normal faults grow vertically and intersect laterally to form coalesced fault traces with polygonal geometries in plan view. The Great Plains PFS have faulted strata throughout Canada and the United States. Covering an area of 2,000,000 km^3 or more, faulting of up to 80 m of relief has been observed in sediments at depth up to 700 m. The faulting has been identified at outcrop and on seismic data but has been attributed to other causes such as slumping at outcrop. Faulting may be responsible for wide ranging processes such as reservoir enhancement, structure at outcrop and other geotechnical hazards, or hydrocarbon seal integrity loss. Numerous examples using 3-D seismic, surface geology and wellbore cross section will show some of the structural characteristics for the polygonal fault system.

Tectonic map of Arctic Canada (TeMAC): A first derivative product from the Canada-in-3D geological compilation work

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The Tectonic Map of Arctic Canada (TeMAC) presents a tectonic synopsis of all onshore and offshore bedrock areas north of latitude 60°N at a scale of 1:4 000 000. Data sources for TeMAC include regional, territorial, and national compilations at scales ranging from 1:100,000 to 1:5,000,000.

One hundred and two tectonic domains of Precambrian and Phanerozoic age are recognized in Arctic Canada. These include 5 cratons, 37 basins, 2 platforms, 3 shelves, 2 plains, 1 ridge, 3 oceanic domains, 7 cover sequences, 15 accreted terranes, 16 magmatic suites and 11 compressional orogens. The tectonic domains are organized based on age and domain type with the resulting tectonic architecture of Arctic Canada, from the oldest Archean cratons to the youngest Neogene basins, captured on the map and reflected in the underlying database structure.

In addition to being organized into tectonic domains, map units are also coded in terms of the dominant lithotectonic environment of formation. Lithotectonic variation is expressed by 24 associations, which include seven sedimentary associations based on gross depositional setting, eight extrusive, six intrusive, and two metamorphic associations, plus an ophiolitic association.

The colour design of the map for Phanerozoic tectonic domains follows as closely as possible that of the International Chronostratigraphic Chart, with new colour shades added for broader age divisions or to distinguish contrasting tectonic domains of similar age. Colours are further modified to convey isopach information for Cambrian to Neogene basins, with saturation increasing with thickness. For Precambrian tectonic domains, a more nuanced colour scheme than available on the chronostratigraphic chart was selected in order to adequately portray the rich Canadian rock record. A distinct colour scheme for oceanic crust present in the Canada basin (Cretaceous) and in the Labrador Sea and Baffin Bay (Paleogene) is based on age range and magnetic chrons.

Pencil stripe patterns are utilized to indicate the extent of orogenic overprinting with the colour of the stripes keyed to individual orogens. If a tectonic domain is overprinted by two orogenic events, a paired set of slanted stripes is shown and in cases of three orogenic overprints, a triad of slanted colour stripes is shown.

The Tectonic Map of Arctic Canada serves as a first example of a derivative product generated from the evolving federal/provincial/territorial Canada-in-3D bedrock compilation and database. It is anticipated that similar products could be available for all of Canada in the near future.

Evolving crustal architecture in magmatic arcs: An example from Fiordland New Zealand

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Fiordland New Zealand is one of few places where the lower crust of a continental arc is exposed. The arc was episodically? active along the eastern boundary of Gondwana from the Carboniferous to Early Cretaceous. Cretaceous plutonic rocks of the arc are included in the Median Batholith and subdivided into the eastern Darran Suite and western Separation Point Suite. The batholith is bounded to the east by its complementary accretionary wedge and forearc (Otago and Alpine schists, Murihiku terrane, respectively), and to the west by the Alpine Fault and oceanic crust beneath the Tasman Sea. Within the batholith numerous shear zones separate the Cretaceous high pressure plutons from Paleozoic metamorphic rocks resulting in complex ca. 10 km scale domal structures with evidence for early Cretaceous contraction followed by late Cretaceous extension.

Exhumed rocks in the western Median Batholith include eclogite, granulite, and pelitic schist and gneiss with evidence for metamorphism and intrusion at pressures ranging from <4 to 18 kbar. Circa 18 kbar orthogneiss originated as ultramafic cumulates and associated monzodiorite, which intruded ca. 122 Ma. The younger 118 to 114 Ma Separation Point Suite orthogneiss intruded as monzodiorite and diorite plutons at 14-12 kbar. These plutons core domes flanked by Paleozoic metasedimentary rocks and metavolcanic schist and gneiss, some of which preserve evidence for Carboniferous metamorphism. South of the Dusky Fault, Paleozoic metasedimentary rocks were metamorphosed at amphibolite facies upper crustal conditions of <4 kbar. Early Cretaceous contractional deformation and magma intrusion north of Dusky Fault led to a crustal thickness of 45-65 km at 120-112 Ma.

U-Pb zircon ages indicate that the younger Western Fiordland Orthogneiss plutons of the Separation Point Suite, with a surface area of ca. 1300 km^2, intruded between 118 - 114 Ma in a high-flux magmatic event. This was followed by widespread ca. 112 Ma, 14-12 kbar granulite facies metamorphism which is mostly restricted to orthogneiss in the cores of the large-scale domes. Sm-Nd garnet and U-Pb titanite dates indicate that localized high-temperature extension began < 111 Ma on mylonite shear zones and this was followed by large scale extensional orogenic collapse 108-106 Ma on amphibolite facies shear zones. High magmatic flux followed by granulite facies metamorphism and partial melting, weakened the lower crust leading to collapse of the formerly thickened crust.

Volcanic, structural, and hydrothermal controls on mineralized environments at the Onaman Property, northern Ontario

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Sage Gold Inc.'s Onaman Property is located 60km northwest of Geraldton, Ontario, within the 2770-2780 Ma Onaman-Tashota Greenstone Belt, a subdivision of the larger Wabigoon Subprovince. The property hosts extensive base and precious metal mineralization that is associated with a range of mineralization styles and textures. Mafic and felsic volcanic rocks of the Onaman assemblage underlie the property and form a large, steeply northwest dipping, homoclinal succession that is bordered to the northwest and southeast by granite batholiths. Approximately 70 percent of the volcanic rocks are mafic flows dominated by massive and pillowed basalts. The flows are intercalated with thin (30-200m by 2-4km) intervals of highly altered felsic volcanic rocks comprised of tuffs and crystal tuffs along with minor massive and porphyritic rhyolite flows. Coarse volcaniclastic units are rare and comprise felsic heterolithic lapilli-tuff and tuff-breccia units containing both disseminated mineralization and pyrite-pyrrhotite clasts. The property contains a large, metamorphosed, Archean alteration assemblage of kyanite-quartz, and chloritoid-sericite as well as a more typical volcanogenic massive sulfide assemblage of chlorite-sericite. Preliminary interpretations suggest the kyanite-quartz and chloritoid-sericite assemblages overprint the chlorite-sericite assemblage. Structurally, the sequence shows strong bedding-parallel foliation that is partitioned into 0.5-15m wide shear zones near lithological contacts. Mapping has revealed three mineralization styles present on the property: (1) Au-Cu-bearing, chlorite-associated, chalcopyrite-pyrrhotite stringers; (2) polymetallic, pyrite-galena-sphalerite-chalcopyrite stringers; and (3) barren, kyanite-quartz-associated, massive and stringer style pyrite-pyrrhotite.

Simulating 100kyr glacial cycles over North America within the University of Toronto Glacial Systems Model (UofTGSM) framework

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We will discuss results from new simulations of the evolution of North American ice-sheets over the last 100 kyr glacial cycle. The University of Toronto Glacial Systems Model (UofTGSM) framework applies surface climate boundary conditions (BCs), basal hydrology, and ice physics approximations derived from the state-of-the-art Parallel Ice Sheet Model (PISM), while constraining the large residual uncertainties in these inputs by nudging simulated ice thicknesses towards the glacial isostatic adjustment-based (GIA-based) ICE-6G_C (VM5a) reconstruction. Pure GIA-based methods mitigate the a priori uncertainties inherent in the formulation of ice dynamical models by adjusting estimates of ice thickness history to fit observational evidence of its effects upon local sea-level change and solid surface deformation. Leading-order fits of ice thickness to observations depend only upon the simple parameter space of a spherically symmetric, viscoelastic Earth model, and nudged PISM-based ice dynamics serve to "smooth" these GIA-based initial fits in a way that determines inherently ice dynamical distributions of temperature, stress, meltwater production, and so on. We will discuss the sensitivity of nudged simulation results to variations in nudging time scale and other important ice dynamical parameters. For a broad range of reasonable parameter selections, results show that the local mass balance adjustments needed to keep smoothed solutions consistent with the ICE-6G_C (VM5a) reconstruction do not exceed the inherent model uncertainties. This establishes the consistency of the leading-order GIA-based reconstruction and allows for the estimation of the local sensitivity of associated ice dynamical fields to model parameters. Local sensitivity to parameter variations consistently depends upon features such as ice margins, ice domes, ice shelves, etc., whose historical distribution is prescribed in an observationally consistent, but probably non-unique, way, by the ICE-6G (VM5a) model. Even the most advanced ice dynamical models lack the skill to predict the spatio-temporal evolution of such features without the assimilation of explicit observational constraints, but we are working to improve the hybrid GIA-ice-dynamical framework of the UofTGSM to better represent crucial processes like surface drainage and proglacial lake evolution. Some results of this work will be discussed along with the sensitivity analyses.

Keynote (40 min): Big models need big data: Integrated hydrosystem modelling in Canada

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Meeting water resources challenges within Canada are a focal point for a wide range of stakeholders who are faced with addressing climate change impacts and resiliency, surface water and groundwater sustainability, and water quality. Because of the complexity of these challenges, modern science-based decision support tools are required. While there are numerous examples in the scientific literature involving 3D physics-based, fully-integrated surface-subsurface hydrologic models being applied at high resolution to watersheds on the order of 10s to 100s of km^2, 3D applications at scales greater than 10,000 km^2 are notably scarce. Recently however, our work in Canada has extended fully-integrated modelling to scales greater than 100,000 km2 in order to simulate transient surface water and groundwater characteristics within a number of Canadian river basins. Examples include the Athabasca (159,000 km^2), the South Saskatchewan (146,000 km^2), the Assiniboine (155,000 km^2), and the entire Canadian land mass. High-resolution modelling at these scales has been made feasible in recent years largely because of advancements in numerical solution methodologies including the parallelization of the non-linear solver, automated model nesting to capture local-scale details within a larger-scale model and access to high-performance computational resources. However, such models also require a significant level of data to parameterize them and to ensure their skill to meet stakeholder demands. The capabilities of physics-based integrated hydrosystem models have, to some degree, advanced beyond what existing input data can routinely support. Needed data include spatio-temporal climatic and land use/land cover information, soil and shallow sediment properties and deeper subsurface hydrostratigraphic information. While the movement towards open, spatially-distributed digital data is recognized as a major impetus for basin-scale model development, some of the datasets required to construct large-scale 3D integrated models are still not widely and readily available over large portions of the Canadian land mass.

This presentation reviews the elements of some of our large-scale modelling initiatives, which are all being carried out with the HydroGeoSphere fully-integrated hydrosystem model. Rationale for the use of a fully-integrated model will be presented, including assessing the impacts of climate change on surface and groundwater resources, impacts of flood and drought on agricultural sustainability, and impacts of land-use change on hydrologic behaviour. Minimum data requirements for the construction of basin-scale integrated models will be presented, but discussion will include the need for organized data collection and assimilation efforts to further advance the skill of such models for understanding of water resource sustainabilty in Canada.

Paleokarst features below the Silurian-Devonian unconformity, southwestern Ontario

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The Bass Islands and Bertie formations are the youngest Silurian deposits in southwestern Ontario. These formations display a variety of paleokarst features under the Silurian-Devonian (S-D) unconformity and are dominantly dolomite successions that record dominantly peritidal sedimentation and episodic subaerial exposure. Regionally, significant sinkhole systems have developed in these formations, marked by underground streams, tufa deposits and minor caves along the Onondaga Escarpment. In the Niagara Peninsula area, a system of solution vugs, extensively leached porosity, solution-widened joints and Trypanites borings are present. Lithofacies and stratigraphic analyses of 39 cores across southwestern Ontario have revealed a wide variety of solution collapsed breccia, in situ breccia with corroded clasts, fractures infilled by Devonian siliciclastic sands, molds, vugs, cavities and intraformational channel ways.

The Bass Islands and the Bertie formations overlie the evaporite-carbonate succession of Salina Group and underlie the Devonian Oriskany Formation siliciclastic sandstones and/or the Bois Blanc Formation cherty carbonates. Two major paleokarstic events are recognizable. 1) Surface karstification and erosion occurred during the Early Devonian, resulting in a variety of breccias and rubble in the uppermost Bass Islands Formation, infilled by sands or cemented by carbonates of Devonian age. A bluish-grey mottled paleosol occurs locally at the top of Bass Islands Formation. The sporadic distribution of the overlying Oriskany siliciclastic sandstone is interpreted as an infill of the karren domain of the eroded Silurian dolomite surface. 2) Collapse breccia, breccia pipes and sinkhole infills, developed throughout the Bass Islands Formation, are interpreted to be related to the draping and collapse from the underlying Salina Group during the first phase of the Acadian Orogeny.

Climatic conditions during S-D boundary interval were probably semi-arid and the regional uplift of the North American craton led to marine regression and karstification. Although overprinted by the grykes and collapse formed during Holocene exposure, the paleokarst profile below the S-D boundary in southwestern Ontario displays significant correspondence to the tectonic uplift and the dissolution of underlying evaporites.

Hydrothermal alteration of the crater-lake sediments in the Ries impact structure, Germany

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The Ries impact structure in southern Germany is one of the most well-preserved impact structures in the world; it provides a rare opportunity to study the contact between the heat source of an impact-generated hydrothermal system and the lake sediments deposited shortly after impact. Here, we highlight the significance of isotope related studies and present preliminary X-ray diffraction (XRD) and petrographic findings from the Wörnitzostheim core (Wör core) received from the Center for Ries Crater and Impact Crater Research (ZERIN) in Nördlingen, Germany.

The 22-24 km wide, 15.1±0.1 Ma Ries impact structure is located in southern Germany where it penetrates the Jurassic limestone and the gneissic Hercynian basement. Ries formed in a flat lying sequence of Jurassic-Triassic sedimentary rock roughly 470-820 m thick with a central basin existing within the tectonic rim. A series of impact melt-bearing breccias termed “suevites” fill in the central basin overlain by roughly 400 m of post-impact biogenic limestone lacustrine sedimentary rocks.

The Wörnitzostheim core was sampled from just outside the inner rim of Ries where it penetrated through crater-lake sediments overlying the suevite. The rock type gradually transitions from the bioclastic limestone to suevite. The lake sediments, comprised largely of green algae encrusted by micritic carbonate, contain the heavily weathered bases of compound cone structures in the upper 10 m of core. The gradual change from 10 to17 m denotes the transition from the crater-lake sediments to the reworked suevite - generally characterized by an increased abundance of polymict clasts and a coarser, muddy- sandy matrix. Notably at 27.3 m a weakly lineated zone with a significant alteration halo and moderately removed fines occurs – highly reminiscent of the degassing pipes observed elsewhere at the Ries, probably suggesting a strong hydrothermal influence on alteration patterns.

Stable isotope analyses could corroborate the detailed mineralogy already conducted on the suevites at the Ries. Strangely, there has been very little focus on using stable isotopes to study hydrothermal alteration at Ries. $\delta^{18}O$ trends would provide a good starting point to study the Ries hydrothermal system, but there are many potential influences on the isotopic trends that would have to be determined before isolating the influences of hydrothermal alteration. The isotopic history of the lake is further complicated by weathering, diagenesis, and biological activity; therefore, each sample must be very well characterized before selecting what to analyze with isotope ratio mass spectrometry (IRMS).

Identification an accretionary orogen by amount of juvenile compositions: An examples from SW Central Asia Orogenic Belt

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It is generally considered that orogens can be generally divided into two types: accreationary and collisional orogens. What are fuandamantal differences between them and how and how to identify them have not been well understood. This study attempts to discuss this problem by juvenile compositions defied by Nd-Hf isotopic mapping of granitoids in the southwestern segment of the Central Asian Orogenic Belt (CAOB), a typical and the world's largest phanerozoic accretionary orogenic belt.

The southwestern sector of the CAOB from north to south comprises the Altai orogen (or terrane), Junggar terrane, Tianshan and Beishan orogens. The Paleozoic and Mesozoic granitoids of the central Altai show εNd(t) = -5 to +2 with TDM = 1.6 - 1.1 Ga, the Western Junggar εNd(t) = +3 to +9 with TDM = 0.8 to 0.4 Ga, the Eastern Junggar εNd(t) = +2 to +8 with TDM = 0.9 to 0.5 Ga and the Tianshan and Beishan large ranges of εNd(t) values and TDM. These data suggest that the central Altai has a remnant of a reworked (old) continental terrane, the Junggar terrane a juvenile accretionary complex (mélange), the Tianshan and Beishan orogens with both juvenile and old recycled crust.

All these signatures indicate that the granitoids in the CAOB have significant differences in Nd isotopic compositions from collitional orogens such as Qinling-Dabie Orogen in the central China, suggesting different deep crustal compositions for them. Compared with the general orogens, the CAOB has much juvnile compositions and much crustal growth (juvenile materials) during Phanerozoic time, distinct with an typical collisional orogen. This study reveals that isotopic compositions of magmatic rocks can trace deep compositions of orogens and provide significant information for understanding compositions and evolution stages (from juvenile accretionary, subductional to collisional) of orogens.

Unknown knowns: A multidiscipline approach investigation previously unknown amber samples and their paleoecological implications

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Amber deposits including animal inclusion are rare in the fossil record, known for only a few localities and time slices. Yet their 3D preservation of both hard and soft tissues offer paleontologists a detailed glimpse into the biology of extinct life that is not possible through other preservation methods. Here we will discuss a new study on a previously unreported amber specimen containing both vertebrate and invertebrate inclusions that has been housed in the collections of the Queen's Miller Natural History Museum. Despite the importance of this specimen there is no record of its locality information or stratigraphic context. Here we present work using a variety of techniques to help determine these critical pieces of geological information for this specimen that will help shape our investigations on the paleobiology of the contained organisms going forward. Using Fourier Transform Infrared Spectroscopy (FTIR) as well as stable isotopic analysis allows us to identify the paleoenvironmental conditions of the depositional environment of this rare specimen. The high Carbon isotopic signal (26.7-270/00) suggested that our sample is derived from Angiosperm resin and of Neogene in age from an area of high humidity. This combination of techniques allowed us to gain a unique glimpse into the paleobiology of this specimen and the ecosystem in which it lived. Finally, we used high resolution X-ray Microscopy scans we have reconstructed a 3-D digital model of this vertebrate and invertebrate as inclusions found in the same sample. The highly detailed nature of the model allows us to document the morphology of these organism specimen which when coupled with our isotopic findings allows for greater granularity in reconstructing this fossil ecosystem.

3D geological modeling of quaternary sediments for seismic shaking assessment on a regional scale

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The Great Lakes and the Western Quebec seismic zones are characterized by low to moderate seismicity. Due to extensive exposure in important urban centers, seismic risk is still very high. The study covers an area of 109 751 km^2 that stretches from Toronto, ON to Quebec City, QC. In the near-surface, the distribution of stiff versus soft surficial sediments and their respective thickness can significantly impact the intensity of ground shaking by affecting the amplitude and frequency of incoming seismic waves. Most importantly, soft and fine lacustrine and glaciomarine sediments can greatly amplify ground shaking. Information about surficial geology is also necessary to make accurate predictions of potential negative seismic effects, such as physical damage, economic and social losses. A simplified continuous 3D geological model of the near-surface sediments was created to address the seismic properties of these units and examine in more detail the impacts on ground shaking intensity. Information from 'Did you Feel it?' (DYFI) reports and records from selected seismic stations from past earthquake events are analyzed within the geological context.

The model created in this study is largely based on existing datasets available from geological surveys and other public organizations. The types of data used for this model include digital elevation models, bedrock topography, sediment thickness, surficial geology, geotechnical boreholes, geophysical logs, water wells, and existing 3D geological models within the study area. Independent seismic surveys were carried out at selected locations to verify existing datasets and collect new data, such as shear wave velocities and horizontal versus vertical ratio from ambient vibration (H/V). All data processing was carried out in ArcGIS and 3D models were generated using SKUA-GOCAD software on a 500m by 500m grid. The model consists of continuous triangulated surfaces representing the tops of units from which 3D stratigraphic grids were generated for volume visualization and property modeling. Continuous maps of sediment thickness, surface material (soft organics, post-glacial sand and clay, till, and bedrock), and dominant material in the stratigraphic column were produced for further use in seismic shake-map generation. Results from the comparison between the 3D model and the distribution of DYFI and seismic station data show the importance of shallow geologic conditions on the intensity and spatial distribution of ground shaking away from an epicenter.

