2023 Virtual & Field Workshop

Program & Abstracts

Canadian Tectonics Group

Division of the Geological Association of Canada

Canadian Tectonics Group
2023 Virtual Workshop

Program & abstracts

Abstracts are in presentation order;
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PROGRAM

Monday, November 13

Start time (PM, EST)	Presenter	Title
6:00	Brendan Dyck	**Keynote presentation:** Epitaxy, muscovite dehydration, and metasomatism: the life cycle of melting in an orogen
6:30	Ludovico G. Scorsolini	Tectono-metamorphic evolution of the Early-Paleozoic Laurentian margin in the Newfoundland Appalachians: Insights from the Taconic eclogites in the Baie Verte Peninsula
6:50	John WF Waldron	Mid-Paleozoic orogenesis in the Appalachian–Caledonian orogen: What drove the Acadian orogeny?
7:10	Martin Schwangler	Kinematics of the Round Head Thrust, western Newfoundland: Integrating 2D Seismic Interpretation and 3D Modelling
7:30		**BREAK**
7:50	Willem Langenberg	Dating transcurrent movements of the Rocky Mountain Trench near Golden, BC
8:10	Laurent Godin	Recent intraplate basement fault reactivation and fluvial drainage modification, Madhya Pradesh, India
8:30	Taylor Rae Morrell	Recognizing Indian Basement Faults based on Along-Strike Diachronous Metamorphism in the Himalayan Metamorphic Core of Far West Nepal
8:50	Taka Kanaya	Fluid Injection Volume Controls the Furthest Extent of Seismicity Induced by Pore Fluid Diffusion in a Shale Gas Field in Northeast British Columbia, Canada

Tuesday, November 14

Start time (PM, EST)	Presenter	Title
6:00	Daniel Coutts	Using Bayesian chronostratigraphic methods to better understand the timing of complex basin fill sequences: Nanaimo Basin, British Columbia, Canada
6:20	Joel Padgett	Low-temperature thermochronology reveals fault-controlled Cenozoic exhumation in the Upper Hyland Valley, Yukon
6:40	Adina Bogatu	Ancient Oceanic Core Complexes: Insights from Ophiolite Records
7:00	Félix Gervais	A new model for the construction of the Grenville Province in the Mesoproterozoic
7:20		**BREAK**
7:40	Fried Schwerdtner	Mesoscopic veining of high-grade gneisses and well-foliated amphibolites in the Grenville Province of central and NE Ontario: Field evidence for lithologically controlled hydrofracturing during mid- to upper-crustal regional deformation
8:00	J. Kim Welford	Crustal structure of onshore-offshore Atlantic Canada and environs from constrained 3-D gravity inversion
8:20	Lyal Harris	Archean deep transverse structures of the western Superior Province imaged by new MT data and seismic tomography: controls on critical and precious minerals
8:40	Maggie Laverge	Structural controls on gold mineralization at the Great Bear Project, Red Lake, Ontario

Epitaxy, muscovite dehydration, and metasomatism: the life cycle of melting in an orogen

Brendan Dyck[1]
[1]The University of British Columbia Okanagan, Kelowna, BC
Contact: Brendan.dyck@ubc.ca

Leucogranites and migmatites are found in the exhumed cores of most orogenic belts. Their formation has ramifications for a myriad of processes including the chemical differentiation of continental crust as well as orogenic heat budgets. In this talk, I will show how sub-grain-scale reaction mechanisms like epitaxial nucleation and fluid-assisted volume diffusion influence the life cycle of crustal melting in an orogen.

Dehydration melting of muscovite is the initially dominant mechanism of melt generation in orogenic belts. In dry siliciclastic crust, muscovite reacts with quartz to produce K-feldspar, sillimanite, and monzogranitic melt. While sillimanite and melt both nucleate on parental muscovite, peritectic K-feldspar nucleates elsewhere in the rock on existing plagioclase. This nucleation preference is a result of the lower barrier energy afforded by the epitaxy of K-feldspar on structurally similar plagioclase. At 7–8 vol.% melt generation, volume diffusion takes over as the dominant reaction mechanism. This transition to volume diffusion marks the shift from isolated domain-scale behavior to an open system on the map unit-scale (1–1000s of metres), where melt is a mobile phase.

Once mobilized, melt coalesces into veins, dykes and ultimately into bodies of leucogranite. As with muscovite dehydration melting, epitaxy and volume diffusion influence the final distribution, appearance and microstructure of these melt products. To illustrate this point, I will use an enigmatic product of crustal melting that is abundant in the Himalaya—the banded tourmaline leucogranite—typified by centimetre-scale compositional banding between tourmaline-rich and quartzofeldspathic domains. Using epitaxial orientation relationships, microstructural analysis and Rb-Sr isotopic chemistry, I will demonstrate that these banded units do not represent a direct product of melt crystallization but instead were formed by metasomatism of psammitic country rock.

The broader implication of these studies is the progression of crustal melting with attendant changes to crustal rheology and chemical differentiation can be directly tied to the progress of melting reactions. Moreover, as illustrated by the case of the banded tourmaline leucogranites in the Himalaya, field estimates based on the volume of coarse-grained leucocratic outcrop may greatly overestimate the amount of melt generated in orogenic cores.

Tectono-metamorphic evolution of the Early-Paleozoic Laurentian margin in the Newfoundland Appalachians: Insights from the Taconic eclogites in the Baie Verte Peninsula

Ludovico G. Scorsolini[1], Cees van Staal[1], Chris Yakymchuk[1], John M. Hanchar[2]

[1] *Earth and Environmental Sciences Department, University of Waterloo, Waterloo, N2L 3G1, ON, Canada*
[2] *Department of Earth Sciences, Memorial University of Newfoundland, St. John's, A1B 3X5, NL, Canada*
Contact: lgscorsolini@uwaterloo.ca

The Appalachians are a complex accretionary orogen formed mainly by the Cambrian (515 Ma) through Permian (275 Ma) closure of the Iapetus and Rheic oceans and culminated with the formation of the supercontinent Pangea. Newfoundland comprises a well-preserved cross-section of the northern Appalachians. In this exceptionally exposed transect, the evidence for the Ordovician Taconic orogeny, the earliest accretionary stage of the Appalachian orogeny, is preserved in the Baie Verte Peninsula. The Early Paleozoic Laurentian margin in the Baie Verte Peninsula underwent subduction, collision and exhumation during the Taconic orogeny. This led to the formation and preservation of high-pressure rocks such as eclogite, which is rarely present, or preserved, elsewhere in the Appalachian orogen. The complex geologic record relative to the Taconic orogeny in this area is further complicated by extensive structural and metamorphic overprinting related to subsequent, superposed orogenic cycles, such as the Salinic and the Acadian orogeneses.

This research has unveiled exceptionally well-preserved eclogite outcrops that escaped the pervasive metamorphic overprint related to later orogenic cycles and eclogites that preserved exhumation-related structures and retrograde metamorphic assemblages. This provides the opportunity to decipher the petro-structural and geochronological evolution of the eclogites, which is the key for unravelling the tectonic processes related to their subduction and exhumation. Microstructural and minerochemical analysis revealed that the eclogite high-pressure peak paragenesis was followed by four subsequent and superposed amphibole generations during metamorphic retrogression: katophorite, pargasite, hornblende, and actinolite respectively.

Phase equilibria modelling has been used to calculate isothermal P-M(H_2O) pseudosections with Theriak-Domino to assess the relevance of fluid infiltration in promoting metamorphic reactions involving amphibole growth during retrograde metamorphism. Garnet isopleth modelling was employed to constrain the metamorphic peak and part of the prograde and retrograde P-T paths.

The possible mechanisms responsible for the exhumation of the Baie Verte Peninsula eclogites will be proposed by comparing their P-T evolution with other exhumed high-pressure terrains and with numerical models. The final objective of the presentation is to illustrate how exhumation processes are captured in the structural and metamorphic record of the Taconic eclogites in the Baie Verte Peninsula.

Mid-Paleozoic orogenesis in the Appalachian–Caledonian orogen: What drove the Acadian orogeny?