Thelon Tectonic Zone: Crustal origins, tectonic setting, and implications for the Thelon-Taltson orogenic belt -- An oxygen isotope perspective

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The Paleoproterozoic Thelon-Taltson orogenic belt comprises two broadly similar, 2.0-1.9 Ga regions separated by the MacDonald fault: the Taltson Magmatic Zone (TMZ) to the south and the Thelon Tectonic Zone (TTZ) to the north. The tectonic setting of the TMZ, situated between the 2.4-2.0 Ga Buffalo Head terrane and Archean Rae craton, has been interpreted as an intracontinental hinterland far removed from a convergent plate margin (Chacko et al., 2000). Schultz et al. (2007) proposed a similar intracratonic setting for the TTZ, which is sandwiched between the Archean Slave and Rae (Queen Maud block) cratons. The TTZ contains a wide spectrum of magmatic rock types, from gabbro to monzogranite, Al-saturated granite and alkali-feldspar granite. Whole-rock oxygen isotope data ($\delta^{18}O_{WR}$), lithogeochemistry and Nd isotope data were acquired for 85 samples, and grouped by U-Pb zircon age: (basement) >2.5 Ga., (early) 2.02 to 1.98 Ga, and (late) < 1.93 Ga. Only the youngest group (<1.93 Ga) of TTZ magmatic rocks displays geochemical trends similar to the 2.0 - 1.9 Ga TMZ granitoid rocks.

Early TTZ rocks have values of $\delta^{18}O_{WR}$ from 5.9 to 8.1 permil that vary systematically with SiO_2 from 49 to 71%; late TTZ rocks span $\delta^{18}O_{WR}$ 7.1 to 11.9 permil, varying from 61 to 75% SiO2. Plots of $\delta^{18}O_{WR}$ vs. wt.% SiO_2 for similar-age rocks mimic open-system, AFC processes involving mafic (mantle) and siliceous (continental) crust. Early and late TTZ rock groups partially overlap on a plot of normative Q/(Q+Ab+Or+An)×100 vs. normative An/(Or+An)×100, but late TTZ rocks exhibit higher Q ratios and lower An ratios typical of continental crust. We interpret that a > 400 km-long belt of ca. 1.9 Ga garnet-bearing leucogranites with $\delta^{18}O_{WR}$ > 10.5 was derived from melting of a continental margin sedimentary basin. Values of εNd1950 for Proterozoic TTZ rocks vary from -1.9 to -11.8, with more negative values in the younger rocks. The above data, along with tectonic discrimination plots (e.g. Nb vs Y), suggest that the early TTZ rocks likely reflect a convergent plate margin origin, whereas the late TTZ rocks formed in a collisional setting. Thus, we suggest that a subduction margin-to-collisional transition is indicated by the geochemistry of the 2.03 to 1.90 Ga TTZ magmatic rocks. Lack of support for a subduction margin in the TMZ (Chacko et al., 2000) may indicate a variation in tectonic history along Thelon-Taltson orogenic belt.

Oxygen isotope zoning at the Archean Izok Zn-Cu-Pb-Ag VMS deposit, Nunavut, Canada: Hanging wall vector to mineralization

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Oxygen isotope compositions were determined for 99 whole-rock, primarily surface-collected samples of felsic host rocks collected in the vicinity of the large, undeveloped Archean Zn-Cu-Pb-Ag volcanogenic massive sulphide (VMS) deposit at Izok Lake, Nunavut. These data complement lithogeochemical analyses and short wave infrared absorption spectra measured in the field. The oxygen isotope data reveal a distinctive zonation pattern that is spatially centred in rocks stratigraphically above the massive sulphide lenses. The oxygen isotope zoning pattern, produced by submarine water/rock interaction, indicates that the orientation of this paleo-hydrothermal system is relatively 'upright'. Analyses, primarily from hanging wall samples, have δ^{18}OV-SMOW values as high as 14.7 permil. The high values characterize the centre ("bull's eye") of the pattern, mark the area of paleo-upflow, and contrast with isotopic studies describing ^{18}O-depletion in footwall and upflow zones. The high δ^{18}O zoning pattern in the Izok Lake area is a clear hanging wall 'vector' to the buried sulphide lenses. This isotopic 'fingerprint' of an Archean hydrothermal system has been retained in the rocks, despite subsequent amphibolite facies metamorphism. The oxygen isotope zonation partially corresponds to a broad, irregular 1% Na_2O isopleth, within which rocks have lost Na_2O. To some extent, oxygen isotope zonation also corresponds with a mapped distribution of the Ishikawa alteration index, and with short-wave infrared spectral mapping of white-mica and biotite+chlorite-related absorption features. However, the pattern of oxygen isotope zonation, derived from fewer analyses than either the spectral measurements or the lithogeochemical analyses, provides a more focused 'target'.

In-situ sulphur isotope study of the Prairie Creek deposit, southern Mackenzie Mountains, NWT: Deciphering the conundrum of three deposit styles in one

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The Prairie Creek district, southern Mackenzie Mountains, NWT, includes base metal sulphide occurrences of three different styles: Mississippi Valley-type (MVT), stratabound replacement, and quartz-carbonate-sulphide veins. The Prairie Creek Zn-Pb-Ag deposit, itself, is comprised of two of these styles: quartz-carbonate-sulphide veins and stratabound replacement bodies. Discerning any relationship between these styles may help develop exploration strategies. In situ sulphur isotope analysis by laser-assisted fluorination of individual minerals in 30 representative samples (17 stratabound replacement; 12 veins, and one MVT) addressed isotopic compositions and states of equilibrium; 303 analyses were performed in total.

The overall range of $\delta^{34}S$ for stratabound pyrite, sphalerite and galena was large, ca. 15 permil, but the distributions of $\delta^{34}S$ for pyrite, sphalerite and galena were more restricted (1σ 2.53, 1.46 and 2.7 permil, respectively) than in quartz-carbonate-sulphide veins. Analyses from the single MVT sample (Root River Formation; pyrite-rimmed vugs in sparry dolomite) suggest MVT occurrences may be unrelated to stratabound sulphide bodies. Similar $\delta^{34}S$ values for pyrite and galena in vein and stratabound sulphide bodies are observed; relationship comparable exists for galena. Some similarity in sulphur isotope systematics for veins and stratabound bodies suggests a general genetic relationship. However, significantly larger ranges and lower values of $\delta^{34}S$ for pyrite and galena in veins may hint at the cause of Pb isotope results that argue for separate origins (Paradis, 2007). The veins, or vein-related flow paths, may have acted as fluid conduits at multiple times, first as conduits for the fluids ($\delta^{34}S \approx 23$ permil) that formed the stratabound bodies, and, subsequently for the veins, disturbing earlier isotopic systematics.

Isotopic disequilibrium was found to be common, and estimated isotopic temperatures are considered approximate at best. Isotopic variance on the mm scale was such that average $\delta^{34}S$ values proved more useful for estimating temperatures of formation. Our high-spatial resolution data suggest caution when interpreting sulphur isotope geothermometry in similar situations; whole-rock analysis may mask important variations, including genetically-significant details. Estimates of formation temperatures for the stratabound bodies fell within the range of ca. 170-250°C. Veins appear to reflect similar, but perhaps a bit higher temperatures of formation. The principal stratabound sulphide body in the Prairie Creek mine appears to record a variation in temperature, from higher values towards the centre which match those from the Prairie Creek vein, and cooler values towards the margins of the stratabound sulphide body.

Deformation and extensional exhumation of Paleoproterozoic high-pressure granulites along the Wholdaia Lake shear zone, south Rae craton, Northwest Territories

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Pervasive high-pressure metamorphism at 2.5 and 1.9 Ga is documented along the eastern margin of the south Rae craton from Baffin Island to beneath the Athabasca Basin. The ~2800 km extent of this high-pressure belt is analogous to the footprint of large orogens such as the Himalayas or Grenville, yet conditions of its formation and exhumation are controversial and are the subject of this study.

New mapping in this poorly understood high-pressure belt in the southern Rae craton, Northwest Territories, has uncovered a 300 km long, 5-20 km wide crustal scale shear zone, referred herein as the Wholdaia Lake shear zone (WLsz). This northeast trending structure dips steeply to the southeast and parallels the Snowbird Tectonic Zone, which separates the Rae and Hearne cratons to the east. To the west of the WLsz, the Firedrake domain consists of polydeformed ca. 2.70-2.66 Ga orthogneiss intruded by voluminous 1.83 Ga magnetite-bearing granodiorite. East of the WLsz, the Snowbird domain contains polydeformed, infolded orthogneiss (2.70-2.66 Ga) and paragneiss (2.07-1.93 Ga) metamorphosed at 1.92 Ga. The total field magnetic signature of the WLsz displays both the Firedrake and Snowbird domain map patterns being transposed into the WLsz with dextral sense of shear.

Metamorphism and movement in the WLsz is recorded by episodic monazite and zircon growth. Metasediments within the WLsz and the hanging wall Snowbird domain contain high-Y prograde monazite included in garnet and yields ages of ca. 1.94-1.92 Ga at conditions of 9 kbar and 850° C. Post-garnet growth, syn-kinematic low-Y monazite grew at ca. 1.93-1.90 Ga indicating continued high grade metamorphic conditions in the garnet stability field. These metasediments also contain 1.91 Ga metamorphic zircon growth, interpreted to have grown post-peak metamorphism. High-pressure mafic granulites within the WLsz have 2.6 Ga igneous crystallization ages and 1.9 Ga metamorphic ages. The high-pressure granulites display two assemblages: 1) an early gneissic (Grt-Cpx bearing) domain with peak estimates of 14 kbar and 750° C, and 2) a sheared domain (also Grt-Cpx bearing) with peak estimates of 9 kbar and 700° C. Dextral normal-oblique shearing in lower grade amphibolite facies mylonites within the WLsz has a minimum age of 1.86 Ga constrained by late crosscutting granite dikes. These results imply the WLsz accommodated exhumation from lower to mid-crustal levels between 1.91 and 1.86 Ga with at least some component of normal-sense extension.

Faults in the late Paleozoic Antigonish sub-basin, Nova Scotia, reinterpreted as potential salt welds

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The Antigonish sub-basin, located in northeastern Nova Scotia and extending from the Antigonish Highlands to western Cape Breton Island, is one of many sub-basins that developed in the late Paleozoic within the Maritimes Basin of Atlantic Canada. The Antigonish sub-basin is structural in nature and bounded by long strike-slip faults. The late Devonian to late Carboniferous basin-fill is primarily clastic yet contains one major marine succession of carbonates and evaporites. Previous mapping estimated a total stratigraphic thickness of 5000 to 6000 m of basin-fill but a present day basin depth of 3000 m. The large discrepancy in stratigraphic thickness and basin depth was attributed to variable unit thicknesses upon deposition and to the removal of a section by faulting along a surface designated as the Antigonish Thrust. This surface was later reinterpreted as a low-angle extensional fault, the Ainslie Detachment, extending under St Georges Bay into western Cape Breton Island.

Preliminary fieldwork in the summer of 2016 examined several regions of interest around Antigonish and western Cape Breton Island from a modern salt tectonics perspective. The discordant surface extending through much of the Antigonish sub-basin is proposed to be a salt expulsion surface. Several salt walls have been previously identified on seismic lines running through St. Georges Bay as well as a salt diapir in a coastal outcrop, suggesting the potential of salt expulsion within the Antigonish sub-basin.

The fieldwork also identified outcrops at Lakevale and MacIsaacs Point on southern Cape George as potential primary salt weld exposures, while another outcrop at Little Judique Harbour may show a secondary salt weld. In addition, evidence of salt tectonics was noted in an area of laminated Macumber Formation limestone. Gypsum pseudomorphs approximately 1 cm^2 in size are abundant here, along with many outcrop-scale faults and folds in the limestone. The observed geometries of the folds suggest that brittle limestone layers were encased in ductile evaporites during deformation, but that the evaporites have been removed by solution.

These preliminary findings suggest that the surface previously identified as the Antigonish Thrust or the Ainslie Detachment is actually an evaporite weld produced by salt expulsion. Future work will examine key outcrops in detail and attempt to constrain the timing of salt expulsion within the sub-basin and its relationship to strike-slip faulting.

Keynote (40 min): From geoscience to metallurgy – improving mining, processing and sustainability

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The earth's crust and upper mantle consist of approximately 4500 minerals with a significant number containing metals at concentration levels that justify separation and recovery. The early use of metals almost 10,000 years ago was based on the recognition of minerals, and this is still the basis of modern exploration, mining and mineral processing.

Geoscience underpins our understanding of minerals and their occurrence in different rocks and diverse environments. The information on rocks related to mineral deposits not only informs our understanding of ore forming processes and exploration criteria, but also provides indications of how rocks will behave during mining, processing to economic products, and effective management of waste materials.

During the evaluation of mineral deposits for potential mining, bulk characteristics are determined to define hardness and breakability, appropriate methods to liberate and recover minerals (e.g., flotation) or to leach metals directly from ore, and the nature of the tailings and waste rock, e.g., their potential to release acid and deleterious elements. Acquiring this information is time-consuming and expensive and is therefore commonly based on a limited number of samples regardless of the size and cost of the deposit. Limited measurements may fail to define variability in critical ore and waste characteristics over the life of mine.

Geometallurgy involves the use of multiple small-scale measurements related to mining and metallurgy and routine geological data (e.g., geochemistry, mineralogy and mineral texture, physical properties, fracture density) to provide proxies for critical mining and processing parameters. These data usually define domains with distinct ore and waste characteristics thus allowing variability to be assessed through the life of the operation, mining and processing methods to be scaled and optimized, and environmental risks to be assessed and mitigated. Furthermore, complete characterization of the ore and waste allows improved cost and energy assessment, and consideration of new technologies such as ore sorting that may increase efficiency and decrease the overall environmental footprint.

Geoscientists play a vital role in the accumulation of appropriate data from exploration through advanced evaluation, communication of results, and participation in multidisciplinary geometallurgical teams. Use of new technologies, such as multi-spectral core scanners, may allow more rapid accumulation of data and further benefits from bulk mineralogical and structural information.

Paleoenvironmental implications of rugose coral growth ridges in the Middle Devonian Hungry Hollow Member, Michigan Basin

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The fossil skeletons of Paleozoic rugose corals feature micron-scale growth ridges on their outer surface (epitheca) that record the successive positions of the coral polyp during longitudinal corallite growth. Epithecal ridges and intervening troughs represent short-term increases (radial polyp expansion) and decreases (radial polyp constriction) in skeletal secretion. Judging by the utility of modern scleractinian corals as climate proxies, studies on short-term growth cyclicity in rugose ancient coral taxa should have some potential in providing insight on the paleoenvironmental factors that affected biota in ancient marine environments. For purposes of characterizing and quantifying the cyclic characteristics of rugose growth ridges beyond the level of ridge counting, specimens of rugose corals Eridophyllum and Cystiphylloides from the Hungry Hollow Member of the Middle Devonian Widder Formation were examined. Specimens with well-preserved epitheca were scanned using Micro-CT to preserve a 3D model prior to being cross-sectioned longitudinally (along their growth axis) for closer examination in thin section and backscatter SEM imaging. Image processing and filtering techniques were applied to a stitched mosaic of SEM images of the edge of the coral epitheca to extract a line representing the coral surface. This will allow statistical analysis methods to be applied to this dataset, to find patterns relevant to possible paleoenvironmental and astronomical cycles. Initial analysis of the images has corroborated previous research; largest-scale ridges contain ~13 smaller bundles, previously interpreted to represent lunar months in the Devonian year. These monthly packages are divided into ~ 30 ridges, believed to represent days for the faster-spinning Earth. Interestingly, these monthly groups seem to be subdivided into two distinct packages of 15 ridges, which may suggest a further connection of rugose coral growth with lunar cycles. By analogue with modern corals, there may have been a possible lunar cycle relationship with reproductive cycles and allocation of the organism's resources. Potential challenges with this task include the determinations of a zero-line against which fluctuations in coral growth can be compared and quantified. The superposition of random non-cyclic or semi-cyclic growth factors, such as those recording episodes of storm disturbance (which can also lead to changes in growth direction), climate variation, predation, or turbidity may have modified the growth of the individual, masking the influence of cyclic factors. This research will provide insight into the paleoenvironmental, and possible astronomical factors that affected marine biota of the Chatham Sag area of Ontario.

Keynote (40 min): Geological mapping in the US

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In 2014, the Association of American State Geologists (AASG) passed a resolution that endorsed USGS planning, and that cited pressing issues related to energy, minerals, water, hazards, climate change, environment, waste, and engineering, as well as research priorities, to call for accelerated progress on a national, regularly-updated, well-coordinated, multi-resolution, seamless, 3D, material-properties-based geological mapping database. Researchers and land use managers increasingly rely on and therefore need to invest in geological mapping that will return benefits, including lives saved, resources discovered, costs avoided, increased efficiency, and improved understanding of earth composition, structure, and history. Provision of standardized and accessible geologic mapping is facilitated by the National Geologic Map Database, which is managed by USGS in cooperation with AASG, with proven arrangements for administration, data, stratigraphy, and standards. Mapping at state and national scales in the US is complete, although in need of updating. At scales needed for planning, coverage is only about 50%, and these maps typically are unreconciled relative to each other. Subsurface mapping needed for groundwater management and sedimentary basin assessments is even less complete. The superb nature of completed mapping, and compelling user needs, thus call for acceleration and enhancement of this activity. There thus is an urgent need for geological mapping to be progressively more: focused on user needs while accommodating unanticipated applications; conducted as part of a well-planned program based on ongoing assessment of required databases; focused on the most detailed mapping where needed; committed to jurisdiction-wide completion at an appropriate level of resolution; reconciled from onshore to offshore with topographic and bathymetric data; coordinated with soil mapping; based on compilation of drillhole and other data, along with strategic drilling and newly acquired geochronology, geochemistry, and geophysics; based on sound stratigraphic naming; categorized using accepted terminology; committed to regular updating; assembled as state-wide seamless compilations; 3D, in which the extent, thickness, and properties of layers, and geometry of selected basement structures are distinguished; material properties-based; coordinated with 3D versions of state, continental, and global-scale maps; accessible through open-source software; and linked to databases as well as searchable publications. Surveys need to aggressively transition to this approach, to better fulfil their essential role in society.

Polyphase structural deformation of low- to medium-grade metamorphic rocks of the Liaohe Group in the central segment of Jiao-Liao-Ji Orogenic Belt, North China Craton: Correlations with tectonic evolution

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After 1 to 50 000 specific geological mapping carried out by China Geological Survey, and recent two years our group mapping for the Liaohe Group in the central segment of Jiao-Liao-Ji Orogenic belt (JLJOB), this abstract mainly presents the implications of structural deciphering work applied to the metamorphic rock geological mapping. The rock unit in our mapping area is the Liaohe Group, is probably the most significant lithostratigraphic unit in the Jiao-Liao-Ji Orogenic belt in the Eastern North China Craton, can further divisible into five formations. From the lowermost Langzishan Formation to the uppermost Gaixian Formation, there is an upwards transition from arkoses and volcanic rocks to carbonates and at the top argillites. Based on the geological mapping in those metamorphic rocks, five useful functions of structural analysis are show: (1) In the metamorphic area, deformation of rocks are complicated due to orogenesis and later denudation, the significant geological boundary of Groups is not easy to recognize, but structural deciphering work can be used to trace the hidden boundary by plant; (2) Previous geological mapping (1 to 50 000 and 1 to 200 000 geological map) in this area, strictly followed continuity of sedimentary strata in different Formations. However, the Liaohe Group was totally mixed up by later deformation, different rock units or formations could be mixed together. However, these different rock units often handled as one Formation in the previous geological map, structural deciphering work therefore can be used in this situation to distinguish difference rock units (strata); (3) When field geologist mapping a new area, especially in the metamorphic area, it is very important to establish the regional geological frame. In this case, structural deciphering work must be carried out to trace all the faults including thrust, strike-slip fault, normal and reverse faults carefully; (4) Measuring the cross-sections make people very upset when mapping in the metamorphic area because of lots of same rock units occurred repetition result from regional thrust faults. Evaluation of the thickness of strata in the metamorphic area therefore should be considered the structural deciphering work in the first time; (5) The relationships between deformation and metamorphism are very important, it can help geologists to recognize the different degrees of metamorphic and deformation rock units in the metamorphic region.