John W.F. Waldron[1,2], Sandra M. Barr[2], Chris E. White[2]
[1]*Department of Earth & Atmospheric Sciences, University of Alberta, Edmonton AB Canada*
[2]*Department of Earth & Environmental Science, Acadia University, Wolfville NS Canada*
Contact: waldronjwf@gmail.com

Most orogenic events in the northern Appalachians and the Caledonides have relatively clear tectonic drivers. The Taconian-Grampian orogeny (latest Cambrian to Ordovician) represents a collision of the hyperextended Laurentian passive margin with an arc above a SE- dipping subduction zone. Salinian deformation (mainly Silurian) recorded accretion at the active Laurentian margin above a SW-dipping subduction zone, culminating in the Scandian collision of Baltica. Late Paleozoic Alleghanian deformation resulted from the arrival of Gondwana. In contrast, the latest Silurian (~423 Ma) to Middle Devonian (~385 Ma) Acadian orogeny is more difficult to interpret. It is widely attributed to Avalonia–Laurentia collision, following NW-dipping subduction recorded by the coastal igneous belt (Maine, New Brunswick, Cape Breton Island, and southern Newfoundland). Nonetheless major nappes in the Acadian orogen in southern New England are rooted to the SE. Further complicating the issue is the Quaboagian or 'Neo-Acadian' orogeny, used to describe 370–350 Ma shortening in New England that coincides with extension in Atlantic Canada. The term 'Neoacadian' has also, confusingly, been applied to earlier shortening (~400 Ma) in the Meguma terrane, during the same time interval as the Acadian in New England.

Transpression provides a potential solution to the apparent contradictions of the Acadian. In Scotland, a mismatch occurs across the Great Glen fault. To the NW, major Scandian deformation occurred, but Grampian deformation was minor. Rocks to the SE show major Grampian tectonism, but were little deformed in the Silurian. British geologists have suggested over 1000 km of sinistral slip, juxtaposing these terranes in the late Silurian to Devonian. Farther south in the British Isles, south of the traditional Silurian "Iapetus suture" a second, Acadian suture may account for the lack of Laurentian detritus in southern Britain until late in the Early Devonian.

Because of the sinuous shape of the Laurentian margin, sinistral shear would have caused transpression in the Appalachians, consistent with sinistral Acadian shear zones in Newfoundland, Cape Breton Island, Maine, and southern New England. Convergence may have brought West Avalonia into collision with the NW-dipping subduction zone that fueled the coastal igneous belt, but the location of the Meguma terrane at this time is uncertain. Collapse of the Mascarene backarc led to the vergence change responsible for the southern New England nappe pile. A change to dextral motion in the mid-Devonian led to continued Quaboagian transpression in New England but transtension in Atlantic Canada.

Kinematics of the Round Head Thrust, western Newfoundland: Integrating 2D Seismic Interpretation and 3D Modelling

Martin Schwangler[1], John W.F Waldron[1]
[1]University of Alberta, Department of Earth and Atmospheric Sciences
Contact: schwangl@ualberta.ca

The Round Head Thrust demarcates the structural front of the Appalachian orogen in western Newfoundland and may play a pivotal role in understanding the kinematics during orogen formation. The Round Head Thrust exhibits a complex history of normal faulting early in the Ordovician Taconian orogeny, followed by "thin-skinned" emplacement of the Humber Arm Allochthon. Subsequent "thick-skinned" thrusting led to inversion, probably in the Devonian Acadian orogeny. Variably oriented open folds in the hanging wall dominate the map pattern at the topographic surface, and probably resulted from movements of the Round Head Thrust. However, despite its significance, the fault's precise movement direction has remained enigmatic.

Leveraging 2D seismic lines, from oil exploration efforts in the area, we generated a detailed provisional 3D model of the Round Head Thrust and the associated hanging-wall and footwall stratigraphy. Our interpretation revealed that three distinct fault-bounded "horses" underlie the Round Head Thrust, potentially moving in different directions. Using restoration techniques in plan view, we deduced precise movement directions of these lower thrusts. To do this, we focused on the restoration of a single horizon, whose extent is defined by the cutoff lines in each thrust. Our analysis shows hanging wall movements of the Round Head Thrust towards ~303° azimuth (NW). Subsequent, in-sequence thrusting events driving two horses beneath the Round Head Thrust footwall between 300° and 340° azimuth). The second horse displayed a clockwise rotational component, while the third horse experienced a northward thrust movement with only minimal displacement. This deduction not only resolves the historical uncertainty surrounding movement direction on the Round Head Thrust but also helps to explain the resulting flexure of the hanging wall.

Our findings underscore the effectiveness of integrating seismic imaging with advanced 3D modelling and restoration efforts to unravel kinematics. It also exemplifies a robust methodology applicable to analogous geological settings worldwide to solve unanswered kinematic questions. The insights we gathered in this study significantly advance our understanding of the regional tectonics within the Appalachian orogen of western Newfoundland.

Dating transcurrent movements of the Rocky Mountain Trench near Golden, BC

Willem Langenberg[1], Kyle Larson[2], Stephen Johnston[1]
[1]EAS, University of Alberta, Edmonton, AB
[2]DEEGS, The University of British Columbia, Kelowna, BC
Contact: cwlangen@telus.net

Two samples with dextral slicken-fibres were collected along the southern Rocky Mountain Trench near Golden, BC. Sample WL23-2 was collected from a grey faulted carbonate 54 km Northwest of Golden. Sample WL23-4 was collected from a phyllitic limestone of the McKay Group 28 km east of Golden along the "White River Lineament" adjacent to the Southern Rocky Mountain Trench. This sample shows dextral slicken-fibres overprinting dip-slip slicken-fibres. Calcite U-Pb geochronological analysis of these slicken-fibres was carried out via laser ablation inductively coupled plasma mass spectrometry in the Fipke Laboratory for Trace Element Research (FiLTER) at the University of British Columbia, Kelowna. Unfortunately, the general lack of U in these calcite fibres precludes the calculation of precise intercept ages. Nevertheless, the ages obtained appear to have significance in the general geological setting.

Ninety spot analyses of dextral slicken-fibres of sample WL23-2 average 0.04 ppm U and define a low precision, lower intercept age of 30 ± 190 Ma (Figure 1).

Seventy spot analyses of older dip-slip slicken-fibres (older than the dextral slicken-fibres) in sample WL23-4 average 0.3 ppm U and define a lower intercept age of 53 ± 49 Ma.

Though these preliminary dates are low precision, they are broadly consistent with previous suggestions that thrusting in the Golden area terminated circa 60 million years ago and that later dextral transcurrent movement of the Rocky Mountain Trench was ongoing by ca. 30 Ma (Oligocene). The context of these low precision ages will be further discussed.

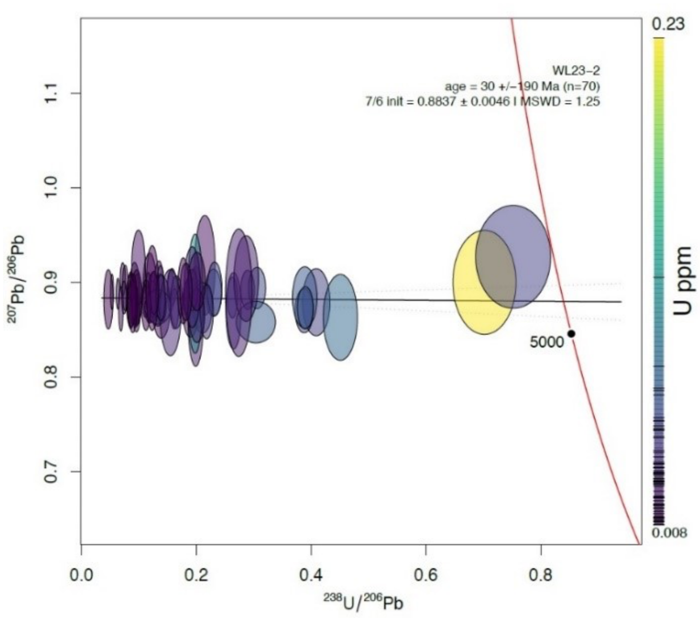


Figure 1. Tera-Wasserburg plot of WL23-2.

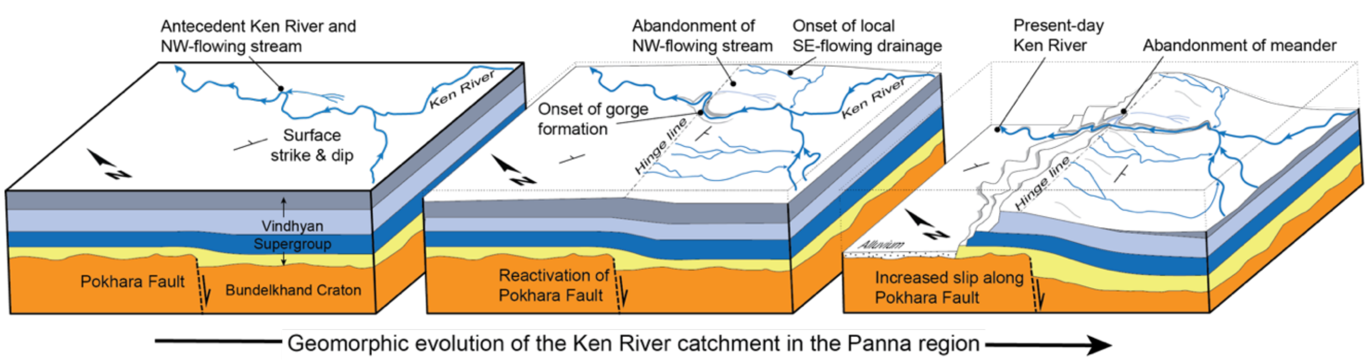
Recent intraplate basement fault reactivation and fluvial drainage modification, Madhya Pradesh, India

Laurent Godin[1], Brendan Crilly[1], Lindsay M. Schoenbohm[2], Joshua Wolpert[2]
[1]Department of Geological Sciences & Geological Engineering, Queen's University, Kingston, ON
[2]Department of Chemical and Physical Sciences, University of Toronto, Mississauga, ON
Contact: godinl@queensu.ca

North-central India is underlain by three northeast-trending paleo-topographic ridges of Precambrian Indian basement, bounded by lithospheric-scale basement faults. The Pokhara Fault defines the eastern edge of the Faizabad ridge. Near Panna, Madhya Pradesh, the Pokhara Fault coincides with a monocline developed in the Proterozoic Vindhyan Supergroup rocks along the Archean Bundelkhand cratonic margin. Fluvial morphology of basins along the monocline, as well as a deeply incised abandoned meander preserved where the Ken River flows through the monocline, are investigated to assess potential linkages with active basement fault reactivation.

Normalized steepness indices in analyzed channel profiles along the monocline increase significantly downstream, with some channels exhibiting convex, over-steepened segments. Normalized steepness indices, knickpoint elevations, and incision depths are much higher in streams along the southwest segment of the monocline. Most channel profiles exhibit a knickpoint with slope-break morphology. The longitudinal channel profiles exhibit characteristics of a fluvial system in a transient state subjected to an increase in rock uplift that intensifies to the southwest over a reactivated basement fault. Using previously published relationships between erosion rates and channel steepness, we conservatively estimate the onset age of monocline growth to be Plio-Quaternary. Fluvial geomorphic features preserved near Panna also suggest that the Ken River is an antecedent river. The incised meander feature near the crest of the monocline appears to be the abandoned river valley of a former Ken River course that was orphaned during the evolution of the landscape by what is now the present-day Ken River.

Our study supports growing evidence that such Indian basement faults have recorded multiple periods of reactivation, control the geometry of the Ganga foreland basin and the ramp-flat geometry of the basal Main Himalayan Thrust, localize east–west extension resulting in the Tibetan graben and, ultimately, contribute to lateral variability in tectonic evolution along the Himalayan orogen's strike. Recent fluvial modification in the Panna region demonstrates that Indian basement faults are also active on the south side of the Ganga Basin, far south of the Himalayan deformation front, and may be linked to intraplate seismicity and active tectonic modification of the landscape.



Recognizing Indian Basement Faults based on Along-Strike Diachronous Metamorphism in the Himalayan Metamorphic Core of Far West Nepal

Taylor Rae Morrell[1], Laurent Godin[1], Renaud Soucy La Roche[2], John Cottle[3]
[1] *Department of Geological Sciences & Geological Engineering, Queen's University, Kingston, ON, Canada, K7L 3N6*
[2] *Centre Eau Terre Environnement, Institut national de la recherche scientifique, Québec, QC, Canada, G1K 9A9*
[3] *Department of Earth Science, University of California, Santa Barbara, California, 93106-9630, USA*
Contact: 15trim@queensu.ca

The geometry of the basal detachment of the Himalaya, the Main Himalayan Thrust (MHT), significantly controls the evolution of the overlying Himalayan Orogen. The MHT geometry can be modified along-strike by the reactivation of pre-orogenic faults rooted in the underthrusted Indian plate during orogenesis. The location and reactivation episodes of Indian basement faults are ascertained using the metamorphic record of the overlying Himalayan metamorphic core as a proxy for the evolution of the MHT geometry through time.

The MHT in far west Nepal contains a present-day MHT lateral ramp that coincides with the northward projection of an Indian basement fault, the Great Boundary Fault. Far west Nepal is consequently an ideal location to link the evolution of the Himalayan metamorphic core with the development of the MHT lateral ramp and reactivation of the Great Boundary Fault.

New pressure-temperature-time-deformation data along the Seti Khola in far west Nepal is compared with the published tectonometamorphic evolution along the adjacent Karnali river valley, on the eastern side of the modern MHT lateral ramp. Quartz <c> axis crystallographic preferred orientation results in addition to field observations are used to compare equivalent structural levels of the Seti Khola samples with the Karnali valley results.

Prograde metamorphism along the Seti Khola initiated at ca. 39 Ma, as recorded by monazite petrochronology. Peak metamorphic conditions of 645-745°C and 0.85-1.1 GPa were reached at 28-22 Ma along the Seti Khola, 10-14 Myr prior to the Karnali valley, indicating segmentation of the Himalayan metamorphic core across the MHT lateral ramp. It is postulated that such segmentation is the result of the Himalayan metamorphic core thrusting over differing ramp-flat geometries on either side of the MHT lateral ramp. The segmentation and change in MHT geometry are interpreted to be caused by the reactivation of the underthrusted Great Boundary Fault during the Oligocene to earliest Miocene. The comparison of tectonometamorphic histories along-strike in far west Nepal helps to define the MHT geometry changes through time and highlights the necessity to consider the pre-orogenic structural features of the plates involved when evaluating orogenic evolution.

Fluid Injection Volume Controls the Furthest Extent of Seismicity Induced by Pore Fluid Diffusion in a Shale Gas Field in Northeast British Columbia, Canada

Taka Kanaya[1], Yajing Liu[1], James D. Kirkpatrick[1], Marco P. Roth[2], Rebecca M. Harrington[2]
[1]McGill University;
[2]Ruhr University Bochum
Contact: taka.kanaya@mail.mcgill.ca

Fluid injection from hydraulic fracturing resulted in seismicity along pre-existing faults within the Montney and adjacent formations in the Kiskatinaw area of the Western Canada Sedimentary Basin. We analyze the detailed space-time progression of fluid injection and previously catalogued seismicity in a two-km^2 gas field with seven horizontal wells stimulated in stages over a nine-day period. Injection-induced seismicity forms 35 spatiotemporally distinct clusters along several reactivated fault segments. Individual seismicity clusters show distinct parabolic time-distance (*t-r*) diffusion profiles, with a median time lag of ~8±4 hours from the nearest injection sequences. Furthermore, the space-time distances between all possible pairs of 351 earthquakes and 187 injections display approximately a common *t-r* envelope. Comparison with results from poroelastic modelling suggests that the observed *t-r* envelope is consistent with pore pressure diffusion and a uniform permeability of ~10^{-14} m^2 (i.e., characteristic of highly fractured rocks) within both fault zones and the surrounding formations. Most importantly, our modelling results indicate that the furthest extent of seismicity induced by pore pressure diffusion is controlled primarily by the total volume of injection (within a several-hours-long injection sequence), rather than the injection rate or the formation permeability (tested in the range of 10^{-12} to 10^{-17} m^2). Analyses of the injection-seismicity distances for four additional, nearby shale gas fields with varying total injection volumes demonstrate that the furthest extent of seismicity is also proportional to the total injection volume at each site. Our results suggest that reducing the total 'effective' injection volume through maximizing the time intervals between individual injection stages (e.g., evenly distributing injection stages throughout the entire hydraulic operation) may limit the spatial extent of induced seismicity.