What small Earth Science institutions can do for education: An example from the Quartermain Earth Science Centre, Fredericton, New Brunswick

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Geological issues are increasingly relevant to the everyday lives of individuals and communities around the world, whether it is the risks to water quality, natural hazards, climate and sea-level change, management of our energy and resources, or the complexities of geological engineering. Earth Science literacy is an urgent and important issue, and to accomplish this involves tough challenges for (1) motivated educators and individuals searching for truthful information, as well as (2) many time-strapped Earth Scientists seeking an approach to provide quality, meaningful facts to schools (K-12) and the general public. Small institutions can recognize that strengthening public engagement in science education involves identifying and addressing what people care about, and developing targeted programs and activities focused on building better communities.

Since its doors opened in 2011, the Quartermain Earth Science Centre, (QESC) has embraced this vital responsibility with initiatives that include inquiry-based hands-on geological activities, interactive public lectures, geo-hikes, and collaborative efforts with other science educators and institutions. Connecting through social media with its website (QuartermainEarthScienceCentre.com), Facebook, and Twitter accounts has proven essential to awareness on programs and events. The QESC offers tours as well as educational activities at the museum and/or remotely.

For a small institution with one part-time curator, the museum benefits from public and private funding, donations, and community support. Useful geological collections that have been procured over the last 120 years thanks to faculty and student university research projects are being organized into teaching kits. Graduate students, volunteers, co-op and work-study programs allow the QESC to function with minimum staff while providing quality outreach programs. The curator manages administration, allowing the professionals and graduate students to focus on connecting with the public.

The QESC has identified and established long-term relationships and partnerships with other community groups. Collaboration with other science educators, events, institutions, and individual professionals has been essential to increasing outreach while keeping expenses low. For example, the QESC provides programs for travelling science fairs, camps and other organized groups. Teacher workshops and collaboration with UNB's Faculty of Education has resulted in developing Teacher Science Kits on Minerals and Rocks in support of the New Brunswick Earth Science curriculum.

The QESC will continue the process of building trust, learning about enduring needs and issues, and seeking new connections by discovering shared visions – recognizing that small museums are a valued community resource, providing opportunities for students and the public at large.

Basaltic lava flow field analog at Craters of the Moon National Monument and Preserve

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By using field analogue sites on Earth, we can tie detailed geochemical and petrographic properties of basaltic lava flows to their surface roughness as determined from remote-sensing radar investigations, with the ultimate goal is to compare them to the lava flows and impact melt deposits on other terrestrial planets. In this study, we use the petrography, geochemistry, and surface roughness of lava flows at the Craters of the Moon National Monument and Preserve (COTM) in Idaho as an analogue for planetary lava and impact melt flows. At COTM, we sampled six lava flows hosting different surface roughness and contrasting compositions. From these lava flows 45 samples were collected for petrographic and geochemical analysis. Airborne Synthetic Aperture Radar (AIRSAR) L-Band (24 cm) data produced circular polarization ratio (CPR) images to distinguish the decimeter-scale surface roughness of the lava flows. CPR values <0.5 are classed as smooth surfaces, 0.5-1 is considered rough and values exceeding 1 are blocky. The CPR data from COTM shows surface roughness changing along single lava flows and between adjacent flows which occurs with distance from source and lava flow crystallinity.

Our initial results indicate that lava flows with similar surface roughness are not limited to one crystalline texture, surface roughness that can be described as blocky, rubbly and slabby pahoehoe contains aphanitic, porphyritic, trachylitic and vitrophyric textures. Geochemical data collected using XRF analysis shows majority of the trachylitic lava flows to be siliceous with SiO2 content reaching 62 wt%. Changes in cooling rates and applied stress from the movement of the lava have arranged elongate plagioclase crystals along preferred planes of orientation. The orientation of plagioclase is observed in the petrographic data along a single lava flow known as Devil's Orchard with relatively uniform surface roughness from source to lip of the flow. Aphanitic glass matrixes are encasing the crystals implying rapid cooling and quenching which can occur during sudden exposure to the surface and along flow margins.

Using COTM lava flows as a planetary analogues field site will improve interpretations of the formation of lava flows on other terrestrial planets exhibiting similar surfaces. Petrographic, XRF and radar data are compared to tie together an explanation for the diversity of surface roughness of basaltic lava flows at COTM. Surface roughness is observed changing along individual flows as well as between adjacent flows implying changes in its rheology as it cools and propagates further from its source.

Two contrasting crustal blocks revealed by Nd-Hf isotope data from Paleozoic granitoids on either side of Erlian-Hegenshan suture

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The Solonker suture zone in the southeast of the Central Asian Orogenic Belt has widely been considered to mark the boundary between the North China and Siberian blocks. However, the formationtime and style of the suture is still highly debated. Zircon U–Pb ages, Hf isotopes and whole-rock geochemistry and Sr-Nd isotope results are reported for six granites from the immediate north area of the Solonker suture. These granites showed had been considered as old basement rocks or Early Paleozoic rocks. Our new zircon U–Pb dating reveals that they were emplaced in the early Permian (291-275 Ma), with the timing of deformation estimated at 275-250 Ma. These granites exhibit weakly peraluminous (A/CNK = 1.08-1.28), and calc-alkaline to High-K calc-alkaline series I-type granites. They have similar whole-rock εNd values (-4.0 - -0.3) with two-stage model ages of 1.38 - 1.07 Ga. However, their zircon εHf values are distinctive, varying from -1.6 to +14, with crustal model ages (TDMc) of 1.38 to 0.72 Ga. This requires the existence of a microcontinent in the basement, which is probably linked with the Xilinhot microcontinent to the east. Therefore, a Precambrian terrane must be present between the Solonker and Erlian-Hegenshan ophiolites. Importantly, Paleozoic granitoids from this block have WR εNd values mostly negative and zircon εHf values mostly <10. In contrast, the granitoids from the block of north Erlian-Hegenshan ophiolite have positive WR εNd values (mostly >0) and εHf values (> 6), indicating more juvenile mantle input. This difference in the Nd-Hf isotopic signatures of the granitoids reveals two contrasting blocks on either side of the Erlian-Hegenshan suture, which means this suture is an important tectonic boundary and did not extent to Solonker suture in west.

A geochemical and petrographic study of Postshield volcanism and the generation of trachyte on West Maui, HI

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The West Maui Volcano provides a complete evolutionary history of a fully developed Hawaiian volcano described by three main phases: (1) the tholeiitic shield-building stage of the Wailuku Basalts; (2) the postshield alkalic stage Honolua Volcanics; and (3) the rejuvenated stage Lahaina Volcanics of silica-undersaturated rocks. On West Maui, the postshield Honolua Volcanics erupted highly differentiated rocks (benmoreite to trachyte), with little to no intermediate alkalic rocks, upon cessation of tholeiitic shield building. We present 73 new major and trace element and petrographic analyses of shield and postshield lavas on West Maui in an attempt to identify the mechanisms present during evolution of Hawaiian plume magmas from basalt to trachyte over broad temporal and spatial ranges. Honolua benmoreites contain microphenocrysts of olivine, titano-magnetite, potassium feldspar, matrix feldspar laths, magnetite, and nepheline. The most evolved trachytes contain phenocrysts of potassium feldspar, hornblende, augite-aegerine, and magnetite in a matrix of oriented feldspar laths. Magnetite grains typically contain small intergrowths of ilmenite. Wailuku basalts are dominated by olivine fractionation, whereas decreasing Sc and CaO/Al_2O_3 with increasing degree of differentiation indicate Honolua benmoreites and trachytes heavily fractionated clinopyroxene while the more evolved trachytes fractionate feldspar. Further, major element trends are consistent with crystallization of titano-magnetite, potassium feldspar, and minor apatite. Trace element patterns of the Honolua Volcanics are highly varied with strong enrichments in LILE and the LREEs indicating fractionation and lower degrees of partial melting compared to shield stage activity. The HREEs are somewhat enriched relative to shield basalts with Gd/Yb values of 1.5-3.0. Fractionating apatite produces a strong depletion in the middle REEs. Major and trace element trends follow the evolution of the postshield Hawi Volcanics of Kohala, where alkalic basalts differentiate up to trachyte. Trachytes from Hualalai Volcano have geochemical trends similar only to the most evolved Honolua lavas in which TiO_2, Al_2O_3, and MgO increase, while Na_2O and CaO decrease with increasing SiO_2. Honolua lavas are generally more enriched in incompatible elements relative to postshield lavas of Kohala, Hualalai, and Haleakala. Compared to shield lavas, the Honolua Volcanics represent a drastic decrease in magma supply rates and frequency of eruptions; with magma residence times long enough to produce highly differentiated magmas with no apparent mafic magma input.

Till compositional inheritance and overprinting in the Hudson Bay Lowland and across onto the Precambrian Shield

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The goal of this work is to determine the effect of multiple glaciations on till composition, in a zone of transition from a multi-till stratigraphy within the Hudson Bay Lowland (HBL) to a single till stratigraphy over the Precambrian shield. The study area, in NE Manitoba, has access to numerous sections that expose multiple tills, in addition to interglacial and postglacial sediments. Sequences of thick till are not easily separated into different units, despite previous field attempts to define four named tills. The compositional transition to thin till overlying the Precambrian Shield in the west is also not well understood. Yet, the two different settings were affected by the same 3+ glacial cycles.

The wide range in eastern- and/or northeastern-sourced calcareous clast concentrations, and 'locally'-sourced shield clast concentrations, combined with variable concentrations of northern-sourced clasts, suggests that the tills of northeastern Manitoba are 'provenance' hybrids. Local tills result from the net effect of multiple glacial processes that underwent spatiotemporal variability. Mixed provenance applies not only to surface tills, but to the subsurface tills as well. Preliminary results suggest that carbonate transport across the shield was continuous throughout several glacial cycles, but the bulk of transport likely occurred prior to the most recent glacial cycle.

Current work has established a northern-Manitoba ice-flow history using the erosional and depositional record, which encompasses 5 to 7 phases. This new compilation is used in conjunction with 'till-clast' stratigraphy and 'till-geochemistry' stratigraphy, to identify a new provenance framework for tills in northeastern Manitoba.

Reconstructing the depositional environment of the Late Ordovician Rouge River Member, lower Blue Mountain Formation, southern Ontario

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There has been renewed interest in the Rouge River Member, an Ordovician black shale unit found across southern Ontario, because of its shale gas potential. However, its depositional environment is not well understood. Redox-sensitive element concentrations, total organic carbon contents, and total sulfur contents were measured on 143 samples from four drill cores to examine temporal and spatial variations in paleoredox and paleoproductivity. The deepest and thickest intervals of Rouge River Member were found in drill cores from southwestern Ontario, near Chatham (872–901 m) and Port Stanley (822–858 m), whereas shallower and thinner intervals were found in cores farther northeast near Mount Forest (464–477 m) and Pickering (26–46 m).

Higher average TOC contents were found in the southwestern cores of Port Stanley (3.2 wt%) and Chatham (2.1 wt%) compared with Mount Forest (1.6 wt%) and Pickering (1.8 wt%). However, average sulfur contents of the four drill cores were relatively similar and do not define a spatial trend (Port Stanley = 1.6 wt%; Chatham = 1.1 wt%; Mount Forest = 1.4 wt%; Pickering = 1.8 wt%). The Fe-TOC-S systematics suggest that sulfur was limiting with respect to pyrite formation. The average Y/Ho from all four cores is 28 (similar to chondrites and igneous rocks), suggesting minimal influence by hydrothermal fluids.

The primary geochemical tool used for reconstructing paleoredox conditions are Mo and U enrichments, expressed as aluminum-normalized enrichment factors compared with Post-Archean Australian Shale (PAAS) values. Across all four cores, the enrichment factors are low, averaging 3.9 for Mo and 6.0 for U, suggesting that bottom waters were predominantly suboxic. The Mo/U ratios in Port Stanley and Pickering show minor redox variation from suboxic (Mo/USW = 0.1–0.3, where Mo/USW is the modern seawater ratio) to rare intermittent anoxic bottom waters (Mo/USW up to 1). By comparison, the Chatham and Mount Forest cores show a consistent Mo/U signature of suboxic waters with little redox variation (Mo/USW = 0.1–0.2). These observations are corroborated by a predominance of Fe/Al ratios of ~0.5 (similar to the average upper crust), with rare intermittent anoxia suggested by a few higher Fe/Al ratios (0.7–1.5). Other redox sensitive metals, such as Cu, Ni, V, and Zn, showed little enrichment across the four cores (enrichment factors predominantly less than 2), further indicating suboxic conditions. The data are more consistent with a relatively open-marine, suboxic basin than a restricted, euxinic basin.

Sulfur isotope fractionation in the Eastern Equatorial Pacific derived from reaction-transport models

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Sulfur and carbon cycles determine the redox states of oceans and oxygen content of the atmosphere through time. Earth system models quantify these cycles to compute changes in seawater and atmospheric compositions on Earth. One of the key input parameters in many Earth system models is the fractionation factor (α) of sulfur isotopes between dissolved sulfate and sulfide during microbial sulfate reduction (MSR). MSR is a major redox reaction that remineralize carbon in the subseafloor.

Recent theoretical models suggest that we should usually observe a large α in marine sediments due to the low cell-specific rate of MSR in most areas of the oceans. Previous studies applying reaction transport models (RTMs) on marginal sediments support this claim and find α close to the equilibrium. Here we apply a RTM on the abyssal plain of the Eastern Equatorial Pacific (Ocean Drilling Program Site 1226, same location as Site 846) to investigate α in sediments of the equatorial open-ocean. We find rates of MSR varying from 346 fmol/cm^3/day at 3 meters below seafloor to 0.4 fmol/cm^3/day in deeper sediments. Using existing cell counts, this implies cell-specific rates of MSR between 10^{-3} and 10^{-6} fmol/cell/day, orders of magnitudes lower than those observed in shallower marine settings (10^{-1} to 10^{-4} fmol/cell/day). We find that the difference of sulfur isotope compositions ($\delta^{34}S$) between porewater sulfate and sulfide is best explained with a constant fractionation of 48‰, considerably lower than the prediction of 70‰ from theoretical models of MSR.

We hypothesize that locations with high sedimentary iron and manganese contents support higher rates of in-situ sulfide reoxidation and disproportionation, masking the original effect from MSR and producing a small apparent α.

Lithostratigraphy, chemostratigraphy, and detrital zircon geochronology of the Mesoproterozoic Hunting Formation, Somerset Island (NU)

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The Hunting Formation, exposed on Somerset Island (NU), was deposited in the Aston-Hunting basin, one of the Mesoproterozoic Bylot basins of the Arctic islands (Nunavut and western Greenland). This formation was equated with carbonate strata in the nearby Borden basin (Bylot Supergroup; Baffin Island) based on composition and lithofacies. The ~900-m-thick formation consists of four members, each logged in multiple overlapping segments owing to pervasive normal faults that offset the stratigraphy. Member 1 consists of pale grey dolomudstone interlayered with granular clastic lags derived from the underlying, unrelated Aston Formation sandstone. Member 2 consists of weakly cyclic, pale grey dolomudstone with abundant, laterally extensive layers of black, partly silicified aragonite sea-floor fans, a lithofacies that resembles that of the platform interior of the Angmaat Formation on northern Baffin Island. Member 3 overlies Member 2 abruptly, and has a lower part consisting of intraclastic tempestities, and an upper part consisting of sub-metre-scale, pink-weathering tepee cycles, in which it crudely resembles platform-margin lithofacies of the Angmaat Formation (Borden basin). Member 4 overlies member 3 gradationally, and consists of buff tepee cycles with upward-increasing terrigenous sand; this member is cross-cut by unusual voids lined with multi-generational cements. The carbon isotope stratigraphy of the Hunting Formation exhibits a wider range of values (+1‰ to >+4‰) and more distinctive vertical patterns than the putatively equivalent Bylot Supergroup carbonate strata, and does not compare favourably with either the whole nor any individual formation in that succession. The idiosyncratic carbon isotopic profiles of the two sub-basins may reflect either different depositional ages or different degrees and/or timing of isotopic evolution in partial isolation from global seawater. Detrital zircon analysis shows that quartzose dolostone in member 4 contains Grenville-aged zircon, but such young zircon are not present in carbonate strata of the Bylot Supergroup, first appearing only in terrigenous units higher in the succession. This difference could reflect either a later depositional age for the Hunting Formation than its reputed correlative, the Angmaat Formation, or an earlier influx of Grenville-derived detritus into the Aston-Hunting basin than in the Borden basin. Collectively, these lines of evidence suggest a complex regional basin history in which the Bylot basins developed roughly contemporaneously in general, but experienced different subsidence and sedimentation histories in detail. Carbonate-dominated formations that contain similar lithofacies in these basins may have been deposited at different times in each basin, and/or may have evolved in geochemical isolation.

Litho- and chemostratigraphic transect of the Cambro-Ordovician Franklin Mountain Formation across the interior plains, NWT

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The Cambro-Ordovician Franklin Mountain Formation, widespread in northwestern Canada, is an enigmatic dolostone succession locally >500 m thick that has remained unstudied owing to poor preservation, dearth of biota, and seeming lack of economic potential. At a reference section (Dodo Canyon; Mackenzie Mountains; 450 m thick) in the formation's western exposure area, the section consists of intraclastic tempestites and microbialites (100 m), metre-scale dolosiltite-oolite cycles (100 m), an interval of burrowed dolomudstone (50 m), and an upper interval (~200 m) of metre-scale oolite cycles with green clay seams and sparse white chert layers. A C-isotope curve at metre-scale resolution indicates deposition from the late Drumian or early Guzhangian (mid-Cambrian) until possibly as late as the Darriwilian (middle Ordovician). The SPICE anomaly (+4‰VPDB) spans >60 m in the reference section (burrowed interval), but the upper part of the formation is difficult to correlate to the global curve. Across ~350 km of sparse exposure in the interior plains between the Norman Range and Horton River, the Franklin Mountain Formation's exposures, limited to the uppermost part of the formation, are characterised by coarsely crystalline dolostone with abundant white chert; although silicified stromatolites are conspicuous, cross-bedding, oolite, and intraclasts are locally evident. Carbon isotope signatures are irregular (between -3.5 and -1.0‰), but stabilise around -1.5‰ at the top of the three exposures examined, resembling the uppermost part of the formation at the reference section. Near the Arctic coast (Hornaday River canyon), the lower part of the formation (~75 m) consists of metre-scale alternations of argillaceous green-brown dolostone and gradationally overlying buff dolostone with symmetrical and asymmetrical ripple cross-lamination and desiccation cracks. The upper part of the formation consists of coarsely crystalline dolostone with white stromatolitic chert. Carbon isotope values from the lower part of the formation at Hornaday River mirror those of the reference section, with a muted expression of the SPICE (maximum +2‰) spanning 20 m in the lower one-third of the formation; values in the upper part of the formation resemble those of the interior plains sections (-3 to -0.5‰). Intra-basin correlation using carbon isotope stratigraphy seems to be valid for much of the Franklin Mountain Formation spanning a ~500 km transect across the epicratonic basin, but correlation to established curves elsewhere is challenging. Accumulation rate in the interior of the epicratonic basin was approximately 1/3 of that at the reference section, close to the ancestral continental margin.

Neoproterozoic lithofacies control ore distribution at the Kipushi Cu-Zn deposit (Democratic Republic of Congo) and Gayna River Zn camp (NWT)

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Ore-bodies of the Kipushi Cu-Zn deposit, Central African Copperbelt (Democratic Republic of Congo; past production 60 Mt at 11% Zn, 7% Cu; Big Zinc (undeveloped) 10.18 Mt at 34.89% Zn) are hosted primarily by dolostone of the mid-Neoproterozoic Kakontwe Formation. The >600-metre-thick dolostone overlies Sturtian (ca. 715 Ma) diamictite, and accumulated in the Katangan basin as supercontinent Rodinia began to disperse. Historically, ore distribution was attributed to the so-called "Kipushi fault", an irregular, decametre-wide zone that truncates the carbonate strata roughly perpendicular to bedding over ~500 m of stratigraphic thickness. This zone juxtaposes the truncated carbonate pile against a purportedly allochthonous block of siltstone-sandstone (the 'Grand Lambeau') on the margin of a halokinetic diapir, along a contact characterised by the enigmatic 'cyclopean breccia'. Examination of new and archival drill-core suggests a primarily depositional origin for the 'Kipushi fault'. The lower Kakontwe Formation (~250 m thick) consists of calcimicrobial reef facies of a type known only from the Gayna River Zn camp, NWT, Canada. At Gayna River, giant microbial reefs developed near-vertical, constructional reef escarpments with hectometric relief above the basin floor, before being buried by unrelated strata. Zinc mineralisation at Gayna River is near or at the steep depositional contact between reef and off-reef facies. At Kipushi, the lateral transition from Kakontwe Formation dolostone to siltstone-sandstone of the 'Grand Lambeau' is re-interpreted as a similar depositional contact rather than a fault, a conclusion supported by the two bodies' similarly oriented bedding and by re-examination of the intervening 'cyclopean breccia', which consists of in situ layers of veined siltstone-shale draping onto the steep carbonate contact. The middle (cortoid grainstone) and upper (interbedded, carbonaceous cortoid grainstone, carbonate mudstone, and carbonaceous shale) Kakontwe Formation accumulated only on the defunct reef top. The Cu-dominated 'Kipushi fault' and 'Big Zinc' ore bodies are spatially related to the depositional escarpment, where migrating ore-fluids exploited permeability produced by the competency contrast during later stress. The 'Nord-Riche' Cu zone occurs where the upper surface of the carbonate edifice abruptly ends at the reef wall, is unconformably overlain by interbedded siltstone-dolostone of the 'Série Récurrente', and is laterally adjacent to siltstone-sandstone of the 'Grand Lambeau'. These superjacent and adjacent strata formed aquicludes that guided and focussed metalliferous fluid. Kipushi's complex sulphide distribution is, therefore, underpinned by the disposition of Neoproterozoic carbonate lithofacies, which influenced the movement of mineralising fluid.

Mineralogy and geochemistry of fracture coatings in Athabasca Group sandstone as records of primary and secondary elemental dispersion

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The McArthur River unconformity-related uranium deposit is located in the Athabasca Basin in Saskatchewan, Canada. The core samples were collected to reflect a spectrum of fracture coating types from near-ore to unmineralized areas, to compare McArthur River fracture mineral chemistry to the Athabasca Group background signature. Because the fracture coatings result from precipitation from various fluids associated with primary and secondary dispersion, as well as from diagenetic background fluids of the Athabasca Group, the main objective of the study is to determine if and how the fractures and their immediate wall rocks record the migration to surface of U mineralization components from depth. Seven types of fracture fillings were identified, representing various colors, mineralogies, and chemistry, as revealed by optical petrography, scanning electron microscopy, X-ray diffraction, shortwave infrared reflectance spectroscopy, and geochemical analysis. Sample digestion using weak acid leach (2% HNO_3) was performed to leach mobile elements, followed by high resolution inductively-coupled plasma mass spectrometry to obtain bulk fracture geochemistry. Continuous leach inductively-coupled plasma mass spectrometry (CL-ICP-MS) was used to determine the relationship between trace elements, including Pb isotopes, and their release from specific mineral phases in real-time through leaching by progressively reactive solutions from water to 30% nitric. The $^{207}Pb/^{206}Pb$ ratios of fracture coatings and of wall rock reflect the effect of secondary dispersion fluids imprinted on near-fractures (low $^{207}Pb/^{206}Pb$ values), followed by a less radiogenic fluid related to the fracture coatings (higher $^{207}Pb/^{206}Pb$ values). Hyperspectral imaging of fractures shows the presence various layers of alteration minerals that reflect precipitation from multiple fluid events. The characteristics of the primary fracture fluid are recorded in the near-fracture, shown by gradational mineral zoning from adjacent to the fracture surface to background away from the fracture surface. CL-ICP-MS data suggest an organic control on common Pb and secondary dispersion of U since these and associated major elements appear to be adsorbed onto organic material, shown by the elemental releases during the 10% hydrogen peroxide leach phase. CL-ICP-MS also suggests a kaolinite and Fe oxide control on radiogenic Pb and primary or secondary dispersion of both Pb and U, as Fe and Al are released during the 30% nitric leach phase. Fractures can be used to detect primary and secondary dispersion from U mineralization at depth through geochemical and mineralogical analyses. This research indicates that the footprint of the deposit extends upwards through some fracture networks.

NSERC CMIC Footprints Exploration Project Contribution #143

Keynote (40 min): From fault dates to orogenic rates

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Absolute dating of crustal deformation is revolutionizing our understanding of regional geology and orogeny. The distribution of shallow-fault dates in fold-thrust belts is becoming sufficiently dense to examine rates of deformation, which is a grand challenge of crustal evolution. Newly-formed, illitic clays are common of foreland fold-thrust belts, and the regional timing of mineralization offers first-order constraints on the timing and progression of deformation. We briefly discuss our robust method of clay dating using illite characterization, encapsulated Ar analysis and grain-size based ages, followed by a discussion of results in three fold-thrust belt settings: the US Appalachians, the Canadian Rockies and the Spanish Pyrenees. Fault ages in the southern Appalachians show that a large foreland wedge was active over a relatively narrow window of time of ~3 m.y. (277-280Ma). Regional fault dating in the Canadian Rockies shows that multiple pulses of orogenic wedge formation occurred, each similarly lasting 3-5 m.y., separated by longer periods of tectonic quiescence; this process may be called "stick-slip orogeny". Given 50-60% shortening, orogenic (longitudinal) strain rates in these (major basin) contractional settings are >1E-15/sec. In contrast, fault ages in the eastern Pyrenees foreland wedge show modest (~40%) shortening over a longer time window of ~18 my (32-50Ma), resulting in a strain rate that is at least an order of magnitude less for this (narrow basin) contractional setting. The contrasting rate styles of these orogenic belts gives lower bounds and may reflect the nature of tectonic convergence. Also, orogenic pulses of a few m.y. accumulate finite displacements of km to tens of km in accordance with modern seismic recurrence (m/k.y.).

Effects of orthogonal compression and dextral transpression on metamorphic evolution of the Paleoproterozoic New Quebec orogen

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The New Québec orogen (NQO) is a Paleoproterozoic belt in the southeastern Churchill Province of the Canadian Shield made up of autochthonous rocks deposited adjacent to the Archean Superior craton, tectonically overlain by allochthonous metavolcanic and metasedimentary assemblages accreted to the cratonic margin. The NQO is bound by two Archean blocks, to the west by the Superior craton, and to the east by the Core Zone, the western edge of which is marked by a crustal scale transpressional shear zone, the Lac Tudor fault. Between the eastern margin of the NQO and the rocks that are unequivocally part of the Core Zone there is a zone of reactivated Archean crust, likely with affinity to the Superior craton. Current models infer early terrane accretion to the Superior margin at ca. 1.82 Ga, followed by terminal collision with the previously amalgamated Core Zone – North Atlantic Craton block, in a bulk dextral transpressional regime at ca. 1.80 Ga. The orogen widens towards the south and preserves several distinct metamorphic domains that increase in grade towards the eastern margin of the orogen, and towards the north. The transition from greenschist to lower amphibolite facies occurs within the supracrustal rocks of the foreland of the orogen in the Kaniapiskau Supergroup and Rachel-Laporte zone with grade increasing towards the east with peak metamorphic conditions of 300-450°C and pressures no higher than 0.4 GPa. The deepest exhumation is recorded in the northern hinterland part of the orogen, and in the reworked Archean rocks along the Lac Tudor fault where they are juxtaposed with the Core Zone. The northern rocks in the Leaf Bay terrane record metamorphic conditions of 600-725°C and 0.6-1.1 GPa in the charnockitic gneiss of the Leaf Bay terrane. In the reactivated Superior margin adjacent to the Lac Tudor fault zone, metapelites with a sillimanite-garnet-melt assemblage experienced temperatures 700-800°C and pressures between 0.6-1.2 GPa with evidence of sillimanite replacing kyanite in pseudomorphs. The metamorphic conditions experienced by different domains within the orogen are closely linked to the styles of deformation. The deformation associated with lower grade metamorphic assemblages of the foreland is primarily thrust stacking reflecting a dominantly compressional deformation regime, later overprinted by a strong transpressional component resulting in low pressure metamorphism. The high grade assemblages of the Leaf Bay terrane and the reworked Archean margin represent areas that were overthrust by the Core Zone and tectonically buried to mid-crustal depths.

Keynote (40 min): Tectonic evolution of the Newfoundland Appalachians

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The Canadian Appalachians preserve a record of more than 80 my of terrane accretion. With exception of Meguma, which is only exposed in Nova Scotia, evidence for most accretionary events is well preserved in Newfoundland. This talk gives a brief overview of the accreted terranes preserved in Newfoundland as an introduction to the post-meeting fieldtrip. Accreted terranes include microcontinents: Dashwoods, Ganderia and Avalonia, as well as juvenile oceanic or extended continental, suprasubduction zone terranes: Lushs Bight oceanic tract, Baie Verte oceanic tract, Annieopsquotch accretionary tract, Victoria arc, Exploits and Penobscot backarcs. These terranes were sequentially accreted to a progressively outboard growing, composite Laurentian margin during short-lived orogenic events ranging from the Late Cambrian-Late Ordovician (Taconic 1, 2, 3 and Penobscot), Late Ordovician-Silurian (Salinic) and Late Silurian-Devonian (Acadian).

Collisions were generally soft and short-lived (≤ 10 my) characterised by localized deformation and low-grade metamorphism. Only the Taconic and Acadian were locally long-lived and hard collisions with extensive deformation and metamorphism of upper plate rocks; the Acadian orogeny affected all terranes preserved in the Newfoundland Appalachians and remained active for more than 20 my. Evidence for the various accretions is well preserved in the sedimentary record. Particularly foredeep-forearc basin pairs and the change of flysch to molasse (Old Red Sandstone) impose tight constraints on the duration and nature of the tectonic events. All collisions were oblique, which commonly led to extensive modification of suture zones by strike-slip related tectonism. Piercing points are rare or absent, but there is circumstantial evidence that some terranes, such as Dashwoods and Avalonia, may have moved laterally over considerable distances.

Geometallurgical analysis of the Decar nickel deposit, British Columbia: Implications for tailings management and CO_2 sequestration

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The Decar is First Point Minerals' flagship nickel property where the naturally occurring nickel-iron alloy awaruite (Ni3Fe, highly ferromagnetic and quite dense) is the mineral of economic importance. The deposit is part of the large Mount Sidney Williams ultramafic/ophiolite complex located 90 km northwest of Fort St. James in central British Columbia. The ultramafic tailings from a mine could present an opportunity for the sequestration of CO_2 via carbon mineralization and lead to cementation of the tailings, with economic benefits to the mine. This process involves the dissolution of Mg-silicate and -hydroxide minerals (e.g. serpentine and brucite) and carbonation using CO_2 sourced from either the atmosphere or flue gases to form carbonate minerals, thereby storing the greenhouse gas in a thermodynamically stable solid form. Although serpentine group minerals are the most abundant in the deposit, typically >85 wt.%, forsterite, diopside, magnetite and brucite are present as minor phases. The pH-dependent dissolution rate of brucite is orders of magnetite faster than serpentine or forsterite, which is highly advantageous from a carbon sequestration perspective as the mineral is more reactive with CO_2. An inexpensive and rapid assay method for determining brucite abundance does not currently exist. However, a reliable method for the prediction of brucite abundances throughout the nickel deposit using geometallurgical techniques would allow for targeting of brucite-rich zones for use in sequestering CO_2. Brucite is present in the deposit in the range of <1 wt.% to approximately 12 wt.% based on quantitative X-ray diffraction (XRD) analyses of select samples. Brucite predictions were made through the projection method, where whole-rock elemental composition data are converted into estimated mineral abundances based on mass balance and the minerals identified by XRD. Whole-rock elemental composition data of ~10,000 exploration pulps collected as part of their exploration programme were provided by First Point Minerals. The predictive model was refined through a sum of squares (SSQ) approach by comparison with quantitative mineralogical results of a subset of samples obtained using XRD methods that are too time-intensive and expensive for routine application. The minimum brucite-specific error (SSQ) coincided with the minimum total SSQ (i.e., the sum of the SSQ for all the model minerals), and the model made relatively accurate brucite abundance predictions when the measured brucite abundance, as determined by XRD, was greater than ~1 wt.%.

Such geometallurgical analyses will enable First Point to target brucite-rich zones for CO_2 sequestration, which may also offer the potential for cementing the tailings through carbonation thereby providing greater stability to the tailings and reducing the costs and risks associated with tailings management.

Structural analysis and shear zone thermometry in the southeastern Churchill Province

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The southeastern Churchill Province (SECP) is located on the eastern flank of the Superior Craton and bound to the east by the North Atlantic Craton. The SECP is divided into three lithotectonic domains, which are from east to west the New Quebec Orogen (NQO), the Core Zone and the Torngat Orogen. This branch of the Trans Hudson Orogen is particularly interesting as it contains a significant amount of juvenile material, with remobilised Archean material and Paleoproterozoic supracrustal belts. The tectonic evolution of the SECP has been interpreted both as a transpressional regime or a thick-skinned thrust belt associated with convergence between the Superior and North Atlantic cratons. However, not much is known about the chronology of the metamorphic and tectonic events or the thermal state of the crust during the inferred transpressional deformation. In particular, the Core Zone has recorded a multistage tectonometamorphic evolution, exhibiting large areas with metamorphism that predates crustal shear zones characterized by sub-horizontal lineations. This project focuses on the southern SECP along a section crossing, from west to east, the metamorphosed part of the NQO, the Lake Tudor Shear Zone (LTSZ), the 1.860 – 1.805 Ga De Pas Batholith and the George River Shear Zone (GRSZ). The interpretations rest on field-based observations coupled with interpretation of geophysical data that allow the identification of distinct structural domains. The LTSZ and the GRSZ present fabrics suggesting they were mainly active during the exhumation of the core zone without any significant vertical displacement. We emphasize two aspects: i) the recognition of a satellite branch linked to the GRSZ showing steeply north plunging lineations that could represent burial or exhumation fabrics, and ii) poly-phase folding in the NQO directly west of the LTSZ. Samples of mylonite and gneiss of igneous or sedimentary protolith have also been collected across both shear zones and their margins. These samples will be used to describe the kinematics, the deformation process and to estimate the temperature of deformation. Two analytical methods will be employed to accomplish this objective: the TitaniQ thermometer and the opening angle of quartz c-axis. To improve the timing constraints on the deformation in the GRSZ, U/Pb dating on zircon will be performed on a syn-kinematic dyke. The new data generated will allow integration of the different structural domains with their evolving thermal architecture thus establishing the relationship between deformation and metamorphism, as well as confirming the transpressional nature of the SECP.

Searching for a deep biosphere, hydrocarbon fingerprint in hydrothermal vent sediments at Guaymas Basin

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The Guaymas Basin, Gulf of California, is formed from a mid-oceanic spreading ridge that hosts various, hydrothermal vent complexes. The vents expel fluids reaching 350°C. Under these conditions, sedimentary organic matter is almost instantly pyrolyzed producing petroleum hydrocarbons. The Cathedral Hill vent site is a cluster of white smokers encrusted with Riftia pachyptila tubeworms surrounded by a Beggiatoa sulfur oxidizing microbial mat. This site receives high inputs of organic matter from elevated surface water productivity and runoff from the surrounding continent. High sedimentation produces near-uniform compositions of sedimentary organic matter that is mixed with the benthic and subsurface micro- and macro-fauna. The sediments are also home to a subsurface microbial biosphere of bacteria and archaea. Four push cores were collected along a transect line running from the center sulfide chimney complex to the outside of the microbial mat using HOV Alvin. Thermal-probe measurements indicate that by 7-9 cm pore-fluids rose to 200°C, indicating the active microbiome resides in the upper 6 cm (from 18-105°C) of sediment. Polar and maltene abundances peak at 5-14 cm depth suggesting this range marks the zone of catagenesis. The core exterior of the mat displayed a broader polar lipid profile consistent with a lower thermal gradient. The maltene and polar fractions were analyzed by comprehensive two-dimensional gas chromatography (GC×GC) and Fourier transform ion cyclotron resonance mass spectrometry (FT-ICR-MS) in electrospray ionization mode, respectively. The maltene fractions contain up to 6200 compounds with abundant bacterial, archaeal, and eukaryote biomarkers. The polar fractions contain an abundant array of acid and neutral compounds. Semiquantitative analysis of Z class (Znumber=CnH2n+z+Hn) and molecular weight distributions display systematic depth and distance changes, with acid and diacid functional groups being most resilient in these hydrothermal settings. These functionalized and hydrocarbon fingerprints are being compared with data on the microbial community composition collected from the same transect site. We hypothesize the conditions in these systems will improve our understanding of how mixed-source inputs of organic matter are naturally transformed into petroleum and help determine to what extent the molecular constituents added by subsurface microfaunal remains can be detected.

Tracking the solidus of cumulates in layered intrusions related to LIPs using trace elements in zircon and rutile from the Bushveld Complex

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The near-solidus crystallization history of the Paleoproterozoic Bushveld Complex, the world's largest layered intrusion and the high-level plutonic component of a preserved large igneous province (LIP), has been investigated using the trace element geochemistry (LA-ICP-MS) of accessory minerals that form from late, highly fractionated pockets of interstitial melt in layered cumulates and from granitic magmas in felsic roof rocks. In mafic-ultramafic rocks, zircon occurs within interstitial patches that contain quartz-biotite-plagioclase and local granophyric intergrowths. Individual subequant zircons display simple to complex sector zoning. Chondrite-normalized rare earth element (REE) patterns are typical of igneous zircon and Ti is negatively correlated with Hf in all samples. Ti-in-zircon thermometry of the cumulates (T=950-730°C) records the onset of zircon saturation down to the solidus, with notably cooler temperatures determined for Upper Zone and roof rock zircon (T=875-690°C). Forward modelling of proposed Bushveld parental magmas using rhyolite-MELTS consistently yields similar zircon saturation temperatures (800-740°C) from highly fractionated melts (~5-20% remaining melt) with late-stage, near-solidus mineral assemblages that are identical to those observed in the rocks. Trace element systematics (Ti, REE, Th/U) of zircon from the uppermost Upper Zone and felsic roof rocks, including the Lebowa (Nebo) granite and Rashoop (Stavoren) granophyre, are similar and distinct from zircon at lower stratigraphic levels. This supports proposals that these Bushveld LIP granites and granophyres formed from expelled residual magmas produced during crystallization of the uppermost portions of the layered cumulates. Rutile occurs throughout the Critical Zone as interstitial grains with quartz and zircon and with chromite, each textural setting displaying distinctive chemistry. Euhedral rutile needles found in crystallized interstitial melt pockets have relatively high HFSE concentrations (Nb=1000-20,000 ppm; Ta=100-1760 ppm), high Zr-in-rutile temperatures (1000-800°C), and are magmatic in origin. In contrast, irregular rutile grains that are found as rims and cores in chromite are strongly depleted in HFSE (Nb<1000 ppm; Ta<100 ppm), Cr, and Sc and they represent sub-solidus exsolution products of Ti from chromite. Exploring near-solidus evolution of mafic layered intrusions like the Bushveld Complex using trace element chemistry of accessory minerals provides a novel approach to constraining the late stages of crystallization of highly fractionated interstitial melt in these petrologically important intrusions, many of which are directly linked to voluminous and extensive flood basalts in LIPs.

Late Cretaceous to Paleocene tectono-metamorphic evolution of southwest Yukon

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The tectono-metamorphic evolution of southwestern Yukon records a complicated history related to the Mesozoic-Paleocene reorganization of the western edge of the northern Cordillera. This study focuses on the Blanchard River assemblage in southwest Yukon, which belongs to a series of Jura-Cretaceous basinal and arc assemblages deposited between the Intermontane terranes (Yukon-Tanana terrane) and the Insular terranes (Wrangellia and Alexander terranes). Along strike these assemblages also include the Late Triassic to Middle Jurassic Bear Creek assemblage, the Jurassic to Cretaceous Dezadeash Formation, and the Cretaceous Kluane schist. Detrital zircon analyses from the Blanchard River assemblage suggests that it was sourced from exhumed Yukon-Tanana terrane and plutons found therein, with a maximum depositional age of Early Cretaceous (130-125 Ma).

Detailed mapping has demonstrated that the Blanchard River assemblage structurally underlies Proterozoic to Devonian meta-siliciclastic rocks of the Yukon-Tanana terrane, a contact that is obscured by the intrusion of the Paleocene Ruby Range batholith. Near this contact, rocks in both packages preserve amphibolite facies metamorphic assemblages that include kyanite, garnet and staurolite. Contractional structures attributed to the structural stacking of the Yukon Tanana terrane over the Blanchard River assemblage provide a mechanism for Late Cretaceous burial of the Blanchard River assemblage that resulted in amphibolite facies metamorphism. This is interpreted to be associated with the closure of the Jura-Cretaceous basins located between the Intermontane and Insular terranes in this region. Within the southern Blanchard River assemblage there is also evidence for decompression and cooling followed by later heating that is reflected in metamorphic minerals that overprint the earlier high-grade metamorphic event.