Using Bayesian chronostratigraphic methods to better understand the timing of complex basin fill sequences: Upper Nanaimo Group, British Columbia, Canada

Daniel Coutts[1], Stephen Hubbard[2], Rebecca Englert[2], Peter Ward[3], William Matthews[2]
[1]Geological Survey of Canada, 3303 33 Street NW, Calgary, Alberta, Canada, T2L 2A7
[2]Department Geoscience, University of Calgary, 2500 University Drive NW, Calgary, Alberta, Canada, T2N 1N4
[3]Department of Biology, Western Washington University, 516 High St, Bellingham, Washington, United States, 98225
Contact: daniel.coutts@nrcan-rncan.gc.ca

Analysis of orogenic systems and their associated basins often rely on chronological data (biostratigraphy, geochronology, magnetostratigraphic) integrated with numerous field and subsurface measurements. Integrating these datasets however can be challenging, as chronologic constraints come in many form (geochronlogic, magnetostratigraphic, or biostratigraphic), have varying uncertainties, and cover large spatial areas.

Bayesian age models, first demonstrated by Johnstone et al. (2021, Frontiers in Earth Science) have only been applied to individual single stratigraphic columns. Here, we construct a novel, chronostratigraphic framework for three transects through the Late Cretaceous-Paleocene units of the Nanaimo forearc basin in western British Columbia, Canada, revealing unparalleled detail into long-term sedimentation processes along a deep-water convergent margin. Additionally, we use the method to validate our use of detrital zircon maximum depositional ages as accurate constraints on depositional timing.

The age and longevity of individual slope-channel systems is determined by constructing a Bayesian Monte Carlo numerical model where biostratigraphic and magnetostratigraphic measurements are used to place additional age constraints on 37 detrital zircon maximum depositional ages. Important context for the refined depositional ages is provided by a detailed stratigraphic dataset composed of 2200 m of measured stratigraphic section and 4207 paleoflow measurements, which demonstrate the facies, architecture, distribution, and orientation of twelve slope-channel systems. Our results reconstruct the spatio-temporal evolution of coarse-grained deep-water sediment-routing along the paleo-margin and enable the timing of sedimentation to be compared with hinterland and forearc processes. This integrative approach demonstrates that submarine channel-system deposits of the upper Nanaimo Group cluster into three long-lived fairways (8-18 M.y.), each with a unique depositional history. Along-strike variations in the timing of sediment routing, channel-system architecture, and channel-system orientation are interpreted to be driven by local subsidence, magmatism, and subduction-related processes. We show how Bayesian age models can be applied at a basin-scale to produce robust chronostratigraphic frameworks for deciphering basin evolution and providing valuable insight into long-term geodynamic processes.

Low-temperature thermochronology reveals fault-controlled Cenozoic exhumation in the southeastern Yukon

Joel Padgett[1], Eva Enkelmann[1], Dawn A. Kellett[2], David Moynihan[3]
[1]Department of Earth, Energy, and Environment, University of Calgary, Calgary, AB.
[2]Geological Survey of Canada, Dartmouth, NS.
[3]Yukon Geological Survey, Whitehorse, YT.
Contact: joel.padgett@ucalgary.ca

The Upper Hyland fault in the Selwyn Fold Belt is one of many assumed-Cretaceous N- NW-striking dextral faults in the Northern Canadian Cordillera. However, we lack information on the kinematics and timing of Cretaceous and younger structures in this region. Here we use low-temperature thermochronology and inverse thermal history modelling to quantify the timing and magnitude of exhumation in the Upper Hyland valley and to investigate the relationship between exhumation and faulting. Other faults in the area include the Shannon fault and the Hyland Valley fault, which strike sub-perpendicular to, and are inferred to connect with, the Upper Hyland fault.

We analyzed 26 samples and present 19 new apatite (U-Th)/He ages, 10 apatite fission track ages, and 15 zircon (U-Th)/He ages. Apatite (U-Th)/He ages range 91–41 Ma, apatite fission-track ages range 64–45 Ma, and zircon (U-Th)/He ages range 97–51 Ma. The youngest ages were obtained from the inferred hanging wall of the Shannon fault and footwall of the Hyland Valley fault. Inverse thermal history modelling suggests coeval pulses of rapid cooling (~13 °C/Myr) in these areas ~60–50 Ma. Samples yield similar cooling histories east and west of the Upper Hyland fault suggesting no differential exhumation occurred across this structure during the Cenozoic.

We suggest that exhumation in the Upper Hyland valley was driven by dextral motion on the Upper Hyland fault. This displacement reactivated the Hyland Valley fault and Shannon fault as a normal and reverse fault, respectively, resulting in ~3–5 km of exhumation. The timing of fault reactivation in the Upper Hyland valley, ~60–50 Ma, is coeval with dextral motion on the Tintina fault, a lithospheric-scale dextral fault that strikes parallel to the Upper Hyland fault ~150 km to the west. We suggest that the early development of the Tintina fault reactivated preexisting structures in the Upper Hyland valley. Deformation ceased in the early Eocene, possibly due to strain localization along the Tintina fault.

Ancient Oceanic Core Complexes: Insights from the Ophiolite Record

Adina Bogatu[1], Alain Tremblay[1], Jean H. Bédard[2], Alex Zagorevski[3], Loïc Labrousse[4]
[1]Geotop, Université du Québec à Montréal (UQAM), Montréal, QC
[2]Geological Survey of Canada, Québec, QC
[3]Geological Survey of Canada, Ottawa, ON
[4]Sorbonne Université (SU), Paris, France
Contact: bogatu.adina@gmail.com

Oceanic core complexes (OCCs) are domiform extensional tectonic structures exposing upper mantle and lower crustal gabbroic material. OCCs mostly form at slow to ultraslow-ridge segments during intermittent magmatic activity. Ophiolites, segments of ocean crust and mantle tectonically exposed on land by obduction (overthrusting), have the potential to preserve and expose ancient OCCs. The Atlin terrane ophiolites (Canadian Cordillera) have a non-Penrose pseudostratigraphy. The interface between upper crust and mantle is superbly exposed in the Squanga Lake ophiolite (SLO) of the Atlin terrane, where a 20 m-wide, shallowly SE-dipping, serpentinite shear zone (Squanga Lake Detachment Zone, SLDZ) separates lherzolitic mantle from faulted and brecciated panels of upper crustal gabbros, sheeted dykes, volcanics, chert and limestone. The SLDZ includes m-sized blocks of ultramafic cumulates, massive gabbro, and basalt fragments. Gabbro dykes are injected into the SLDZ, but locally are affected by shearing, suggesting syn-deformation magmatism along the mantle/crust contact. Recent research suggests that the non-Penrose geometry at the Squanga Lake Ophiolite could represent an ancient OCC. In the Mirdita ophiolite (Dinaro-Hellenic Alpine fold belt), the Western-type massifs consist of harzburgitic to lherzolitic mantle in tectonic contact with upper crustal basalts and locally gabbro dykes and tens of meter-scale pods of gabbro. This geometry has been interpreted to be a preserved OCC, where mantle and crustal rocks are separated by structures of the Mirdita Detachment System (MDS). The upper part of the mantle sequence and the lower crust display zones of lithospheric ductile flow 10s of m wide, where amphibolitized layers of crustal and mantle rocks are affected by intense NNW to NE dipping ductile shearing. The amphibolite layers are locally associated with cataclastic breccias developed within surrounding peridotite, gabbro and basalt. The amphibolite-breccia complexes are interpreted as slivers of crust/mantle entrained into syn-oceanic extensional detachments. The ductile foliation is offset by NE steeply dipping normal faults which are possibly also syn-oceanic. Although Mirdita Detachment System and Squanga Lake Detachment Zone originated during distinct geological epochs, both exhibit a continuum of progressive deformation and alteration compatible with exhumation. This continuum spans from ductile (i.e., mylonite, schists) to brittle (i.e., cataclasite, breccia) and from upper- to lower-amphibolite facies (838 °C-602 °C). This pattern is a distinctive hallmark of extensional detachment systems formed within Oceanic Core complexes.