In-situ U-Th-Pb monazite ages acquired in this study range from 83-61 Ma and provide constraints on the timing of metamorphism and deformation. Older and younger ages can be correlated with low and high yttrium zoning, respectively. Typically, low yttrium domains are ca.78 Ma and can be correlated to the prograde growth of garnet and attainment of peak metamorphic conditions (635-650 °C, 6.3-6.7 kbar). High yttrium zones are ca. 69 Ma and are interpreted to reflect the consumption of garnet during decompression (~3-4 kbar). This exhumation pre-dates the intrusion of the Ruby Range batholith which is responsible for a low pressure sillimanite overprint indicating an increase in temperature at relatively shallow crustal levels (<3 kbar).

From a tide- to storm-dominated depositional system in a mixed carbonate-siliciclastic succession: The Upper Ordovician Vauréal Formation, eastern Anticosti Island, Québec

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The early Paleozoic ice age was a long, protracted event some tens of millions of years in duration and centered around the end Ordovician, with several internal waxing and waning of glacial ice masses. The upper 900 m of the >2 km thick Sandbian to Telychian Anticosti succession constitutes a comprehensive, late Ordovician to early Silurian record where we can test the presence of a composite eustatic signal in a far-field paleotropical setting. Mid to outer ramp carbonates facies prevail in the western part of Anticosti Island and grade eastward towards the basin margin into more siliciclastic-rich shallower ramp facies that include several discontinuities. In this study, we examined a 30-m thick coastal section superbly exposed at Mill Bay at the eastern end of the late Katian Vauréal outcrop belt on the island. The studied section shows sediments deposited in tidal to storm-dominated shelf environments; more specifically a lower tide-dominated carbonate-siliciclastic facies assemblage and an upper storm-dominated siliciclastic facies assemblage. Small metre-scale transgressive-regressive cycles are present in both facies assemblages. In the tide-dominated facies assemblage, the stacked metre-scale cycles display a lower transgressive cross-bedded (sigmoidal, herringbone) and channelized skeletal grainstone fining upward into siliciclastic mudstone and an upper regressive coarsening upward tidally bedded fine sandstone. In the storm-dominated facies assemblage, the stacked metre-scale cycles have little or no transgressive deposit and are largely composed of shallowing-upward, coarsening upward sandstone tempestites. The sequence analysis (facies and stacking cycle pattern) indicates that three to five metre-scale cycles form thicker transgressive and regressive cycles. The latter cycles also bundle together defining a longer term transgressive-regressive succession in which the tide- and shelf-dominated facies assemblages occupy the lower transgressive and upper regressive segments respectively. Abundant ice conditions on the globe during the end Ordovician, and the resulting multi-order glacio-eustatic signal, appear to have left distinctive stratigraphical imprints on the Anticosti paleotropical mixed carbonate-siliciclastic ramps. The final stratigraphic and depositional motif, however, was also influenced by the sediment dynamic present along the Anticosti coast.

Characterization of the mode of occurrence and compositions of strategic elements in the Vazante willemite ore and hematite-rich breccia, Minas Gerais, Brazil

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Concerns over supply-security for high-tech strategic elements, indium, gallium, germanium and cadmium, have resulted in their international designation as critical raw materials. These semi-conductive metals are all by-products of zinc and lead-zinc-copper sulphide ores, with additional resources of gallium sourced from bauxite ores, and indium from cassiterite ores. Although, significant research has been conducted to understand the residence of these metals in these deposit types, little is known about their occurrence in nonsulphide zinc ores, such as the willemite-dominated Vazante and North Extension silicate zinc deposits in Minas Gerais, Brazil. In this study petrographic, SEM and LA ICP-MS analyses were conducted on willemite ore breccia and hematite breccia to investigate the occurrence and residence of In, Ga, Ge and Cd from the Vazante deposits. The results indicate that there are distinct affinities between these elements and the major hydrothermal minerals associated with the Vazante willemite ore and hematite-rich breccia. In the willemite ore breccia, indium is most prominent (average 37.9 ppm) in an intermediate void-fill dolomite phase, although elevated concentrations were measured in both willemite (average 2.8 ppm) and other carbonate phases (average 13.8 ppm). Conversely, germanium, and similarly gallium and cadmium, are the most enriched in willemite, and especially in second generation fibrous willemite (respective averages of 4.7 ppm, 47.5 ppm and 313.6 ppm). Enrichment in germanium (12.0 ppm average), gallium (3.2 ppm average), cadmium (870.6 ppm average), and to lesser extent indium, documented in the late carbonate is closely tied to the presence of micro-inclusions of hematite, sphalerite, galena and franklinite. Results for the hematite breccia revealed elevated gallium (7.6 ppm average) and germanium (5.6 ppm), whereas cadmium and indium were below the detection limit, suggesting that although the greatest enrichment of the strategic elements reside in the later willemite ore breccia, appreciable concentrations reside within the earlier hematite breccia. Further studies are required to evaluate the potential to recover these elements as by-products of willemite ore.

Tectonic versus sedimentary mélanges, mélanges within mélanges, and megathrust slip accommodation in subduction complexes

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The transfer of materials from a subducting oceanic plate to a subduction-accretionary complex takes place as subduction megathrust slip slices into the downgoing plate. Mélange zones have been proposed as broad zones of megathrust slip accommodation (subduction channels) preserved in subduction complexes. Many such mélanges have blocks of higher metamorphic grade than the matrix proposed to have been incorporated and exhumed by return flow in the subduction channel. Field studies in the Franciscan Complex of California, however, suggest that the mixing of such blocks into the matrix of mélanges took place by sedimentary sliding prior to deformation during subduction and exhumation. In contrast, block-in-matrix units formed by progressive tectonism (tectonic mélanges), apparently accommodating megathrust slip, have uniform metamorphic grade. These units span a lithologic range from "broken formation" of sandstone blocks in shale matrix to siliciclastic (shale to conglomerate) matrix with pelagic and volcanic blocks, to serpentinite with mafic and pelagic blocks. These tectonic mélanges grade into "coherent" imbricated units comprising the same lithologies. These units represent accreted ocean plate stratigraphy with a range of ocean crust types and a variable clastic (trench fill) fraction. The sedimentary serpentinite and siliciclastic matrix mélanges are part of the clastic fraction of accreted units, interfingering with and interbedded with coherent turbidites. Accordingly, larger-scale tectonic imbricates may have a sedimentary mélange horizons within them, and larger-scale tectonic mélanges may deform sedimentary mélanges. The structurally highest horizon in the Franciscan appears to range from imbricated sheets of metabasite, metachert, and ultramafic schist to ultramafic schist with blocks of metabasite and metachert. Similar features may be seen on a smaller scale within blocks in sedimentary mélanges. During accretion, megathrust slip is primarily distributed on discrete fault zones imbricating the accreted units. Whereas the accreted units range in structural thickness about 3 km, fault zones are generally tens of m or less in thickness. During non-accretion or subduction erosion (when megathrust slip slices into the hanging wall of the subduction system), megathrust slip was apparently accommodated in narrow zones of tens of m thickness with abundant fault rocks and local tectonic mélange. Some of these zones may record a metamorphic gradient across them, but most do not and they do not include blocks of higher-grade than surrounding rock. Non-accretionary megathrust zones separate units accreted at different time.

Diachronous Palaeozoic accretion of peri-Gondwanan terranes in the Caledonides and northern Appalachians

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Reconstructions of the Caledonides and northern Appalachians go back 50 years to the original "Wilson Cycle". Subsequently published reconstructions differ in the positioning of the North American and European components and in the correlation of major sutures between these components. Using gravity data, it is possible to restore Mesozoic stretching of the Atlantic margins; the resulting reconstruction places Ireland significantly closer to Newfoundland than has been previously proposed.

In the original Wilson Cycle, the Northern Appalachian - Caledonide Orogen resulted from the collision of two continental masses separated by a single ocean. One of these corresponds to the modern concept of Laurentia, but the colliding continent to the east has been variously subdivided into many smaller terranes and domains, including Ganderia, Avalonia and Megumia. Using published stratigraphic evidence and detrital zircon provenance data from units of known depositional age, the timing of arrival of these units at the Laurentian margin between the Early Ordovician and Early Devonian can be constrained. Several of the accreted terranes do not extend over the entire length of the orogen, with the result that the lines separating them change character along strike from terrane-bounding sutures to simple accretionary thrust faults. The domain Ganderia consists of at least four separate terranes that share a common origin on the continental margin of Gondwana, but were separated by back-arc oceanic crust as they crossed the Iapetus Ocean and collided diachronously with the Laurentian margin.

Large layered intrusions in LIPs as amalgamated stacks of out-of-sequence sills from high-precision dating of the Stillwater Complex

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The Neoarchean Stillwater Complex, one of the world's largest layered intrusions and potentially a sub-volcanic reservoir related to a large igneous province (LIP), represents a cornerstone for the study of magmatic processes in the Earth's crust. A complete geochronological framework for crystallization of the Stillwater Complex based on trace element geochemistry of zircon and comprehensive U-Pb zircon-baddeleyite-titanite-rutile geochronology of 22 samples is presented. Trace element concentrations and ratios in zircon are highly variable and support crystallization of zircon from highly fractionated interstitial melt at near-solidus temperatures in the ultramafic and mafic cumulates (Ti-in-zircon thermometry = 980-720°C). U-Pb geochronological results indicate that the Stillwater Complex crystallized over a ~3 million-year interval from 2712 Ma (Basal series) to 2709 Ma (Banded series); late-stage granophyres and at least one phase of post-emplacement mafic dikes also crystallized at ca. 2709 Ma. The dates reveal that the intrusion was not constructed in a strictly sequential stratigraphic order from the base (oldest) to the top (youngest). Two distinct age groups are recognized in the Ultramafic series. The lowermost Peridotite zone, up to and including Chromitite G, formed at ca. 2710 Ma from magmas emplaced below the overlying uppermost Peridotite and Bronzitite zones that crystallized earlier at ca. 2711 Ma. The age and locally discordant nature of the J-M Reef indicate that this sequence represents an intrusion-wide magmatic unconformity and that it marks the onset of renewed and voluminous magmatism at ca. 2709 Ma. The thick anorthosite horizons in the Middle Banded series are older (ca. 2710 Ma) than the rest of the Banded series, a feature consistent with a flotation cumulate ("rockbergs") model. The anorthosites are related to fractional crystallization of mafic and ultramafic rocks now preserved in the Ultramafic series and in the lower part of the Lower Banded series below the J-M Reef. The U-Pb geochronology results indicate that the Stillwater Complex formed as a stack of amalgamated sills representing repeated injections of magma, some of which were emplaced out-of-sequence, and does not represent the crystallized products of a progressively filled and cooled magma chamber. This calls into question current concepts regarding the intrusive and crystallization histories of major open-system layered intrusions associated with LIPs and challenges us to rethink our understanding of the timescales of melt generation, emplacement, and crystallization processes in these large magmatic systems.

Differentiating tills in the Hudson Bay Lowland; Gillam area, northern Manitoba

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Areas of complex glacial stratigraphy contain valuable information about the effect of past glacial erosion, transport, and deposition, but they also hinder mineral exploration of targets under cover. The Hudson Bay Lowland (HBL) is one such area, where intricate multi-till stratigraphy over carbonate bedrock transitions to a thin till over the Canadian Shield. The record of at least three glacial cycles is preserved. Previous workers have identified four till units in the Gillam region of Manitoba (e.g. Sundance Till, Amery Till, Long Spruce Till and Sky Pilot Till) qualitatively (e.g. site descriptions, color, texture); however, correlations beyond the type sections are highly uncertain due to variability in descriptions and criteria between localities and studies. Here we use major and trace element geochemistry from 245 till samples to discriminate till units and gain insight into the glacial processes at work in this transition area. Element concentrations in till matrix geochemistry provide information about till provenance, as well as transport process via insight into dilution and mixing. Till units are differentiated using multivariate statistics. Specifically, we employ principal component analysis and k-means cluster analysis to group samples with similar geochemical characteristics. In total, 6 geochemical groups are recognized and applied to establish a chemo-stratigraphic framework for the study area. Four tills are clearly differentiated in our dataset, while two tills overlap sufficiently in their geochemical characteristics to be regarded as hybrid tills. However, the four chemically distinguished till do not correlate well with four described tills in the type sections. From this work, we conclude that multivariate data analysis of till matrix geochemistry is helpful in discriminating and classifying tills, and can thus complement the overall facies and stratigraphic analysis. Results of this chemical classification will thus be integrated to those from other quantitative data sources such as pebble lithology counts and fabric measurements to determine a new quantitative and qualitative till stratigraphy for the Hudson Bay Lowland.

290–270 Ma volcanism along the Central Asian Orogenic belt: Reworked or a process of the accretionary orogeny?

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Although the Central Asian Orogenic belt (CAOB) has been considered a multiple-stage and complicated accretionary orogenic belt, still there are some issues remained the contrary interpretations. Between Siberian and China continent (including Tarim, Alaxa, North China, etc), there are at least three-cycle volcanism related to the continental growth: 460–420 Ma, 350–320 Ma, and 290–270 Ma.

The 450–440 Ma granites and schists represent an earlier island arc and accretionary complex, related to the closing of an Ordovician–Silurian ocean. ~350–320 Ma volcanism and sedimentation remain controversial: rift system or the oceanic plate-arc island system? Recently, we have found that the 290–270 Ma volcanism was accompanied with the rapid sedimentation and consistent with the opening of a rift; thus we exclude the ophiolite complex hypothesis.

What happened to this 290–270 Ma volcanism along the whole Central Asian orogenic belt? The eruptions ranged from felsic to intermediate to mafic in composition in zones that were wider in the west and narrower in the east, and extending in the east to the west Pacific plate margin. These volcanic belts became active after the formation of the Tianshan–Inner Mongolia orogenic belt and after the amalgamation of the CAOB. Formation of the rifts involves the reworking or re-extension of the continental margins during regional and continuous continental assembly. Therefore, we suggested that upwelling of the lithospheric mantle and magma sourced from asthenosphere would be in a horizontal flow state during the formation of the Pangean supercontinent.

Keynote (40 min): When does monazite crystallise in metamorphic rocks?

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A key aim of modern metamorphic geochronology is to constrain precise and accurate rates and timescales of tectonic processes. These in turn provide constraints on the mechanisms by which crust is buried, transformed, deformed and recycled. Precise and accurate measurement of isotope ratios in minerals used as geological clocks is now routine, providing tightly constrained mineral ages. High spatial resolution in-situ laser ablation datasets commonly yield a range of dates rather than a single "bulk" age. This range could be due to protracted crystallization of the geochronometer minerals over a range of PT conditions, or an artefact due to analytical sampling of multiple growth zones. We have analysed U-Th-Pb monazite dates in six samples collected within a few metres of each other from a layered Grt-Bt-Sill +/- St +/- Ky gneiss outcrop in central Bhutan. Taken together, the yielded dates range from ~32-16 Ma. However only one of the samples provides dates that span the whole range; other samples contain monazites that yield a much more constricted range of dates. Monazite therefore formed either as the product of subtly different crystallisation reactions in different samples, or as a product of the same reaction(s) occurring at subtly different PT conditions due to bulk composition variations. Our dataset show that minor variations in mineralogy between different samples from the same outcrop can have a major effect on the age that sample yields, which in turn can have major implications for the tectonic interpretation(s) arising from that dataset. In young orogens such as the Himalayas where events occurring 0.5 Ma apart can now be separated by modern geochronological analyses, it is critical that the reaction that formed the geochronometer mineral are tightly tied to the pressure-temperature-deformation evolution of the bulk rock.

Age and preliminary paleomagnetic assessment of the Silurian Mavillette gabbro, Meguma terrane, Nova Scotia, Canada

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The Mavillette gabbro is a plagioclase-rich gabbroic sill in southwestern Nova Scotia closely related to metavolcanic and metasedimentary rocks of the Silurian White Rock Formation. This rift-related magmatism was emplaced on turbiditic rocks of the Halifax Group, and likely marks the beginning of Meguma terrane drift towards Laurentia. The age of the gabbro has been determined to be 426 ± 2 Ma (U-Pb baddeleyite), making it slightly younger than ca. 440 Ma bimodal volcanic rocks of the White Rock Formation. The Mavillette gabbro forms an arcuate body, folded about a regional southwest-plunging syncline of Neoacadian age (ca. 390 Ma). It has a sub-ophitic to ophitic texture with visible sulfide minerals and planar foliation defined in hand sample by plagioclase laths that appear to be a paleohorizontal indicator. Paleomagnetic investigation of the gabbro aimed to stepwise demagnetize the natural magnetic remanence (NRM) to reveal ancient magnetic field directions. Previous paleomagnetic studies in the Meguma terrane have been unsuccessful due to pervasive metamorphism and deformation; as a result, little is known about the paleogeographic origin and drift history of the terrane. The sill was sampled in thirteen sites (223 specimens) exposed in two quarries, representing both east and west limbs of the syncline. Based on the preliminary data, it is not yet known whether the remanence was pre- or post-folding, as a fold test has thus far been inconclusive. Of the thirteen sites, eight produced interpretable results despite the prevalence of multi-domain (MD) magnetite within the samples. Demagnetization of the specimens revealed magnetizations that are resolvable as two magnetic components: V and M. The V component is interpreted to be a Viscous Remanent Magnetization carried by MD magnetite, typically removed by 20 mT and showing a direction similar to the present-day field direction. Sixty-one per cent of the pilot specimens demonstrated MD magnetite-dominated behaviour, with less than 12 % NRM intensity remaining by 20 mT. The remaining specimens displayed an M component magnetization that was coercively hard, but removed during thermal demagnetization in higher temperature steps, up to 580° C, in which magnetite unblocked and an ancient, south-southeast and shallow-down direction was removed. The expected magnetic field direction at Meguma as it arrived at Laurentia in the mid-Devonian is approximately 180°, 60°, based on the reference apparent polar wander path for Laurentia. The ancient directions exhibited by the samples may contain a significant mid-Devonian overprint, acquired during the Neoacadian orogeny.

Vertical stacking patterns of matrix-rich and matrix-poor sandstones in a deep-marine channel-margin succession, Isaac Formation, Windermere Supergroup, British Columbia

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Matrix-poor and lesser matrix-rich sandstones have long been recognized in the deep-marine sedimentary rock record, yet their depositional mechanisms, especially for matrix-rich rocks, remain poorly understood. At the Castle Creek study area a remarkably well exposed, recently deglaciated, vegetation free, 30m thick by 350m wide section containing both matrix-rich and matrix-poor strata was measured in bed-by-bed detail to document changes in facies and stratal assemblages. Based on these data three facies are recognized: (F1) matrix-poor, traction structured turbidities (T_bc, T_b, T_c); (F2) sharp planar-based, structureless, coarse-tail graded, matrix-rich sandstones (~30-70% matrix), with common mudstone chips and clasts; and (F3) scour-based, coarse-tail graded matrix-poor sandstones (<10% matrix). These facies stack to form three distinctive stratal assemblages: (SA1) consisting of classical (matrix-poor) turbidites (F1) that stack to form units 2-6m thick; (SA2) comprising matrix-rich sandstones (F2) that build units up to 2.0m thick; and (SA3), which consists of a single bed of matrix-poor sandstone (F3) overlain sharply by 2-3 matrix-rich sandstone beds (F2), and collectively form dm- to m-thick bedsets that then stack into units 1.5-4.5m thick.

Units of classical turbidites (SA1) are overlain abruptly by sharply bounded intercalated units of (SA2) and (SA3). Notably, the range of grain sizes varies little between units but the matrix content does, suggesting an abrupt but also recurring change in local depositional conditions. Additionally, sharply bounded matrix-rich units of SA2 and SA3 with its intercalated matrix-rich and matrix-poor parts not only stack vertically, but also grade into one another laterally, suggesting the compensational stacking of different parts of the lateral facies transect. The abrupt and exclusive introduction of matrix-rich lithologies (SA2, SA3) is interpreted to indicate the voluminous introduction of fine-grained sediment into the throughgoing turbidity currents, which quite possibly was related to upflow avulsion and local erosion of a mud-rich seabed. The lateral transition from SA2 to SA3, and vice versa, reflects spatial differences in particle settling within the now mud-engorged and negligibly-sheared parts of a turbulent suspension – reduced shear being a consequence of turbulent kinetic energy being rapidly consumed by particle acceleration. These conditions were then abruptly terminated with the return of classical turbidite deposition from fully sheared flows. This abrupt transition is interpreted to reflect the cessation of local sea bed erosion, quite possibly by burial in sand, and resumption of more typical out-of-channel flow conditions, and thereby patterns and lithological characteristics of the depositional record.