A new model for the construction of the Grenville Province in the Mesoproterozoic

Félix Gervais[1], Alexandre Beaudry[1], Charles Kavanagh-Lepage[1], Abdelali Moukhsil[2], Kyle P. Larson[3], Carl Guilmette[4]

[1] Département des génies civil, géologique et des mines, Polytechnique Montréal, Montréal, QC, Canada;

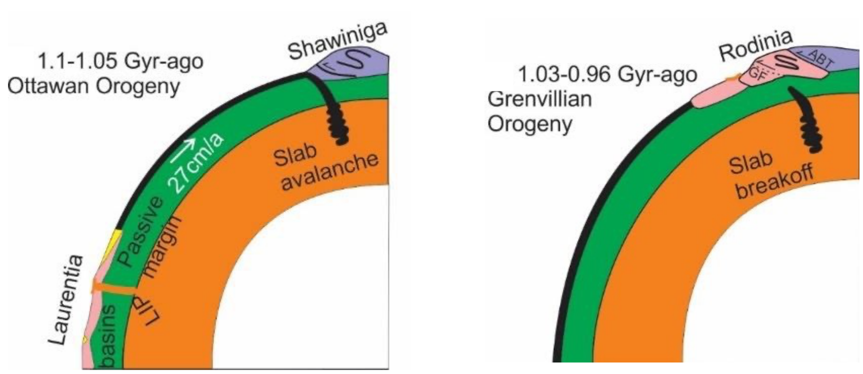
[2] Direction de l'acquisition des connaissances géoscientifiques, Ministère des Ressources naturelles et des Forêts, Québec, QC, Canada;

[3] Earth, Environmental and Geographic Science, University of British Columbia, Kelowna, BC, Canada;

[4] Département de Géologie et Génie Géologique, Université Laval, Québec, QC, Canada;

Contact: felix.gervais@polymtl.ca

The actual Laurentian-centred paradigm for the construction of the Grenville Province during the Grenvillian Orogeny involves a protracted phase of Andean-style tectonism between ca. 1.8 and 1.15 Ga followed by a continental collision with another craton, postulated to have been Amazonia, at ca. 1.1 Ga. In this contribution, we argue that this model is incompatible with several key geological datasets from the >1000 km along-strike exposure of the Grenville Province in Quebec, such as: 1) the absence of Mesoproterozoic igneous rocks in Archean basement of the Parautochtonous Belt (PB); 2) the absence of basement exposure in the Allochthonous Belt (AB); 3) the largely juvenile signature recorded in igneous rocks of the AB; 4) the absence of Ottawan igneous or metamorphic ages in the PB. At the continental scale, this model is further incompatible with: 5) the development of the Midcontinent Rift in the hinterland of the proposed collision zone and major rift basins in the Arctic synchronously with continental collision; 6) the marine origin of the sediments deposited in the Midcontinent Rift; 7) paleomagnetic data indicating migration of Laurentia at velocities in excess of 20 cm/yr, which is incompatible with an upper plate setting, yet with a collision. We present a completely revised model for the construction of the Grenville Province that resolves all these inconsistencies. In contrast with the current paradigm, our model involves the construction of a newly revealed continent, which we name Shawiniga, by amalgamation of oceanic arcs/backarcs (perhaps also with another Archean craton, such as Amazonia) far away from Laurentia. A continental arc did develop on this amalgamated continent, but it was during the Ottawan phase of the Grenvillian Orogeny (1090-1060 Ma), which was previously considered as the main continental-collision phase. We argue that the driving force for this event was a slab avalanche process (sudden sinking of a subducted oceanic plate into the lower mantle) that exerted a strong pull on Laurentia, putting it under extension and dragging it rapidly towards Shawiniga. The final collision between this continent and Laurentia occurred at ca. 1.03 Ga and marked the final assembly of Rodinia, further explaining the protracted melt-present ductile flow between 1010-960 Ma that we have been documenting throughout the PB.



Mesoscopic veining of high-grade gneisses and well-foliated amphibolites in the Grenville Province of central and NE Ontario: Field evidence for lithologically controlled hydrofracturing during mid- to upper-crustal regional deformation

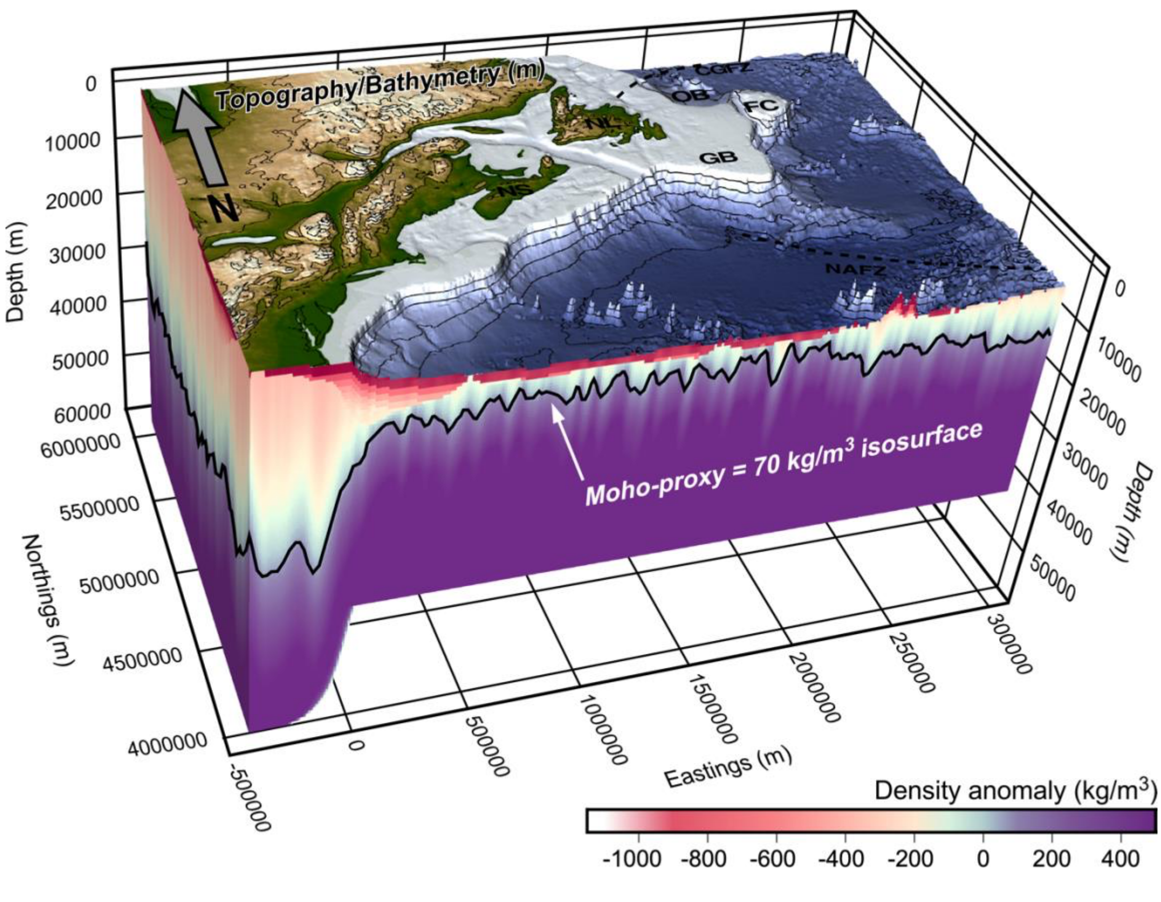
W.M. Schwerdtner[1], D.H. Waddington[2], Anjali Jarvis[1], Lingfei Liu[1], Fannie Yiu[1]
[1] *Department of Earth Sciences, University of Toronto*
[2] *Geological consultant (retired), Toronto, Ontario*
Contact: fried.schwerdtner@utoronto.ca

By means of analogue modelling and detailed field work, structural geologists have recently shown that mid- to upper-crustal hydrofracturing, also called natural hydraulic fracturing, results in vein arrays with 'chaotic' 3D geometry. We have identified 3D arrays of nonfibrous 'chaotic' veins in several parts of the westernmost Grenville Province (Ontario), notably the Parautochthonous Belt of the Sudbury-North Bay region. Here, we focused closely on clean road cuts across deformed units of banded gneiss and well-foliated amphibolite replete with interconnected irregular veins of biotite, quartz or quartz-feldspar. Except in major high-strain zones, the hydrofracturing and 'chaotic' veining are commonly restricted to mafic rocks comprising mesoscopic boudins or dismembered isoclinal folds. This suggests that much of the selective hydrofracturing occurred while felsic gneisses hosting deformed amphibolite layers underwent solid-state ductile flow. Southeast of Sudbury, the hanging wall of the Wanapitei Igneous Complex includes a body of highly deformed potassic pegmatite mined for feldspar crystals about 100 years ago. Well-exposed in a clean road cut along Hwy. 537, this pegmatite is replete with 1 – 3 mm thick, closely-spaced, biotite veins ranging in length from a few centimeters to 1 meter. At first glance, the vein pattern appears to be chaotic in most of the road cut. Closer inspection reveals, however, that some of the largest biotite flakes occupy arcuate fracture surfaces outlining mesoscopic lozenges akin to triaxial foliation boudins. Other large biotite flakes decorate bent cleavage surfaces in variously-oriented, 10 – 100 cm-scale feldspar crystals. The sum of our field observations points to tectonically aided, natural hydrofracturing and migration of metamorphic fluids, probably at different times during the Grenvillian Orogeny.