Sulfur cycling over the past 70 million years

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Sulfate, the most abundant form of sulfur in the modern ocean, plays an important role in the global biogeochemical cycle. Sulfate concentration in seawater is the key factor controlling the load of atmospheric sulfate aerosols, which can cause a cooling effect on global climate. The amount of dissolved sulfate in seawater and its S-isotope ($\delta^{34}S$) are controlled by the input and output fluxes of sulfur to/from the oceans and their respective isotopic compositions. The pronounced fractionation of sulfur isotopic compositions exists between seawater sulfate and mineral sulfide, which is produced by microbial sulfate reduction (MSR: $2CH_2O + SO_4^{2-} \rightarrow 2HCO_3^- + H_2S$) in organic-rich sediments. 80-95% of H_2S generated from MSR are subsequently reoxidized to sulfate through oxidative sulfur cycle, modifying O-isotope of seawater sulfate ($\delta^{18}O$). Abiotic sulfide reoxidation dominates the oxic organic-limited sediments in abyssal environments producing lighter sulfate $\delta^{18}O$, while biological sulfide reoxidation pathways are favored in the low-oxygen, organic-rich sediments on continental shelves producing heavier sulfate $\delta^{18}O$. Consequently, the redox condition has a strong influence on sulfate isotopes. Most previous studies analyze seawater chemistry using sulfate $\delta^{34}S$ or $\delta^{18}O$, respectively, but few of them investigate the correlation between sulfate $\delta^{34}S$ and $\delta^{18}O$ throughout the geologic time. Different processes determine different correlations. For example, sulfate $\delta^{34}S$ and $\delta^{18}O$ are positively correlated during sea level increase/decrease, while in the anoxic water, sulfate $\delta^{18}O$ may be modified without altering sulfate $\delta^{34}S$ nor depleting sulfate concentration. To extrapolate this hypothesis, this study will combine laboratory and modeling techniques to systematically reconstruct biogeochemical sulfur cycling over the past 70 million years. Results from this study will 1) simultaneously provide seawater sulfate $\delta^{34}S$ and $\delta^{18}O$ data at different geologic time; 2) identify different isotopic correlations as a new insight to reveal different paleoenvironments; and 3) lead to better understanding of the interactions between oceanography, biology, petrology, and atmosphere, especially the contribution of seawater sulfate concentration to the long-term cooling trend over the past 70 million years.

Deep and long-lasting mantle plumes with enriched mantle-1 signatures

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Hawai‘i and Kerguelen are two of the three largest oceanic islands. Kerguelen has evolved from a ridge-centered position at ~40 Ma to an intraplate position today, in a setting comparable to Hawai‘i. Both Hawai‘i and Kerguelen have long hotspot tracks, respectively spanning 85 and >115 million years and forming the longest hotspot track (Hawai‘i) and the longest linear feature on Earth (Kerguelen). On the islands of Hawai‘i and Kerguelen, basalts carry enriched mantle “EM-1” signatures. When projected to the core-mantle boundary (CMB), Hawai‘i and Pitcairn overlie the edges of the Pacific large low-shear-velocity province (LLSVP), whereas Kerguelen and Tristan are located on the eastern and western edges, respectively, of the African LLSVP. At Hawai‘i, the ultra-low velocity zone at the CMB is proposed to be the repository for enriched components in the mantle that are responsible for the Loa-trend geochemical enrichment. For the Kerguelen Archipelago, the enriched component dominates the chemistry of the alkalic basalts (25-24 Ma), whereas the older (28-26 Ma) tholeiitic-transitional basalts also contain a depleted Southeast Indian Ridge component from when the plume was close to the ridge. In isotope plots, Kerguelen compositions form sub-parallel trends that are distinctly more enriched (higher $^{87}Sr/^{86}Sr$, lower εNd and εHf and more radiogenic Pb) than those from Hawai‘i. Kerguelen and Tristan basalts carry the strongest enriched signature (DUPAL anomaly), whereas Pitcairn (although very different in Pb isotopes) and Hawaiian-Loa trend basalts have a distinct, slightly less pronounced enriched signature. We infer that some of the materials constituting the African and Pacific LLSVPs at the base of the mantle are distinct, reflecting the different geodynamic settings of these oceans. The ambient deep mantle is also different beneath the Indian Ocean than the Pacific Ocean. The Pacific deep mantle is sampled by Kea trend volcanoes in Hawai‘i and many other Pacific oceanic plateaus, such as Ontong-Java and Wrangellia. In Hawai‘i, the EM-1 signature is traced back for at least 5 Ma and appears episodically along the Hawaiian Ridge as early as 45 Ma. In Kerguelen, it can be traced back until 34 Ma on the archipelago and Northern Kerguelen Plateau, and until 82 Ma along the 5000 km-long Ninetyeast Ridge. These isotopic signals indicate that LLSVP are long-lived features of the deep mantle and play a significant role in the geochemical signature of strong mantle plumes and their associated basalts and mineralizations.

Fluids in the Los Azufres Geothermal Field, Mexico traced by noble gas isotopes and $^{87}Sr/^{86}Sr$

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A total of 35 geothermal wells and 2 hot springs were sampled for isotopic measurements of noble gases (He, Ne, Ar, Kr and Xe) and Sr in the Los Azufres Geothermal Field (LAGF) in Mexico to understand the evolution of fluid circulation following three decades of exploitation and re-injection of used brines. The LAGF, divided into two production zones, the Southern Production Zone (SPZ) and the Northern Production Zone (NPZ), is hosted in a Miocene to Pliocene andesitic volcanic complex covered by Quaternary volcanic products of rhyolitic-dacitic composition and crosscut by extensional E-W faults.

$^{3}He/^{4}He$ ratios (R), normalized to the atmospheric ratio (Ra= 1.384×10^{-6}) range from 1.03 to 7.93 and point to a binary mixture between a fluid carrying a pure upper mantle helium component and one with helium diluted by atmospheric and/or radiogenic ^{4}He. $^{3}He/^{4}He$ ratios correlate well with $^{4}He/^{20}Ne$, and point to diluted helium of crustal origin with contributions up to 48% and 18% in the NPZ and SPZ, respectively. Comparison between R/Ra and $^{87}Sr/^{86}Sr$ ratios points to mixing of three magmatic sources for He and Sr isotopes. Specifically, a pure mantle He (R/Ra = 8) and Sr (0.7035) source, a mantle helium with some radiogenic Sr (0.7049) possibly resulting from the late rhyolitic volcanic activity, and a fossil mantle He component diluted by radiogenic ^{4}He (R/Ra = 3.8) and slightly contaminated by radiogenic Sr (0.7038), corresponding possibly to Miocene andesite reservoir rocks.

$^{40}Ar/^{36}Ar$ ratios are generally higher in SPZ (up to 597) and suggest the presence of a mantle or crustal Ar component. Although overall the NPZ displays lower $^{40}Ar/^{36}Ar$ ratios, high $^{40}Ar/^{36}Ar$ ratios (up to 365) in some NPZ samples point to the addition of radiogenic ^{40}Ar. $^{40}Ar/^{36}Ar$ ratios correlate also well with $^{3}He/^{36}Ar$ ratios for both NPZ and SPZ. Estimated $^{40}Ar/^{3}He$ ratios in the magmatic component are 16,220 and 8,060 for the SPZ and NPZ, respectively. Although both ratios are lower than those in the mantle (45,000 to 60,000), mantle contributions appear to be greater in the SPZ.

Atmospheric noble gas isotopic ratios ($^{20}Ne/^{36}Ar$, $^{84}Kr/^{36}Ar$ and $^{132}Xe/^{36}Ar$) suggest that boiling-phase separation processes affect many wells. Some wells contain also different proportions of re-injected brines. Geothermal wells located closer to the western re-injection zone show greater contribution of injectate. The area affected by boiling in the NPZ has further extended to the north and the west since last noble gas sampling campaign in 2009.

The Silurian-Devonian Rockville Notch Group, Nova Scotia, Canada – unique to Meguma

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The Silurian - Devonian Rockville Notch Group (White Rock, Kentville, Torbrook, and New Canaan formations) forms a discontinuous northeast-trending belt in the Meguma terrane of southern Nova Scotia. On its northwestern margin it unconformably overlies the Cambrian to Lower Ordovician Goldenville and Halifax groups whereas its southeastern margin is a major fault zone. The fault zone and Rockville Notch Group were intruded by the ca. 375 Ma South Mountain Batholith. The White Rock Formation consists mainly of mafic and felsic volcanic rocks, now dated at 4 locations near both the bottom and top of the volcanic pile; ages and errors overlap at 441 ± 4 Ma, with maximum range of 446 to 435 Ma. These dates confirm a 30 Ma time gap with the youngest formation in the underlying Halifax Group. Sedimentary rocks interlayered with the volcanic rocks are also early Silurian (Llandovery) based on trace and sparse shelly fossils, and contain Fe- and Mn-rich beds. They are overlain by mainly siltstone with abundant quartz arenite and conglomerate lenses; some of the latter were previously interpreted to be Ordovician diamictite. They are conformably overlain by the slate- and siltstone-dominated Kentville Formation containing Upper Wenlockian to Pridolian graptolites and microfossils. The overlying Torbrook Formation, consisting of limestone, sandstone, and siltstone interbedded with ironstone and minor mafic tuff, contains Pridoli to early Emsian fossils, and is laterally equivalent to the New Canaan Formation of the Wolfville area, which is dominated by pillowed mafic volcanic rocks, fossiliferous limestone, and slate.

Volcanic rocks in the Rockville Notch Group are alkalic and formed in a within-plate setting, likely related to extension as the Meguma terrane rifted from Gondwana. Previously published and new detrital zircon data indicate that the major sediment sources for the Rockville Notch Group have ages of ca. 670-550 Ma and ca. 2050 Ma, similar to ages from the underlying Goldenville and Halifax groups. However, minor ca. 1200 Ma and ca. 1900-1750 Ma sources are not represented in the latter groups.

The Rockville Notch Group has been correlated previously with the Arisaig Group of the Avalonian Antigonish Highlands. However, the Arisaig Group contains different rock types and fossils, lacks volcanic rocks other than K-bentonite layers, and has detrital zircon signatures indicating that sediment sources have age peaks at ca. 635-510 Ma and ca. 950 Ma. Hence, these Silurian units are not consistent with Avalonia and Meguma having been amalgamated by the Silurian.

Keynote (30 min): The varieties of fault experience (with apologies to William James)

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The range of fault-related phenomena observed as functions of crustal depth, scale and tectonic regime has begat numerous explanations that, notwithstanding a few generalizations, are too often explicable in detail as "one-off" features; that is, in the end we are describing macroscopic geometries that may or may not fall within some model. Faults and shear zones are essentially energy sinks for deformation, and despite the large size of these phenomena, the dissipation of energy remains controlled by disruption at the atom scale. Deformation is fundamentally quantized, discrete (diffusion, glide, crack propagation) and reliant on the defect state of rock-forming minerals. The strain energy distribution that drives thermo-mechanical responses is in the first instance established at the grain-scale where the non-linear interaction of defect-mediated micromechanical processes introduces heterogeneous behaviour described by various gradient theories, and evidenced by the defect micro-structures of deformed rocks. Hence, the potential for non-uniform response is embedded within even quasi-uniform, monomineralic materials, seen, for example, in the spatially discrete evolution of dynamic recrystallization. What passes as homogeneous or uniform deformation at various scales is the aggregation of responses at some characteristic dimension at which heterogeneity is not registered or measured. Nevertheless, the aggregate response and associated normalized parameters (strain, strain rate) do not correspond to any condition actually experienced by the deforming material. This may help reconcile paradoxes such as the consistency of stress drops for a range of earthquake types and magnitudes against a background of anticipated strength difference. The micromechanical characteristics of several fault/shear zones are discussed in terms of how this information can be utilized in interpreting macroscopic phenomena.

The foreland basin offshore western Newfoundland: Concealed record of northern Appalachian orogen development

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The Anticosti Basin, largely hidden beneath the Gulf of St. Lawrence, includes foreland basin successions that record four distinct tectonic loading events associated with the Middle Ordovician to Early Devonian evolution of the northern Appalachian Orogen. Due to the absence of wells drilled in the offshore region, important correlations of reflections to geologic boundaries cannot be made using well ties. By using a combination of available 2D seismic reflection, aeromagnetic and bathymetry data, along with imagery from Google Earth, it is possible to tie onshore outcrops to seismic reflections and produce a 3D model of the foreland basin successions.

Seismic isochron maps for each succession show important differences in geometry, and imply that orogenic loading varied through time in amount, distribution and location. The geometry and sedimentation rates of the Middle Ordovician Goose Tickle Group, the first foreland basin succession, imply formation in a proarc setting associated with loading from the Newfoundland portion of the Appalachians. Facies variations, in the Newfoundland and Québec portions of this basin, imply diachronous collision of arcs and Laurentian microcontinents during Taconian Orogenesis. The geometry and sedimentation rates of the overlying Long Point Group indicate that loading of the Laurentian margin, by Taconian allochthons along the Québec segment of the Appalachians, was responsible for generating this second foreland basin succession. Diachronous subduction polarity reversal along the margin positioned the Long Point Group in a unique tectonic setting, a combined retroarc and proarc setting. The latest Silurian to Early Devonian Clam Bank Formation and Early Devonian Red Island Road Formation represent retroarc foreland basin successions formed during the Salinic and Acadian orogenies respectively. The consistent thickness and dominantly terrestrial nature of the Clam Bank Formation suggests it filled a broad, shallow basin, probably due to lithosphere cooling and strengthening at this time. By combining structural, stratigraphic and geophysical data, we are able to produce a model of the foreland basin of the Newfoundland Appalachians and improve our understanding of the diachronous tectonic events along the northern portion of the orogen.

Keynote (40 min): High-temperature metamorphism and Grenville orogenesis in the Adirondack Highlands, New York, USA

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Becky Jamieson has had a major impact on our understanding of metamorphism, particularly the development and implications of metamorphic rocks within the orogenic cycle. The Grenville orogen of eastern Laurentia is a particularly significant example, as Becky's observations, interpretations, and models have shaped the way we see the metamorphic rocks and interpret the architecture of the larger orogen. The Adirondack Highlands (AH) have an unusually high percentage of strongly migmatitic rocks, and the timing, nature, and especially the tectonic context of the high-grade metamorphism is uncertain. Any of four thermo-tectonic events may have involved melting: (1) the 1.17 Ga Shawinigan orogeny, (2) the 1.15 Ga emplacement of AMCG magmas, (3) the 1.09-1.05 Ga Ottawan orogeny, and (4) post-Ottawan orogenic collapse. Monazite-bearing migmatitic gneisses have been analyzed along a broad swath from Fort Ann (South) to Ticonderoga (North) in the eastern Adirondack Highlands to constrain the timing and setting of melting. Phase relations and modes suggest biotite-dehydration melting with garnet as a peritectic phase. Biotite mode varies widely, but some ultra-melted rocks are essentially biotite free, sillimanite-bearing "khondalites". Following Becky Jamieson we combine multi-scale compositional mapping, petrologic and microstructural analysis to place monazite domains within the context of the reaction and deformation history. The rocks can be divided into several subdomains or blocks. Rocks from the northern and western blocks, especially "khondalites", contain monazite with three main domains: 1.18 Ga cores (Shawinigan), 1.15 Ga outer cores (AMCG), and rims that are younger than 1.05 Ga (Post-Ottawan). Y and Th compositions suggests that garnet growth, partial melting, and deformation occurred just before 1.15 Ga. We suggest that significant (extreme) melting and deformation occurred during heating by AMGC magmas. These rocks record little Ottawan tectonism possibly because they existed in the tectonic lid during this event, but perhaps also because the highly restitic compositions resulted in little recrystallization during Ottawan metamorphism. Rocks in the southeastern block contain monazite with rare Shawinigan- and AMCG-aged core domains. Most grains have large 1.08-1.05 Ga (Ottawan) outer core domains and 1.05-1.0 Ga (Post-Ottawan) rims. Monazite compositions suggest significant Ottawan garnet growth and lesser garnet growth during the Shawinigan or AMCG events. Rim compositions and textures indicate syn-tectonic monazite growth during the early stages of post-Ottawan extension. Thus, the two block types record different parts of the overall Grenville cycle. One controlling variable involves the degree of AMCG-related melting, which in turn, may reflect the position (superstructure vs. infrastructure) within the evolving Grenville orogen.

Comparing climate signals obtained from encrusting and free-living Southwest Greenland coralline algae

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Coralline algae have been widely used for sclerochronological studies throughout the last decade. These studies have focused on two different growth morphologies of the photosynthetic coralline algae: massive crusts forming small buildups on hard substrate, and free-living branching algal nodules, known as rhodoliths. The latter are generally found on soft-substrate, where they are frequently overturned by water movement and bottom feeding organisms, leaving one side of the rhodolith partially buried in the sediment at any given time. Here we test whether either of these growth morphologies is more suitable for proxy reconstructions by comparing Mg/Ca ratios – a temperature proxy – in multiple replicates of rhodoliths of Lithothamnion glaciale and in rhodoliths as well as encrusting specimens of Clathromorphum compactum. With both species being widespread throughout the Subarctic and Arctic, we have chosen two North Atlantic localities at Nuuk Fjord, Greenland, and off the southeastern coast of Newfoundland, Canada for this study. Two to three Mg/Ca ratio transects spanning 18 years of growth were analysed on multiple specimens with encrusting morphologies and along different sides of rhodoliths using later ablation inductively coupled mass spectrometry and compared to remotely sensed sea surface temperature (SST) data. Monthly Mg/Ca values from multiple transects within each individual were compared and in samples from Nuuk fjord significant correlations were found in 6 of 6 encrusting C. compactum transect comparisons (from $r=0.36$ to $r=0.52$), 8 of 13 C. compactum rhodolith comparisons (from $r=0.39$ to $r=-0.03$), and 5 of 9 L. glaciale rhodolith transects (from $r=0.61$ to $r=-0.02$). In Newfoundland significant correlations were found in 6 of 6 encrusting C. compactum transect comparisons (from $r=0.77$ to $r=0.4$), and in 6 of 6 L. glaciale rhodolith comparisons (from $r=0.58$ to $r=0.41$). Finally, all transects from all individuals of each growth type were averaged. The combined annually averaged data from encrusting C. compactum samples in Nuuk fjord showed significant correlations to instrumental SST ($r=0.54$, $n=9$, $p=0.06$), while the L. glaciale ($r=0.36$, $n=9$, $p=0.17$) and C. compactum ($r=0.37$, $n=9$, $p=0.16$) rhodoliths did not. Both encrusting C. compactum ($r=0.39$, $n=18$, $p=0.05$) and rhodolith-forming L. glaciale ($r=0.4$, $n=18$, $p=0.05$) from Newfoundland samples correlated significantly with local SST. In summary, each coralline algal growth form has limitations but in this test, encrusting coralline algae exhibited stronger relationships with local SST than rhodoliths.

Compositional evidence for magma recharge and mixing in CFB reservoirs: Evidence from melt inclusions in HALIP basalts

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Small pockets of melt trapped as inclusions during crystal growth may provide constraints on the compositional diversity of melts in basaltic magmatic systems, and ultimately shed light on the nature of their mantle source(s). Melt inclusions preserved in continental flood basalts (CFB) may represent more primitive compositions than the erupted magmas, hence their importance in deepening our understanding of CFB petrogenesis.

We report the trace element concentrations of plagioclase-hosted melt inclusions in HALIP flood basalts exposed near Bunde Fiord, northern Axel Heiberg Island. The Arthaber Creek (AC) volcanic succession consists of lava flows with well-defined oxidized flow tops and an average thickness of ~ 10 m. Whole rock geochemical analyses for 20 samples of basalt yielded compositions typical of continental tholeiites with (e.g.) SiO_2 values of 45.7-53.7 wt.%; MgO values of 3.3-6.6 wt.%; and TiO_2 values of 1.45-2.89 wt.%. REE patterns show enrichment in LREE (La_N/Sm_N: 1.66-2.43) and evidence of differentiation within the volcanic succession. The lava flows are characterized by abundant, inclusion-rich plagioclase phenocrysts with disequilibrium textures. A strong correlation between higher Mg# in the bulk rock and the presence of An-rich cores in phenocrysts suggests that episodic magma recharge and mixing processes operated at depth. Melt inclusions range in size from 100 to 200 µm; glass inclusions with altered rims (30-50 µm in size) are commonly found in the cores of larger inclusions. Overall, the size and texture of melt inclusions are ideally suited for geochemical analysis by LA-ICP-MS.

The analytical methodology involved the following steps: (1) detailed textural analysis of melt inclusions using the Scanning Electron Microscope (SEM); (2) selection of targets in four thin sections of basaltic lava; (3) major element analysis of 17 inclusions by Electron Probe Microanalysis; and (4) LA-ICP-MS spot analyses of melt inclusions using a Teledyne Photon Machines Analyte G2 excimer laser ablation system and an Agilent 7700x ICP-MS.

The experiment demonstrated that melt inclusions ablated without prior homogenization can yield reliable geochemical data. However, the interpretation of results is critically dependent on the availability of textural information at the micron scale. Our data show a high degree of coherence, particularly for REE and HFSE. A comparison of REE patterns for bulk rocks and melt inclusions leads us to conclude that some of the glass inclusions represent primitive melts trapped during magma recharge and mixing in shallow reservoirs; and that partial crystallization modified a significant number of large, plagioclase-hosted melt inclusions.

Volcanology and geochemistry of HALIP flood basalts, Axel Heiberg Island, Nunavut

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Geochemical studies of continental flood basalts are often hindered by a lack of stratigraphic control in areas where sheet flows were emplaced over geologically short time intervals. The advantage of studying flood basalts in a basin setting is that the time-sequence of eruptions is well-defined, thus providing a robust stratigraphic framework for lithogeochemical studies.

Fieldwork in the Sverdrup Basin was carried out in 2015 and 2016 as part of the GEM 2 (High Arctic Large Igneous Province (HALIP) research activity. A particular emphasis was placed on the stratigraphy, physical volcanology and geochemistry of flood basalts in the Strand Fiord Formation. Detailed investigations were carried out at two locations on western Axel Heiberg Island: along the south shore of Bunde Fiord, and near Plateau Lake, to the north of Strand Fiord.

Previous studies demonstrated that the ~ 95 Ma Strand Fiord Formation consists of sheet flows of uniformly basaltic composition displaying aa and pahoehoe textures. Fieldwork near Plateau Lake suggests a total thickness of 980 m at this locality. The 3-D exposure of ~500 m of section alongside a retreating glacier makes this a world-class example of flood basalt volcanism. Invasive flows near the base of the succession consist of a mélange of basaltic lava and blocks of sandstone. These chaotic flows are overlain by a bed of shale containing volcanic bombs and discontinuous lenses of fine-grained sandstone that locally contain fiamme. Thick lava flows are characterized by grey, unoxidized flow tops and show complex structures such as basalt colonnades and entablatures. In contrast, volcanic successions near Bunde Fiord consist of lava flows separated by well-defined oxidized flow tops. A single bed of crystal tuff occurs near the base of the succession. The flows are of aa type, and lack the complex intraflow structures observed at Plateau Lake and in the type area at Strand Fiord.

Flood basalts in the Strand Fiord Formation should ideally form a continuous petrogenetic series if individual sections were once part of a single basaltic plateau. A comparative geochemical study of lava flows in both areas suggests that most eruptions tapped steady-state magmas rising from a shallow reservoir. At Bunde Fiord, the mineralogy and geochemistry of lava flows show compelling evidence for episodic magma recharge and mixing processes consistent with periods of quiescence between eruptions. We propose a model for the emplacement of HALIP flood basalts that integrates field observations with the results of petrochemical studies.

Geochemistry of shield basalts from the island of Kauaʻi and the emergence of the Hawaiian geochemical trends

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The chemical variations in Earth's heterogeneous mantle can be mapped by determining the geochemistry of mantle plume-derived magmas, including those that form Large Igneous Provinces (LIPs). Volcanic rocks of the ~6000 km long Hawaiian-Emperor chain, produced by the Hawaiian mantle plume, are a direct record of Pacific mantle chemistry over the past 85 million years. Two parallel geochemical trends exist in the Hawaiian Islands that match the geographic distribution of volcanoes. From the island of Hawaiʻi to Oʻahu (0 to 4 Ma), volcanoes are divided into southwestern (Loa) and northeastern (Kea) trends distinguished by isotopic 'fingerprints' of lead and other radiogenic isotopes. These are interpreted to directly reflect the chemical structure of the underlying mantle plume and its corresponding deep mantle source. The adjacent older segment of the Hawaiian-Emperor chain, the Northwest Hawaiian Ridge (NWHR; 6 to 49 Ma), is dominated by Kea compositions. The island of Kauaʻi occupies a key location as it represents the transition point between the Kea-dominated NWHR and the bilaterally zoned younger Hawaiian Islands. High-precision Pb-Sr-Nd-Hf isotopic analyses on a new sample set, including previously unsampled basalts from eastern Kauaʻi, tightly constrain distinct isotopic groups in Kauaʻi shield-stage basalts. Basalts from the Nāpali Member on West Kauaʻi have Pb-Sr-Nd-Hf isotope ratios within the range of Kea-like compositions, whereas basalts from the Nāpali Member on East Kauaʻi have isotope ratios that are Loa-like. Eastern Nāpali basalts from newly sampled locations have Pb isotope ratios that overlap those from Koʻolau volcano's main shield stage and that are less radiogenic in Nd and Hf than other Nāpali basalts. The distinct isotopic groups preserved in Kauaʻi shield basalts from the same volcanic unit require a heterogeneous mantle source. In the younger Hawaiian volcanoes, geochemical variations are dominantly controlled by the spatial distribution of mantle plume heterogeneities, which may be the case for Kauaʻi. Alternatively, heterogeneities in the Kauaʻi source may have varied in time, however age constraints on eastern Nāpali Member samples are required to test this hypothesis. Furthermore, the geographic distribution of isotopic compositions on Kauaʻi is opposite and perpendicular to that preserved on the younger Hawaiian Islands, requiring an altogether different chemical organization of the Hawaiian mantle plume between 6 and 4 Ma. The continued study of shield basalt from Kauaʻi highlights its essential role in constraining the emergence of the Hawaiian trends and the chemical structure of the increasingly complex Hawaiian mantle plume.

Keynote (40 min): Quantitative mineralogy of gossans and stream sediments in the High Arctic Large Igneous Province (HALIP) via SEM-MLA: Implications for economic potential

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Gossans are a common geological feature of the Canadian North, and of the High Arctic Islands in particular. Due to the lack of archetypal vegetative cover as in boreal regions, gossans are a highly visible component of the landscape in tundra areas. Fundamentally, gossans represent intensely oxidized surficial or bedrock material, and are most intensely developed on sulphide-rich substrate. As such gossans have been used as exploration vectors in the search for significant mineral deposits in the Canadian North, including the Voisey's Bay orthomagmatic Ni-Cu-Co sulphide deposits of Labrador. Since gossans can also be developed on geological materials with sparse or nil sulphide contents, recognition of the parental material to a gossan, and hence discrimination of potentially economically significant gossans, could prove to be a significant tool for regional mineral potential evaluation. One problem with sampling gossans, however, is that they can be quite thick and/or layered, hence collection of representative material for traditional geochemical and/or petrographic determination of protolithlogy can be difficult.

We used the automated mineral analysis capabilities of the SEM-MLA system to examine: 1) gossans developed on three different lithologies, and 2) stream sediments downstream from the gossan occurrences in the HALIP exposed in western Axel Heiberg Island. The South Fiord study area is underlain by Cretaceous sedimentary rocks intruded by Carboniferous evaporate diapirs (expressed as sulphate domes) and by HALIP intrusive and extrusive igneous rocks. Gossans examined were developed on evaporite, shale-sill and shale-volcanic rock substrates. The different gossans, and in part stream sediments, are readily distinguishable in terms of sulphate, sulphide, and silicate alteration minerals as defined by the SEM-MLA. The technique appears to offer the ability to distinguish gossan protolithogies during regional surveys and thus define economic potential.

The beginning and end of metallogeny in the Labrador Central Mineral Belt; 1868 to 1064 Ma Re-Os molybdenite dates bracket the widespread polymetallic mineralization

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The Labrador Central Mineral Belt (CMB) comprises a series of six successive Proterozoic supracrustal sequences and associated Archean basement rocks that occupy a 260- by 75-km area in central to coastal Labrador. The CMB juxtaposes and contains elements of the Nain, Churchill, Makkovik and Grenville structural provinces of the Canadian Shield. The belt hosts most of the known base-metal and uraniferous deposits in Labrador, along with significant molybdenum and Rare Earth Element resources. The constituent Proterozoic sequences are the Post Hill, Moran Lake, Aillik, Bruce River, Letitia Lake and Seal Lake groups, which range in age from ca. 2000 to ca. 1225-1275 Ma. The CMB supracrustal sequences have been variously overprinted by the ca. 1900-1780 Ma Makkovikian, ca. 1710-1620 Ma Labradorian and ca. 1080-970 Ma Grenvillian orogenic events. There were also four significant plutonic events within the CMB at ca. 1895-1870, 1815-1790, 1720-1715 and 1650-1640 Ma.

We have dated molybdenite separates via Re-Os techniques from five different syngenetic occurrences across the belt which coincide with peaks in magmatism/metasomatism/metamorphism in the CMB and a set of two samples from sediment-hosted stratiform copper mineralization in the Seal Lake Group which formed as vein systems related to the Grenville Orogeny. As a complete set, these samples are brackets to CMB metallogeny. At Tom's Cove, near Makkovik, molybdenite, from a silicate skarn hosted by amphibolite rocks that are part of the ca. 1883-1865 Ma Aillik Group, has been dated at 1868.2 + 7.5 Ma; this sample also contains the most elevated Os (4395 ppb) and Re (221.2 ppm) contents of all CMB molybdenites. Molybdentite from quartz veins at the partially developed, subeconomic, Aillik Mo Deposit (11 km NE of Tom's Cove) returned an age of 1786.2 + 23.7 Ma; the sample curiously also contained the lowest Os (1.47 ppb) and Re (0.077ppm) contents of all CMB molybdenites. At the LM-12 showing, 10 km E of Tom's Cove, molybdenite from a well-developed Aillik Group-hosted stockwork was dated at 1787.4 + 7.5 Ma. A small granite cupola at Duck Island, 15 km SW of Tom's Cove, contains molybdenite within miarolitic cavities that was dated at 1665.7 + 10.1 Ma. The Burnt Lake showing, 65 km SW of Tom's Cove, contains molybdenite in ca. 1670-1650 Ma granite along its contact with Aillik Group host rocks; the molybdenite here returned a 1659.2 +6.7 Ma age. Finally, two molybdenite separates from the Whisky Lake Cu Showing (185 km SW of Tom's Cove) hosted by the 1225-1270 Ma Seal Lake Group, were dated at 1069.6 + 4.7 Ma and 1064.6 + 5.1 Ma, respectively.

Neoarchean to Paleoproterozoic evolution of the south-central Rae margin, Tehery-Wager area, Nunavut: Insights from field mapping, U-Pb geochronology, and Sm-Nd isotope data

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The Tehery-Wager area, situated along the south-central margin of the Rae craton in Nunavut, occupies an important location at the core of the Paleoproterozoic supercontinent Nuna. Supracrustal successions within this region provide insight on Nuna's crustal architecture and the factors that controlled the amalgamation of one of Earth's earliest supercontinent cycles at 1.9–1.8 Ga. The Rae craton within the Tehery-Wager area can be divided into two crustal blocks (i.e., the Mesoarchean Repulse Bay block to the east and the Neoarchean Committee Bay block to the west), the boundary of which closely corresponds to a complexly folded supracrustal belt (Lorillard belt) south of the Chesterfield fault zone. U-Pb and Sm-Nd isotope data indicate that the Repulse Bay block comprises 2.90, 2.86, and 2.71–2.66 Ga tonalitic to monzogranitic gneiss and a crustal substrate as old as 3.71–3.57 Ga. Current data for the Committee Bay block is relatively sparse, but indicate 2.71–2.70 Ga granitoid magmatism derived from source regions with 3.01–2.72 Ga Nd model ages. The intervening Lorillard belt contains diverse lithologies (e.g., quartzite, psammitic–semipelitic gneiss, iron formation, garnetite, intermediate to mafic rocks, and minor carbonate rocks) that record andesitic volcanism at ca. 2.70 Ga and broadly concomitant K-feldspar porphyritic monzogranite magmatism at ca. 2.70–2.695 Ga. Quartzite contains abundant Paleoarchean detritus (up to 3.69 Ga), which was likely derived from the Repulse Bay block. The presence of coeval 2.7 and 2.6 Ga rocks across the study area requires that the Archean blocks were amalgamated by 2.7 Ga. The extent of the Archean crustal boundary north of the Chesterfield fault zone, and by extension the Lorillard belt, is not straightforward owing to large-scale transposition associated with the Paleoproterozoic Wager shear zone.

Younger supracrustal successions contain thick white quartzite interlayered with psammitic to pelitic and mafic volcanic rocks. Lower quartzite units contain detrital zircon that yields >2.70–2.74 Ga ages, similar in age to the local Neoarchean basement. In contrast, younger detrital age peaks of 2.60–2.59, 2.31, and 1.985–1.975 Ga in overlying semipelitic rocks point to some distal source(s) for the detritus. These rocks bear lithological and detrital zircon age similarities to the Ketyet River Group, and are interpreted to record extension of the Rae margin and subsequent amalgamation of Nuna. Major fault structures interpreted to have formed during the extensional event may explain the restricted spatial distribution of these supracrustal successions across the study area.

Using integrated zircon U-Pb-Hf-O isotopes to unravel Archean crustal evolution: Example from the Southern Jilin Complex in the North China Craton

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The great technical advancements in high-precision in situ analysis of zircon U-Th-Pb, Lu-Hf and O isotopes have significantly promoted our approaches to study the origin and evolution of continental crust. Zircon Hf isotopes provide the timing of crust-mantle differentiation, and O isotopes are sensitive to low temperature processes like erosion and sedimentation. The potential of an integrated approach to trace the crust origin and evolution is explored with new zircon U-Pb-Hf-O data from the Southern Jilin Complex (SJC) in the northeast North China Craton (NCC) in this study. The SJC is comprised mainly of Archean granitoid gneisses hosting minor supracrustal rock xenoliths. Zircon U-Pb dating of granitoid gneisses and supracrustal rocks have revealed three episodes of magmatism at ~2.78, ~2.69 and ~2.58-2.53 Ga, respectively, of which the former two granitoid magmatic events are recognized for the first time in northeast NCC. All metamorphic zircons document consistent metamorphic age of 2.51-2.48 Ga, suggesting only one regional metamorphic event occurred. To minimize the possible ambiguity of interpretation caused by alteration, metamorphism and age discordance, only Lu-Hf and O isotopes of concordant magmatic zircon are integrated to trace the magma sources and crustal evolution in the SJC. Most concordant magmatic zircons, regardless of different crystallization ages, preserve "mantle-like" $\delta^{18}O_{VSMOW}$ values (<6.5‰) and dominant positive εHf values with model ages much older than the crystallization ages, suggesting the protoliths were possibly derived from reworking of aged juvenile (mafic) crust without input of recycled metasedimentary materials into the magma sources. Only minor magmatic concordant zircons show higher $\delta^{18}O_{VSMOW}$ values (6.5-10.0‰), similar to average Archean supracrustal rocks, with εHf values scattering from positive to slightly negative, suggesting a magma source that is either derived from an upper oceanic crust or a mixture of mantle-derived magma and recycled metasedimentary materials. Hf models ages from concordant magmatic zircons reveal one significant peak at 2.9-2.8 Ga and two subordinate peaks at 3.3-3.1 Ga and ~2.6 Ga. These ages reveal multi-stage crust-mantle differentiation periods. In light of the increasing recognitions of early Neoarchean rocks (~2.7-2.6 Ga) and predominate Hf model age peak of ~2.9-2.7 Ga over the NCC, it is conclusive that early Neoarchean is the most significant juvenile crustal growth period. We speculate that the NCC might be correlated to the Kenorland supercontinent based on similar extensive ~2.8-2.7 Ga crustal growth and end-of Neoarchean rifting records on other Archean cratons in the globe that constituted the Kenorland supercontinent.

Tectonic transformation from the Paleo-Pacific to west Pacific plate subduction – based on the geologic evidence of the southeastern China continental margin

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Deformation, metamorphism and magmatism on the continental margins and interiors would be much better constraints to the oceanic plate subduction/collision and or accretionary processes. Here, we refer an example to reconstruct the paleo-Pacific to west Pacific plate subduction and transformation histories based on the geologic evidence of the southeastern China continental margin.

Although the initial subduction of the paleo-Pacific plate is still in debate, in eastern China, tectonic transformation was temporally and spatially linked to the rapid formation of the Pacific plate at 180–160 Ma. The intensive deformation and metamorphism were characterized by NW–SE shortening during the period 170–165 Ma, and following that event there was magmatic activity including large volcanic eruptions.

Subsequently, sedimentation during the period 120–110 Ma was related to large-scale continental strike-slip movement, the formation of pull-apart basins, and oblique subduction and transcurrent faulting along the East Asian continental margin during the period 130–80 Ma. Meanwhile, the East Asian continent underwent east–west extension related to rollback of the paleo-Pacific Plate. The structural features, sedimentation, metamorphism, and magmatism all show that the deformation and metamorphism occurred after the Late Cretaceous in Taiwan. The marginal or back-arc basins formed during middle Cenozoic followed with the subduction of the west Pacific plate, and late Cenozoic compression and metamorphism triggered to the arc-continent collision strongly influenced the tectonic framework and the sedimentary sequences of the Taiwan region, and basaltic eruptions in eastern China continent.

Episodic subduction of the Proto-Tethyan Ocean along the NE Tibet-Qinghai Plateau: Evidence from Lajishan ophiolites and arc-related magmatism

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The Qilian orogen along the NE edge of the Tibet–Qinghai Plateau records the evolution of Proto–Tethyan Ocean that closed through subduction along the southern margin of the North China block during the Early Paleozoic. The South Qilian belt is the southern unit of this orogen and is dominated by Cambrian–Ordovician volcano-sedimentary rocks and Neoproteozoic Hualong complex that evolved as a basement of late Neoproterozoic rocks into which convergent plate margin granites were intruded during ca. 460–440 Ma. Due to structural complexity as well as lack of systematic works on petrology, geochemistry and age dating, several distinctly different models have been proposed to interpret the tectonic setting of these volcano-sedimentary rocks. Differences between these models impede understanding of the evolution of the Qilian orogen and the Proto-Tethyan Ocean during the early Paleozoic.

Spatially, Cambrian-Ordovician rocks are discontinuously distributed in the Lajishan Mts. along the northern margin of the Hualong Complex. They comprise ultra-mafic rocks, intermediate-basic lavas, gabbro-dolerites, rhyolites and minor chert, limestone and turbidites. Although these rocks are dismembered and have been dislocated by later tectonics, results of petrology, mineralogy, geochemistry and SHRIMP zircon U-Pb dating, together with our geological mapping, demonstrate that five tectonic units are juxtaposed in the Lajishan Mts. They are ca. 550–530 Ma MOR-type and ca. 530–480 Ma SSZ-type ophiolite complexes, ca. 515 and ca. 460–440 Ma volcanic arcs, and an accretionary complex. Spatially, MOR-type ophiolite is situated in the south of an accretionary complex and to the north of a ca. 515 arc. Radiolarians from the accretionary complex indicate that the ocean still existed until the end of the Ordovician. These observations indicate the likelihood that subduction of the Proto-Tethyan Ocean was south-directed during the Cambrian.

A ca. 460–440 Ma volcanic arc, consisting of andesites, dacite, rhyolite, and pyroclastic rocks, is exposed to the north of the accretionary complex. Subduction-related I-type granitoids are intruded into the ophiolite complexes and Cambrian arc. These intrusions appear to young southward across the South Qilian belt, together with ca. 460–440 Ma subduction-related calc-alkaline granitoids, which intruded into the Hualong Complex. These observations indicate that a broad continental arc developed in response to a northward subduction of the Proto-Tethyan Ocean along the southern margin of the South Qilian belt from 460 to 440 Ma. This culminated a collision between this arc and the Central Qilian belt and is evidenced by overlapping molasse deposits sourced from both terrains.

Numerical investigation into reducing mechanisms in the precipitation of unconformity-related uranium deposits

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A 2-D conceptual model is developed to address possible reducing mechanisms in the precipitation of unconformity-related uraninite deposits in sedimentary basins. A series of numerical scenarios are investigated using TOUGHREACT to examine the role of graphite zone and Fe-rich chlorite as the reducing agents in the ore genesis. It is revealed that graphite is more efficient in reducing oxidized uranium than Fe-rich chlorite, though both the reducing mechanisms can lead to the precipitation of uraninite. A uranium deposit forms in the basement either away from the fault zone or along it, and its locale appears to be controlled by a dominant downwelling convective flow and the resultant temperature and pH regimes, which is determined in turn by the orientation and hydraulic properties of the fault zone. Uraninite precipitates simultaneously with hematite in the areas experiencing the reduction of oxygen fugacity and having a temperature of 180-200°C and a pH of 2.5-4.5. Wide-spread alteration halos in the basement and around the deposit include hematite, chlorite and muscovite accompanied by minor amounts of pyrite and K-feldspar alteration.