Crustal structure of onshore-offshore Atlantic Canada and environs from constrained 3-D gravity inversion

J. Kim Welford[1]
[1]Department of Earth Sciences, Memorial University of Newfoundland, St. John's, NL
Contact: kwelford@mun.ca

Atlantic Canada encompasses geological evidence of the orogenic and rifting episodes that inspired the development of the theory of plate tectonics and the fundamental concept of the Wilson cycle. To provide a regional crustal-scale view that can complement surface mapping studies and sparse seismological investigations, an onshore-offshore 3-D constrained gravity inversion methodology is proposed involving incorporation of topography and an inversion mesh that is laterally variable in terms of its maximum depth extent. A 3-D density anomaly model for the entirety of Atlantic Canada and its environs is generated, with the inverted density distribution structure and extracted isodensity surfaces showing excellent correspondence with independent and co-located controlled source and passive seismic constraints. The full density model and crustal thicknesses from this work will ultimately be used for further study of present-day structures and as inputs for deformable plate reconstruction modelling.



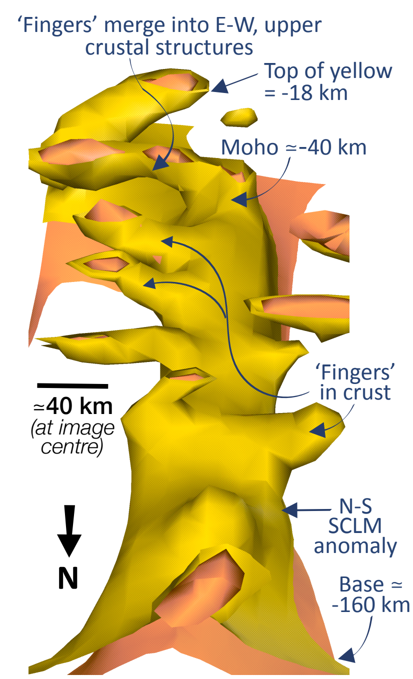
Archean deep transverse structures of the western Superior Province imaged by new MT data and seismic tomography: controls on critical and precious minerals

Lyal B. Harris[1], Wule Lin[2], Adam Schultz[3], Parham Adiban[1], Jean H. Bédard[4,1]
[1]Institut national de la recherche scientifique, Centre Eau Terre Environnement, Québec, QC
[2]China University of Geosciences, School of Geophysics and Geomatics, Wuhan, China
[3]College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR, USA
[4]Geological Survey of Canada, Québec, QC
Contact: lyal.harris@inrs.ca

There is increasing evidence worldwide incompatible with Archean subduction/arc accretion, the conventional model for formation of the N American Superior Province. A non-plate-tectonic model of Neoarchean rifting of the Mesoarchean Hudson Bay Terrane and regional deformation by cratonic mobilism due to mantle traction was proposed by Bédard and Harris. E-W trending Archean sub-province boundaries and sub-parallel structures in the western Superior have long been thought to represent its lithospheric-scale architecture and to localise mineralisation. Geophysical data enhanced in our study, however, show that transverse, deep crustal and upper mantle (SCLM) structures have played a significant, hitherto unrecognised role, and that their formation and timing are incompatible with previous plate tectonic models. A Metal Earth-NRCan seismic study likewise concluded Superior basement was autochthonous and that there was no evidence for subduction, but the transverse structures identified were interpreted as Proterozoic.

Depth-slices and 3D isosurfaces from an inversion of EarthScope USArray combined with *all* Lithoprobe data show alternating N-S trending resistive | conductive SCLM domains north of the Wabigoon Subprovince; these broaden, deepen and swing to the NW-SE southwards. Deep-source aeromagnetic images of the mid-lower crust show parallel N-S faults intersecting concentric features (N of the area covered by MT data). Finger- and mushroom-shaped conductive zones rise obliquely from N-S trending SCLM anomalies, forming a complex, inter-digitating pattern in the crust (3D-image on right); many Au deposits, e.g., Red Lake, Hemlo, Cameron Lake, Beardmore-Broadbank, occur above these zones or their flanks.

2D and 3D P-wave seismic tomographic images of western Superior SCLM (data provided by T. Bollmann, Northwestern University) depict a high velocity western domain, a low velocity eastern domain, and an intervening transition zone. N-S to NW-SE faults are again interpreted. Several major Ni-Cu-Pt-Pd±Cr deposits and carbonatites overly the irregular margins to smaller high velocity domains in the central zone or above the interpreted regional transverse faults separating domains. No regional E-W accretionary terrane boundaries were identified.



3D, oblique S-looking view of high conductivity MT isosurfaces, NW Superior

Results provide compelling evidence for Archean formation and preservation of: (i) a autochthonous Mesoarchean SCLM terrane boundary, reactivated as a transfer zone during Neoarchean rifting and (ii) younger SCLM and deep crustal extensional structures formed during extension and mantle upwelling; both sets of structures are at high angles to those mapped at the surface. Our resulting mineral system model showing fluid/magma migration paths from SCLM to the upper crust has potential to generate new exploration targets for critical and precious minerals.

Structural controls on gold mineralization at the Great Bear Property, Red Lake, Ontario

Margaret Laverge[1], Bruno Lafrance[1], Stefanie M. Brueckner[2], Wieland H. Boehme[2], Jack Simmons[1], Rick Greenwood[3], Juan C Ordóñez Calderón[3]
[1]Mineral Exploration Research Centre, Harquail School of Earth Sciences, Laurentian University, Sudbury, ON, Canada P3E 2C6
[2]Department of Earth Sciences, University of Manitoba, Winnipeg, MB, Canada R3T 2N2
[3]Kinross Gold Corporation, Toronto, ON, Canada M5J 2V5
Contact: mlaverge@laurentian.ca

The Great Bear property, located south of the productive Red Lake gold camp (>29 Moz gold) in the NW Superior craton, is host to a new world-class structurally controlled gold deposit with a combined resource estimate of 5.0 Moz Au. The property consists of two distinct lithological domains separated by a NW-SE trending, crustal-scale fault, known as the LP Fault. The felsic northeastern domain of greenschist to amphibolite facies, metasedimentary rocks, metavolcanic rocks and subvolcanic porphyries, while the southwestern domain is characterized by greenschist facies mafic volcanic rocks. Mineralization occurs in the northwestern domain as foliation-controlled disseminated gold and within foliation-parallel and oblique quartz veins (LP Zone). In the southwestern domain, gold is hosted in silica-sulphide replacement in the limb (Limb Zone) and within quartz veins in the hinge (Hinge Zone) of a regional scale fold.

Along the LP Fault, the main structures consist of an early foliation, lineation and isoclinal folds, and a later generation of Z-shaped, tight-to-isoclinal, folds with a locally developed, steeply-dipping, axial planar crenulation cleavage. The early foliation is NE-SW striking, steeply dipping, and penetrative across the property. A moderately to steeply plunging, NE to SE-trending, stretching lineation lies along the foliation and is defined by stretched feldspar phenocrysts in intrusions and aligned micas in metasedimentary rocks. The early foliation is axial planar to mm-dm scale isoclinal folds that transpose bedding. The later Z-shaped folds strike E-W and are associated with steeply dipping dextral shear bands overprinting the early foliation.

The development of structures along the LP Fault may be explained by (1) early thrusting along the early foliation followed by late dextral transcurrent faulting or (2) a single long-lived dextral transpressional event. More competent mafic dykes within the LP Fault Zone contain a steeply dipping foliation oriented anticlockwise to the main early foliation along the fault. The steep plunge of the stretching lineation along this oblique foliation, together with dextral asymmetrical strain shadows on the horizontal surface around vertically stretched quartz phenocrysts in strongly deformed intrusions, indicate simultaneous vertical extension and transcurrent movement consistent with dextral transpression. Thus, gold mineralization within the LP Fault Zone was likely emplaced during a major regional dextral transpressional event, which also resulted in the formation of the structures controlling the orientation and geometry of the gold-bearing zones.

Abstracts
2023 CTG fall field workshop poster session

October 20th – 22nd, Grenville Province, Lac Bouchette, Québec

Organised by Renaud Soucy La Roche,
Institut national de la recherche scientifique and the
Ministère des Ressources naturelles et des Forêts du Québec

An introduction to the geology and structure of the Lac Bouchette area

Renaud Soucy La Roche[1], Eve Gosselin[1], Yannick Daoudene[2]

[1]Centre Eau Terre Environnement, Institut national de la recherche scientifique, 490 rue de la Couronne, Québec, Canada, G1K9A9
[2]Direction de l’acquisition des connaissances géoscientifiques, Ministère des Ressources naturelles du Québec, Quebec, Canada
Contact: Renaud.soucy_la_roche@inrs.ca

The Grenville Province is best known for amphibolite to granulite facies metamorphic rocks and high-temperature (>650°C) shear zones typical of deformation in the deep to middle crust during the Mesoproterozoic. Other styles of deformation are present near Lac St. Jean, Quebec. The Lac Bouchette area, mapped by the MRNF in 2018, exposes ca. 1.4 to 1.35 Ga and ca. 1.15 Ga metaplutonic rocks, <1.2 Ga volcanic & sedimentary units, and ca. 1.1-1.0 intrusive magmatic suites. Rocks in the area record upper amphibolite to granulite facies and yield Shawinigan (1190–1140 Ma) and Ottawan (1090–1020 Ma) metamorphic ages. Several phases of deformation have affected the region, ranging from folding and shearing in the middle crust to brittle faulting in the upper crust. The fieldtrip will provide an overview of the local geology, with particular emphasis on the Saint-François-de-Sales shear zone. Many of the outcrops visited are located in the Travers Plutonic Suite (ca. 1076 Ma), which simplifies the interpretation of structures related to the shear zone, since tectonometamorphic fabrics associated with pre-Grenvillian deformation are not recorded by this suite. Five-star quality outcrops of mylonite and ultramylonite therefore display textbook examples of deformation gradients, shear sense indicators, intersecting relationships between dextral and sinistral conjugate shear structures, and deformation-related alteration (hematization, epidotization). This sinistral shear zone formed at ~400–500°C, continuously or episodically between ca. 1035 and ca. 1000 Ma. The Saint-François-de-Sales shear zone marks the transition between exhumation-dominated tectonics in the second half of the Ottawan phase of the Grenvillian orogeny (ca. 1060-1035 Ma) and renewed shortening accommodated by strike-slip structures until the beginning of the Rigolet phase (ca. 1035-1000 Ma). The area provides a good overview of the type of deformation that occurred in the upper crustal levels of the Central Grenville during this time interval.

Compaction pocket: a new mechanism to explain the occurrence of alkaline melt in orogenic settings

Azam Soltanmohammadi[1,2] and Michel Rabinowicz[2]
[1]Geological Survey of Canada, Quebec, Canada
[2]Paul Sabatier université, Toulouse, France
Contact: azam.soltanmohammadi@nrcan-rncan.gc.ca

Orogenic settings are ideal places to study the genesis of volatile rich alkaline melts because of the history of subducting slabs-derived materials is relatively well constrained. Post-collisional or subduction-related scenarios are proposed to explain the origin and huge diversity of alkaline magmatism throughout the convergent margins. All models require hot upwelling asthenosphere, associated slab break-off or slab tearing. Similarly, lithospheric delamination resulting from orogenic crustal thickening also leads ultimately to its replacement by a hot mantle up to the base of the crust. In present study, we propose a physical model of the formation of alkaline melts which involves great depth sources, within the Mantle Transition Zone (MTZ). The model is based on petrological and geophysical data from the modern-style tectonic zone, the Turkish-Iranian Plateau (TIP), resulting from the collision of the Arabian and Indian continents with Eurasia. The region is characterized by alkaline magmatism and the long history of the Tethys subduction which likely led to the accumulation and density stratification of stacked stagnant slabs within the MTZ. We show that the alkaline magmatism observed in the plateau requires a relatively cold mantle. Our synthesis of the most recent seismic tomography images shows the presence of a large set of low velocity elliptic bodies, 100 km in size, referred to as "*compaction pockets",* scattered beneath the TIP. Our model shows that the low velocities in these compaction pockets result from the percolation and concentration of volatile-rich alkaline melt. The volatile-rich melts interact with a surrounding mantle that has a temperature of 100 °C lower than the usual sub-continental mantle adiabatic. We argue that this results in the precipitation of hydrated and carbonated mineral phases at certain critical depths. Our calculations show that alkaline melt extraction via dykes occurs when the top of the compaction pocket successively crosses the defined critical depths. As a result, compaction pocket model offers a robust new concept to explain volatile rich alkaline melts in the context of the orogeny settings.

Investigating the evolution of the Llewellyn-Tally Ho deformation corridor, Yukon, Canada, using in situ apatite and titanite geochronology

Dana Šilerová[1], Dawn Kellett[1,2], Catherine Mottram[3]
[1]Saint Mary's University, Halifax, NS, Canada
[2]Geological Survey of Canada Atlantic Division, Dartmouth, NS, Canada
[3]University of Portsmouth, Portsmouth, UK
Contact: dana.silerova@smu.ca

The Llewellyn-Tally Ho deformation corridor is a complex structural network that extends over 200 km from southern Yukon into northern British Columbia, Canada. The crustal-scale high-strain zone occupies a significant position between two major terranes of the Canadian Cordillera, Stikinia and Yukon-Tanana terrane, and it is associated with several hydrothermal ore deposits and past mines. However, its role in regional tectonic and mineralizing events remains poorly understood, in part due to a lack of absolute timing constraints on ductile and brittle deformation episodes. This project aims to characterize and directly date ductile and brittle deformation along the Llewellyn-Tally Ho deformation corridor through a combination of field mapping, petrography, microstructural analysis and *in situ* U-Pb dating of key minerals via laser ablation-inductively coupled plasma-mass spectrometry.

The Tally Ho shear zone deforms Late Triassic amphibolite and gabbro, which contain abundant apatite and titanite minerals. Apatite was characterised and dated from six samples within the Tally Ho shear zone. In two samples of sheared gabbro, apatite exhibits a wide range of textures and yields ^{207}Pb-corrected dates between ca. 185–145 Ma, with recrystallized apatite typically recording younger dates than pre-kinematic apatite. In two ultramylonitic samples, pre- to syn-kinematic apatite preserves evidence of dynamic recrystallization and yields lower intercept dates of ca. 105–100 Ma, interpreted as dating ductile deformation. These overlap with ca. 105–95 Ma dates recorded by brittlely-deformed igneous apatite in cataclastic granodiorite samples, indicating that pluton emplacement and cooling may have coincided with ductile shear. While these results highlight the apatite U-Pb system's potential to record the timing of cooling as well as syn-kinematic dynamic recrystallization, the age discrepancy observed between samples points to a complex long-lived shear zone system. Preliminary analyses of titanite indicate a lack of recrystallization textures and significantly older dates (Late Triassic to Early Cretaceous) than those recorded by apatite in the same samples.

Additional geochronometers, including the U-Pb systems in calcite and epidote, will be employed to fully document the deformation and cooling history of the shear zone. Further electron backscatter diffraction microstructural analysis will confirm which mineral phases have undergone dynamic recrystallization, thus linking U-Pb dates to deformation fabrics.

Résultats géochronologiques LA-ICP-MS du projet de maîtrise: Contexte tectono-magmatique de mise en place des gîtes de terres rares près de la Zone de bordure de la Ceinture métasédimentaire centrale

Jeanne Carabin[1], Félix Gervais[1], Anne-Aurélie Sappin[2]
[1]Département des génies civils, géologiques et des mines, Polytechnique Montréal, Montréal H3T 1J4, Québec, Canada
[2]Commission Géologique du Canada, Ressources Naturelles Canada, 490 rue de la Couronne, Québec, Québec G1K 9A9, Canada
Contact: jeanne.carabin@polymtl.ca

Une étude géochronologique est présentée afin de mieux caractériser les évènements syn- et post-déformation près de la Zone de bordure de la Ceinture métasédimentaire centrale (ZBCMC) au Québec. Cette zone est d'intérêt, notamment car le long de celle-ci, des indices d'éléments des terres rares (ETR) ont été identifiés dans des pegmatites granitiques et des carbonatites (p. ex. : indice de Baie-Mercier). Selon leur description lithologique, les roches hôtes de ces indices sont associées à la Suite alcaline de Kensington-Skootamatta (K-S) mise en place entre 1090 et 1060 Ma, mais cette hypothèse n'est pas appuyée par d'autres données.