Flotation mechanism of sulphide melt on vapor bubbles in crystal mush

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Recent published observations confirmed that when droplets of immiscible vapour and sulphide phases immersed in the third host melt are brought into contact, the sulphide liquid will attach to vapour bubbles to form compound drops owing to surface tension. However, the flotation of compound drop should also undergo the interaction with crystals as their formation are accompanied by other minerals' crystallization in crystal mush. The force balance of three-phase contact line and continuity of pressure across vapour-sulphide interface require that compound drop regulates the volume ratio between vapour and sulphide itself to ensure the equilibrium state during its initial squeeze into the pore throat among neighboring crystals. If the force balance between buoyant body forces and capillary forces permits static formation of a spherical cap of radius equal to the radius of pore throat on the top of compound drop, then its buoyancy will drive upward migration. The associated variations of radius, volumes and pressures within three-phase system are conducive to hold the equilibrium state during flotation; if 1) bulk compound drop density is less than that of interstitial melt; 2) the buoyancy force overcomes the capillary pressure; 3) the three-phase line remains static, compound drops can migrate through the cylindrical pore throat (radius equals to ~1-2 mm or less) in crystal mushes under almost all plausible circumstances. Thermodynamic models were adopted to estimate the saturation conditions of sulphide and vapour during magma evolution in the Bushveld complex, Talnakh intrusion, White Island New Zealand, and magma mixing in Farall'n Negro Volcanic complex. The results show that the nucleation of vapour commonly occurs either slightly before or simultaneous with the saturation of sulphide liquid in these systems, promoting compound drop formation in magmatic ore deposits and andesitic porphyry systems. Steady-state diffusive coarsening in magma produces mm-sized bubbles in 100-500 years, which is much larger than the size of sulfide droplets controlled by growth kinetics and settling dynamics, guaranteeing enough buoyancy to trigger the migration of compound drops. In all, the formation and flotation of compound drops are liable to occur in crystal mush, providing a feasible mechanism for the upward migration of sulphide liquid in vapour-saturated magmas.

Early Cretaceous metamorphism of the Fiordland magmatic arc, Fiordland, New Zealand

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Continental arc magmatism may be dominated by episodic high flux events (HFE) which produce tonalite to granodiorite batholiths. These crustal magmas must form at or near the mantle-crust boundary possibly in lower crustal magma assimilation storage and homogenization (MASH) zones. Metamorphism in the mid to lower crust is also episodic; however, links between HFE, the origin of intermediate magmas, and metamorphism are poorly understood. Therefore, dating metamorphism and determining pressure - temperature histories of lower crustal rocks is critical to making connections between the initiation of magmatism, emplacement, and regional metamorphism in magmatic arcs.

Fiordland, New Zealand provides a rare and ideal exposure through the root of a magmatic arc and the Paleozoic cover-sequence. The northern Fiordland transect discussed here includes the Worsley Pluton, oldest pluton of the Western Fiordland Orthogneiss (WFO), and paragneiss and orthogneiss of the Arthur River Complex (ARC). The highly deformed Paleozoic ARC was intruded by the unmetamorphosed Darran Suite plutons to the east and deformed granulite-facies WFO plutons to the south. The mid-to-lower crustal rocks of the ARC were metamorphosed during the Cretaceous possibly related to emplacement of the Worsley Pluton to the south, and, as such, provide a metamorphic record for the evolving thermal structure of the arc.

Garnet Sm-Nd ages from the Pembroke Granulite, which intruded older ARC rocks, indicate initial garnet growth from 126-123 Ma (Stowell et al., 2010). A preliminary garnet Sm-Nd age from the Camp Oven Creek Paragneiss of 118.3±1.5 Ma indicates a prolonged metamorphic event, or possibly a later metamorphic event that did not affect Pembroke garnet. The ca. 125 Ma garnet in the Pembroke Granulite overlaps with emplacement of the Worsley Pluton from 120-125 Ma (U-Pb zircon). The ca. 118 Ma garnet age from Camp Oven gneiss matches ca. 120 Ma metamorphic zircon rim data from other ARC samples, suggesting a prolonged metamorphic event throughout the ARC likely due to emplacement of the WFO.

Samples from the Camp Oven Creek Paragneiss, Milford Orthogneiss, and the Mount Edgar Diorite display prograde garnet zoning, an unusual feature in lower crustal rocks. Current work includes phase diagram modeling and thermobarometry to calculate pressures and temperatures, and garnet Sm-Nd ages from additional rocks in the ARC and from granulite facies gneisses in the Worsley Pluton. Ages from a transect through the Worsley and ARC will be used to determine the timing and extent of metamorphism in Western Fiordland.

Terrane boundaries and terrane boundary displacements: Application of Appalachian concepts to British Columbia and Yukon

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Northwestern British Columbia is underlain by rocks of the Cache Creek and Stikine composite terranes. These terranes comprise vestiges of oceanic arc, backarc basin and accreted seamounts that originated outboard of the Laurentia in the Panthalassa Ocean and were assembled at the Laurentian margin by the Middle Jurassic. The timing of interaction and the nature of the terrane boundaries between these terranes is still poorly understood. Regional and detailed mapping of the Cache Creek terrane reveals significant complexity that is not reflected in any of the terrane maps. Specifically, the northern Cache Creek terrane can be divided into three broad tectono-stratigraphic units – Late Permian to Middle Triassic arc-ophiolite, Carboniferous to Permina carbonate platform and plateau, and Late Triassic to Early Jurassic chert-silicilastic-limestone overlap assemblage. The Late Permian to Middle Triassic ophiolite is obducted onto the carbonate platform-seamount above a fundamentally important, but previously unrecognized suture zone. This suture zone is imbricated by a Jurassic thrust belt, including the Nahlin and King Salmon faults. Development of this thrust belt was finished by ca. 172 Ma, marked by emplacement of post-collisional plutonic suites.

Cretaceous deformation resulted in significant terrane displacements along the northeastern and southwestern margins of the Cache Creek terrane. Reconnaissance mapping indicates that a steep fault bounds the Peridotite Peak and Calliston Ranch massifs to the north, separating them from the Nahlin massif. This fault appears to continue to the northwest, where it generally marks the southwestern boundary of the Carboniferous to Permian Horsefeed Formation carbonates. The presence of major truncations along this fault, herein called Silver Salmon Fault, and spatial association with Cretaceous basins along strike suggest significant, but poorly unconstrained displacement sub-parallel to the Teslin fault. The Silver Salmon Fault may extend across Cache Creek-Stikinia boundary and structurally duplicate Stikinia.

Novel approaches to 3D geologic mapping using kinematic mobile laser scanning and LiDAR intensity

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Ground-based Light Detection and Ranging (LiDAR) scanning allows for rapid collection of high-resolution topography data for geomorphology research, but also provides valuable information for outcrop mapping using laser intensity data. This paper presents cases studies of geologic applications for both a new, backpack-mounted kinematic mobile LiDAR scanning field instrument (KLS) and tripod-mounted laser scanning instruments (TLS).

Our KLS system, developed at the Finnish Geospatial Research Institute (consisting of a Riegl VUX-1HA LiDAR scanner, Novatel UIMU-LCI Inertial Measurement Unit (IMU) and Flexpak6 GNSS antenna) provides ultra-high resolution topography for large areas traversed on foot or by ATV. In field studies from the Canadian High Arctic, we have collected 2500-m^2 DEMs with resolution of << 2 cm/pixel of periglacial patterned ground and ice-wedge polygons from 35 different areas that allow for surface morphometry and surface roughness analyses. These DEMs allow for characterization of periglacial processes at unprecedented scale, particularly in terms of rock shape, unit, sorting, and local slope. The instrument also allows for large-area (hectares) data collection, where gullies, fluvial channels, and large-scale outcrops can be mapped in a fraction of the time (minutes to hours) needed for tripod LiDAR scanning (hours to days), with the added benefit of better resolution and fewer data gaps (shadows). The system offers considerable improvement in data quality, collection, and processing times compared with current state-of-art techniques such as dGPS traverses, photogrammetry, and even unmanned aerial surveys (UAS aircraft and drones). Kinematic LiDAR provides direct measurement of surfaces and can penetrate vegetation, unlike photogrammetry, with better vertical resolution, smaller data volumes, and less processing time. Compared to UAS systems, which are expensive and limited by weather and remote-access operation, the KLS system provides better understanding of vertical outcrops and caves, with considerably less instrument risk and longer operating times.

We have also used traditional TLS scans for outcrop and surface mapping in multiple field projects at the Tunnunik, Haughton, and Kaali Impact Structures. In addition to topography, TLS provides useful information from intensity data that is being used for rudimentary lithology classification (informed by ground-truth geology). Combined with the KLS scans (which have a different laser wavelength), and photogrammetry, progress is being made toward spectral classification of outcrops from LiDAR scanning. The combination of LiDAR scanning methods allow for better visualization and interpretation of outcrop data in context with remote-sensing and field-geologic mapping, providing better understanding of geological models.

Cambrian to Silurian ophiolite in the northern Tibetan Plateau

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The Qiangtang terrane is a major tectonic unit of the Tibetan Plateau. Geological studies of the Qiangtang terrane have been severely limited by the poor accessibility due to its high elevation (>5000 m) and rudimentary road network. The Paleozoic ophiolites have recently been documented in the middle of the Qiangtang terrane, and they mainly occur in the W. and E. Gangma Co and Guoganjianian areas. These ophiolites are composed of serpentinite, pyroxenite, isotropic and cumulate gabbros, basalt, hornblendite and plagiogranite. Most rocks have been metamorphosed to the greenschist or blueschist facies. Whole-rock geochemical data suggest that all mafic rocks were formed in an oceanic-ridge setting. Furthermore, positive whole-rock ƒÕNd(t) and zircon ƒÕHf(t) values suggest that these rocks were derived from a long-term depleted mantle source. The data allow us to conform that these rocks represent an ophiolite suite. Zircon U-Pb dating of gabbros and plagiogranites yielded weighted mean ages ranging from 437 to 501 Ma for the W. Gangma Co ophiolite, 345 to 357 Ma for the E. Gangma Co and 345 Ma for the Guoganjianian ophiolite. The occurrence of the ophiolite suites suggests that a Paleozoic Ocean basin (Paleo-Tethys) existed in middle of the Qiangtang terrane. We hypothesize that the ophiolite in the middle of the Qiangtang terrane represents the western extension of the Sanjiang Paleo-Tethys ophiolite in the east margin of the Tibetan Plateau, and they mark the main Paleo-Tethys Ocean. The Paleo-Tethys Ocean basin probably opened in the Middle Cambrian, and continued to grow throughout the Paleozoic. The ocean was closed in the Middle to Late Triassic as inferred from the metamorphic ages of eclogite and blueschist that occur nearby. The Paleo-Tethys Ocean was probably formed by the breakup of the northern margin of Gondwana, with southward subduction of the proto-Tethys oceanic lithosphere along the northern margin of the supercontinent.

Ocean-climate system and bioevents from Hirnantian-Wenlock conodonts and integration with graptolite biozones, Cape Phillips Formation, Cornwallis Island, Canadian Arctic Islands

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Cornwallis Island in the Canadian Arctic Archipelago provides one of the world's best areas for establishing an integrated graptolite-conodont biozonation for the Late Ordovician-Silurian and likewise for interpreting ocean-climate changes given the well-exposed interfingering relationship of the basinal shale and carbonate platform facies. Results of a companion study of conodonts from the latter facies from Devon and Ellesmere islands was published in 2016 (with Mirza). Building on earlier graptolite work, 180 conodont samples were collected from nine sections of the Cape Phillips Formation, of which 118 yielded approximately 7600 conodont elements representing 54 species in 25 genera; the conodonts are exceptionally well preserved with minimal thermal alteration (conodont Colour Alteration Index value of 1). Nine conodont zones are recognized and defined for this region, namely the Amorphognathus ordovicicus, Distomodus kentuckyensis, Aspelundia expansa, As. fluegeli and Pterospathodus celloni Interval zones, Pt. a. amorphognathoides Taxon-range Zone, Pt. pennatus procerus and Kockelella ranuliformis Highest-occurrence zones, and K. ortus absidata Taxon-range Zone. These are integrated with graptolite biozones established by others (e.g., Thorsteinsson, Lenz, Melchin), with many from the same stratigraphic sections. Conodont community patterns were established previously and compared to those from correlative faunas on Anticosti Island, Quebec, with interpretations of regional eustasy patterns and the geodynamic effects of the eastern and northern collisions with Laurentia by Baltica and Peary, respectively. Paleontological and isotope geochemical studies have demonstrated the dynamic nature of the Silurian ocean-climate system and identified major faunal turnovers or events, including those from Baltica, Avalonia, and Laurentia paleoplates where many Primo (P) and Secundo (S) Episodes and specific brief Events marking faunal turnovers occurred during the Hirnantian and early Silurian. Five of these are recognized in the Cornwallis faunas and related to oceanographic and climate changes, particularly aided by oxygen isotope data ($\partial^{18}O$ using ANU SHRIMP ion microprobe, published in 2016 with Trotter and Williams) from Cornwallis conodonts: the Hirnantian mass extinction event (Ashgill), Sandvika Event (late Aeronian, Llandovery), Snipklint Primo Episode (early Telychian, Llandovery), Ireviken Event (late Telychian, Llandovery-Sheinwoodian, Wenlock) and the Mulde Event (early Homerian, Wenlock).

New insights into Ordovician stratigraphy and petroleum potential on Akpatok Island and in Ungava Bay

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Akpatok Island is one of the uninhabited Canadian Arctic islands in the Baffin Region of Nunavut and the largest island in Ungava Bay. Geologically, Akpatok Island is one of the many Ordovician outliers on the Canadian Shield and the only location where Paleozoic rocks outcrop in Ungava Bay; therefore, it plays a key role in understanding the Paleozoic stratigraphy and petroleum potential in Ungava Bay and Hudson Strait.

The carbonate sequence on the island is poorly understood; the division and correlation, and in particular the stratigraphic position of petroleum source rocks, are unclear. Following extensive sampling at different elevations from the shoreline to the top of the island, studies of numerous conodont elements from both outcrops and rubble have identified three conodont faunas through over 280 m of strata on the island, which are represented by Belodina confluens, Amorphognathus ordovicicus and Rhipidognathus symmetricus. The three conodont faunas support a new stratigraphic division, i.e. over 280 m of strata can be divided into Upper Ordovician Amadjuak, Akpatok and Foster Bay formations with ages ranging from Edenian to Richmondian, rather than just one unit (Akpatok Fm.) as previously concluded (Sanford and Grant 2000). The petroleum source rock with 4.19% total organic carbon is recognized from rubble; based on the conodonts recovered from it, it is stratigraphically located in the upper Akpatok or lower Foster Bay formations, rather than between the Amadjuak and Akpatok formations as formerly presumed (Sanford and Grant 2000). The biostratigraphy is combined with geographic information system (GIS) data in estimating the thickness of the three rock units and making a new geological map of the island. These insights resolve some fundamental stratigraphic issues in the region, and provide important information for stratigraphic correlation between the Hudson Bay, Foxe Basin and Hudson Strait areas.

On the importance of geological data for three-dimensional transient hydraulic tomography at a highly heterogeneous multi-aquifer-aquitard system

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The geostatistics-based transient hydraulic tomography (THT) has shown to be robust for subsurface heterogeneity characterization through the joint interpretation of drawdown records from multiple pumping tests. However, the spatially variable hydraulic conductivity (K) and specific storage (Ss) estimates can be smooth or even erroneous for areas where pumping/observation data densities are not high. In addition, rarely are drawdown data obtained from aquitards used in THT analysis. To investigate these issues, several approaches differing in model conceptualizations and complexities are used to simultaneously interpret drawdown data from a highly heterogeneous multi-aquifer-aquitard system at a well characterized field site located on the University of Waterloo (UW) campus. Specifically, we compare: (1) the effective parameter approach; (2) geological zonation approach relying on high resolution borehole logs; and (3) geostatistical inversion approach considering different prior information (with and without geological data). Model performances among the various approaches are compared for their abilities in capturing aquifer heterogeneity and drawdown predictions at the site. In particular, the K values estimated for each heterogeneous model are compared with permeameter-estimated K profiles along nine boreholes. The models are also rigorously assessed through the prediction of independent pumping tests not used in the calibration effort. Results reveal that the simultaneous calibration of geological models to eight pumping tests yields K values that correctly reflect the general patterns of vertical distributions of permeameter-estimated K. In addition, we find that jointly interpreting drawdown data from aquifer and aquitard layers is necessary in recovering the full heterogeneous pattern of the investigated area, and using a geological model as prior information in the geostatistical inversion approach preserves geological features and their connectivities where drawdown measurements are lacking. Overall, our results suggest the joint use of drawdown data from both aquifer and aquitard layers for THT analysis and including geological information when accurate data are available.

The mid-lower-crustal Chinese Central Tianshan: Implications for continental growth and accretionary orogenesis

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The Chinese Tianshan Belt is subdivided by several major E-W striking faults and sutures into the North Tianshan, Yili Block, Central Tianshan (CTS) and South Tianshan. The CTS Baluntai block consists of voluminous continental-arc-type intrusions and Precambrian migmatite and gneissic basement rock. The country rocks of the intrusions exhibit a broad, north-to-south increase in metamorphic grade from greenschist to amphibolite facies. It has recently been suggested that the CTS may have been part of the Paleozoic Northern Tarim active continental margin and separated from the Tarim craton by South Tianshan back-arc basins. Our study aims to determine the emplacement depths of the Paleozoic plutons and the mechanism of their exhumation, and to better understand country rock metamorphism and its relationship with the plutonic magmatism. We conducted structural analyses, zircon U-Pb dating, zircon Lu-Hf isotopic, Al-in-Hlb termobarometric and whole-rock geochemical studies on the foliated plutons, along with zircon U-Pb dating and magnetic fabric analyses on the metamorphic country rocks. The results suggest that: (1) The arc-type magmatism took place during 480 to 420 Ma. The Neoproterozoic (732 Ma) country rocks may be affected by the migmatization happened between 460 to 410 Ma. (2) The Early-Mid Paleozoic plutons and the Neoproterozoic country rocks were deformed with foliations generally dipping to the south. However, after tilt corrections the magnetic foliations are horizontal and the lineation trends are horizontally dispersed. (3) The samples from southern part of the block experienced higher-pressure conditions (5.8-7.6 kbar, 695-739°) compared to those from northern part (2.4-4.3 kbar, 667-683°). (4) The mafic-intermediate plutons exhibit a wide range of zircon εHf(t) values (-15.4 to 5.7), which broadly indicates complex melt derivation from both juvenile and evolved/old crust. We propose that at least part of the migmatization in the CTS was coeval with arc-type magmatism at mid-lower-crustal level, and may have significantly contributed to bulk magma generation. The Baluntai block was subsequently differentially uplifted along several E-W striking faults due to the closure of adjacent oceanic basins.

Joint inverse modeling of groundwater level and multi-extensometer data for improved characterization of heterogeneous aquitards

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The accurate characterization of heterogeneous low hydraulic conductivity (K) units (i.e., aquitards) play a vital role in protecting aquifers from contamination, in groundwater resources management and land subsidence investigations. Some countries are also proposing to utilize such low K units for the safe long-term storage of radioactive waste. Aquitards are typically characterized using laboratory methods, but core samples are disturbed which necessitates reliable field-based methods. In this study, we propose a new field method to characterize heterogeneous aquitards through joint inverse modeling. In particular, the classical aquitard-drainage model COMPAC (Helm, 1975) is modified to simulate the compaction process of a heterogeneous aquitard consisting of multiple sub-units (Multi-COMPAC). By coupling Multi-COMPAC with the parameter estimation code PEST++, the vertical hydraulic conductivity (Kv), elastic (Sske) and inelastic (Sskp) skeletal specific storage values of each sub-unit can be estimated using observed long-term multi-extensometer and groundwater level data. We first test our approach through a synthetic case with known parameters. Results of the synthetic case reveal that it is possible to accurately estimate the three parameters for each sub-unit. We then apply the methodology to a field site located in Changzhou city, China. Based on the detailed knowledge of stratigraphic information and borehole extensometer locations, the aquitard of interest is subdivided into three sub-units. Parameters Kv, Sske and Sskp of each sub-unit are estimated simultaneously and compared with laboratory results, bulk values of Zhuang et al. (2015) and geologic data compiled by Konikow and Neuzil (2007), demonstrating the reliability of parameter estimates. Estimated Sskp range within the magnitude of 10^{-4} m^{-1}, while Kv range over 10^{-10} - 10^{-8} m/s, suggesting the moderately high heterogeneity of the aquitard. However, the elastic deformation of the third sub-unit consisting of soft plastic silty clay is masked by delayed drainage, and the inverse procedure leads to large uncertainty in the Sske estimate for this sub-unit.

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