Nous avons cartographié cette zone de cisaillement dans le Réservoir Baskatong, où un très haut niveau de déformation est exposé dans plusieurs lithologies. Le marbre de la Ceinture métasédimentaire centrale (CMC) est recoupé par des dykes mafiques cisaillés et boudinées. Le gneiss migmatitique granitique de la Ceinture allochtone (CA) est caractérisé par une linéation de grains de quartz fortement étirés. Des métabasites de la CA sont observées localement sous forme de boudins à grenat dans le gneiss. Des brèches de clinopyroxénite sont aussi présentes dans les carbonatites et les gneiss. Plusieurs indicateurs cinématiques (p. ex : structures C/S, *shear band* boudins) indiquent un mouvement sénestre-normal de cisaillement dans la zone.

Dans cette étude géochronologique, la déformation dans la ZBCMC est datée à partir de deux échantillons importants : (a) une pegmatite granitique à cristaux de titanite automorphe centimétrique formant une linéation magmatique, située localement dans la ZBCMC; et (b) un leucosome à orthopyroxène en bordure du quadrant extensif d'un boudin mafique, entraîné par le cisaillement. L'échantillon (a) donne un âge de 1165 ± 6 Ma et l'échantillon (b) donne un âge de 1162 ± 7 Ma (données U-Pb sur zircon). De plus, deux échantillons de dykes tardifs associés à la Suite de Guénette sont datés à 1027 ± 12 Ma et 1017 ± 8 Ma dans le réservoir Baskatong. Ceux-ci sont utilisés comme marqueur chronologique de mise en place post-déformation. Enfin, l'interprétation de ces résultats géochronologiques permet de faire un lien avec la mise en place des carbonatites dans la région.

La déformation des carbonatites varie selon son emplacement avec la zone de cisaillement. La carbonatite de l'indice de Baie-Mercier est située en bordure de cette zone de cisaillement et est peu déformée. Par contre, des carbonatites forment des L-tectonites dans la zone de cisaillement, ce qui implique qu'elles se sont mises en place avant le cisaillement. Les résultats géochronologiques permettent donc de révéler que les roches hôtes des indices d'ÉTR près de la ZBCMC se sont mises en place avant ca. 1160 Ma et donc sont non-reliées à la Suite de K-S.

Crystallization of vein-hosted glaucophane and phengite coeval with greenschist facies metamorphism: a fluid-buffered 'blue herring'?

Taylor Ducharme[1], David Schneider[1], Bernhard Grasemann[2], Kyle Larson[3], Alfredo Camacho[4], Konstantinos Soukis[5]
[1]University of Ottawa, Canada
[2]University of Vienna, Austria
[3]University of British Columbia Okanagan, Canada
[4]University of Manitoba, Canada
[5]National and Kapodistrian University of Athens, Greece
Contact: tduch009@uottawa.ca

Subvertical glaucophane + quartz ± phengite veins exposed in the footwall of a major extensional detachment on southern Evia (NW Cyclades, Greece) record mode-I brittle fracturing with variable principal stress orientations. The veins display systematic cross-cutting relationships with a prominent youngest vein set spaced 5-10 cm apart transecting all other veins. Interlayered jadeite-rich metabasalt and quartzite host the veins and promote a pronounced rheological control on fracturing, with veins preferentially hosted in metabasalt layers and terminating abruptly as pressure solution seams or shear bands at contacts with the ductily deformed quartzite. Vein-hosted ferromagnesian minerals do not exhibit recrystallization or dissolution-reprecipitation microstructures. Jadeite in the veined layers forms both 'fuzzy' euhedral crystals overgrown by hematite and forming symplectitic intergrowths with quartz and albite. Vein-hosted glaucophane and phengite grew at fixed angles (normal and oblique) to vein walls. Phengite is compositionally homogeneous with elevated Si content (3.41–3.52 apfu). Glaucophane from all veins shows a homologous concentric compositional zoning with core chemistry intermediate between glaucophane and magnesioriebeckite, glaucophane-rich mantles, and rims of magnesioriebeckite or winchite. Phengite yields consistent single-grain total-fusion $^{40}Ar/^{39}Ar$ dates with a weighted mean of 22 ± 1 Ma (*n:* 22), whereas the low-K glaucophane produced equivocal and dispersed dates. Phengite (*n*: 44, 20) and glaucophane (*n*: 8, 42) *in-situ* $^{87}Rb/^{87}Sr$ isochrons from two samples yield mutually indistinguishable dates of 21 ± 5 Ma and 25 ± 4 Ma, within uncertainty of the $^{40}Ar/^{39}Ar$ dates. The uniform mineral chemistry, compositional zoning, and geochronology indicate that the veins likely formed over a short time without major shifts in ambient pressure-temperature conditions. Contrary to the apparent mineralogically-defined high pressure-low temperature paragenesis of the veins, dates obtained from pristine high-Si phengite support crystallization in the latest Oligocene to earliest Miocene, coincident with regional extension in the Aegean and widespread greenschist-facies retrogradation. Abundant hematite and the predominance of Fe^{3+}-rich sodic amphibole and clinopyroxene species implicates a highly oxidizing fluid in the stabilization of these nominally 'high-pressure' minerals under conditions widely responsible for producing retrogradational greenschist-facies assemblages throughout the Cyclades.

Decoding the timing of polyphase metamorphism in the Mauricie region, central Grenville Province, Québec

Muhammad Zahoor Iqbal[1], Renaud Soucy La Roche[1]
[1] Centre Eau Terre Environnement, Institut national de la recherche scientifique, 490 rue de la Couronne, Québec, Canada, G1K9A9
Contact: Muhammad_Zahoor.Iqbal@inrs.ca

The Grenville Province in North America is composed of high-grade metamorphic rocks that record evidence of protracted crustal growth, pre-Grenvillian accretionary episodes between ca. 1665 and 1140 Ma, and the final continent-continent Grenvillian collision at ca. 1090–980 Ma that marked the assembly of the supercontinent Rodinia. The Mauricie-Portneuf area exposes several lithotectonic domains metamorphosed and deformed at different structural levels and subsequently juxtaposed tectonically during the Ottawan phase of the Grenvillian orogeny. The variable Ottawan overprint provides the opportunity to better characterize pre-Grenvillian accretionary events. From structurally lowest to highest, the Mékinac-Taureau, Shawinigan and Portneuf–St. Maurice domains collectively record limited geochronological evidence for metamorphism during the ca. 1390 Ma accretion of the Montauban arc to the southeast Laurentian margin, the ca. 1190–1140 Ma Shawinigan orogeny and the ca. 1090–1020 Ma Ottawan orogeny. However, the spatial extent and metamorphic grade during each of these events is poorly constrained. Understanding the timing and metamorphic conditions of the pre-Grenvillian accretions and the final collision is therefore crucial to decipher the crustal assembly of the central Grenville Province.

The peak metamorphic mineral assemblage in paragneiss from the Mékinac-Taureau and Shawinigan domains contains garnet, biotite, prismatic sillimanite and K-feldspar, indicative of upper amphibolite to granulite facies conditions. Garnet in the Shawinigan domain is characterized by inclusions-rich cores and inclusions-poor rims separated by sharp euhedral to subhedral boundaries, which may indicate polyphase garnet growth during two distinct metamorphic events. In contrast, the mineral assemblage in paragneiss from the Portneuf–St. Maurice domain is characterized by garnet, biotite, cordierite, and sillimanite, which indicate lower temperature and pressure conditions. *In-situ* Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry (LA-ICP-MS) petrochronology on monazite will be used to constrain the timing of metamorphic events. The textural setting of monazite will be used to determine the timing of growth of metamorphic index minerals; inclusions of monazite in garnet and cordierite are expected to provide a maximum age constraint on porphyroblast crystallization. The trace element contents of monazite will be measured concurrently with isotopic ratios and utilized to establish a relationship between monazite growth and metamorphic reactions that release or sequester Y and REE. The new results on the timing of metamorphic episodes will provide robust constraints on the Mesoproterozoic tectonometamorphic evolution of the Mauricie region in the central Grenville Province, Québec.