CTG 2018

Saints-Martyrs-Canadiens, Quebec Appalachians

Program, Abstracts and Field Guide
28-30 September 2018

Deformed pillow basalt - Ascot Complex

Alain Tremblay[1], David Corrigan[2] and Morgann Perrot[1]

1- UQAM

2- Geological Survey of Canada

LIST OF PARTICIPANTS

Ankit, Bhandari
Atkinson, Elizabeth
Bagherpur, Omid
Bethune, Kathryn
Bogatu, Adina
Brochard Crystal
Carr, Sharon
Corrigan, David
Cutts, Jamie
Darbyshire, Fiona
Dazhi Jiang
Debruyne Thomas
Delporte Rémy
Ducat Thibaut
Eves, Erin
Faber, Carly
Fontaine, Arnaud
Gassot Loren
Généreux, Carol-Anne
Guiraud, James
Harris, Lyal
Helmstaedt, Herb
Hill, Mary Louise
Honsburger, Ian
Howell, Tim
Kellett, Dawn
Lafrance, Bruno
Landry Jessica
Laraibi Zeinebou
Lu Xi
Maestracci Barbara
Marasa Héléna
Ménard Josée
Nucciarone, Mario
Perrot Morgann
Petkau, Kait
Pierre Guillaume
Rivera Lucas
Rowe, Christie
Rui Yang
Samson, Brendon
Saumur, Benoit
Shoufa Lin
Staszak-Devouassoux Paul
Strasser Alison
Théas Éliott
Tremblay, Alain
Waddington, Dennis
Waddington, Janet
Waldron, John
White, Shawna
Wu, Qihang
Xiaohui Zhou
Zimmermann Maxime

PROGRAM

Friday Sept 28th – Arrival

- 16h Mini-buses departure from UQAM
- 17h onwards General arrival at Camp Beauséjour.
- 19h Ice-breaker, informal introduction talk and local geology maps.

Saturday Sept 29th – Oral and Poster Presentations

- 8:15 h *Welcoming Remarks*

1- Lithosphere/Geophysics

- 8:20 - 8:40 h ***H. Helmstaedt***, Structural and tectonic considerations in decyphering the evolution of primary diamond deposits.
- 8:40 – 9:00 h ***L. Harris***, Implications of a 'millefeuille' lithospheric rheology model for mineral exploration in Archean terranes.
- 9:00 – 9:20 h ***Lu Xi***, The strength of polyphase rocks and the rheology of continental lithosphere.
- 9:20 – 9:40 h ***F. Darbyshire***, Lithospheric structure across eastern Canada.
- 9:40 – 10:00 h ***O. Bagherpur,*** Phase velocity variations in southeastern Canada and the northeast USA.

- 10:00 – 10:20 h ***Coffee break and posters***

2- Mineral Exploration and related themes

- 10:20 – 10:40 h ***B. Lafrance***, Structural modifications of VMS deposits.
- 10:40 – 11:00 h ***J. Guiraud***, The Montagne d'Or auriferous volcanogenic massive sulphide deposit: Towards a polyphase mineralization event.
- 11:00 – 11:20 h ***B. Samson***, Deformation history of the Cadillac and Timiscaming groups along the Malartic segment of the Larder Lake - Cadillac deformation zone and timing of gold-bearing quartz veins.
- 11:20 – 11:40 h ***C-A. Généreux***, Quartz crystallographic fabrics and P-T constraints on the Creighton-Victoria mylonite zone, Southern Province.
- 11:40 – 12:00 h ***Rui Yang,*** The L-tectonite formation: a multiscale investigation

- 12:00 – 13:20 h ***Lunch break and posters***

3- Tectonics

- 13:20 – 13:40 h ***C. Rowe***, Why do subduction thrusts lock?
- 13:40 – 14:00 h ***J. Cutts***, Craton stabilization and supercontinent cycles recorded by Lu-Hf garnet chronology on orogenic peridotite.
- 14:00 – 14:20 h ***A. Bogatu***, Cordilleran mantle massifs of the Cache Creek terrane, BC and Yukon, Canada - Evidence of oceanic extensional core complexes.
- 14:20 – 14:40 h ***S. Lin,*** Promontory collision and the Paleozoic Wuyi-Yunkai orogeny in South China.
- 14:40 – 15:00 h ***J. Waldron***, Carboniferous Ainslie detachment of Atlantic Canada: is it everywhere a salt weld?

- 15:00 – 15:20 h ***Coffee break and posters***

4- Tectonostratigraphy – Rheology

- 15:20 – 15:40 h ***M. Perrot***, Detrital zircon U-Pb geochronology of the Magog Group, southern Quebec - stratigraphic and tectonic implications for the Quebec Appalachians
- 15:40 – 16:00 h ***S. White***, Diachronous development of the Taconian pro-arc foreland basin in the northern Appalachian Orogen.
- 16:00 – 16:20 h ***J. Ménard,*** Sedimentary Provenance of the Elliot Lake and Hough Lake groups, Huronian Supergroup, Sudbury Area.
- 16:20 – 16:40 h ***A. Bandari,*** A numerical modelling investigation of outcrop-to-thin section scale quartz CPO variation observed in nature: Flow field partitioning or activation of slip system?
- 16:40 – 17:00 h ***Q. Wu***, A weighed, least square finite element method for modelling viscous geological flow

5- POSTERS – All day Saturday

- ***E. Atkinson et al.,*** Seismic interpretation of Ellesmerian, Mesozoic and Cenozoic structural trends in the subsurface of Banks Island, NWT, in support of surface geological and petroleum systems
- ***E. Eves***, Evolution of coseismic faults: An observational study
- ***A. Fontaine***, Structural control on gold mineralization at the Éléonore mine and the Cheechoo showing, Eeyou Istchee Baie James, Superior Province, Québec
- ***L. Harris,*** Deep structures in the Pilbara Craton, Western Australia: Relationship to overlying deformation, mineralization and kimberlite emplacement
- ***D. Kellett***, Cooling history of Southern Rae craton – spatio-temporal evolution of cratonization
- ***M. Nucciarone***, The effects of metamorphic events and water concentration levels on quartz grains
- ***M. Perrot***, Diachronic structural and metamorphic evolution of orogenic basins – the Connecticut Valley-Gaspé trough, Northern Appalachians.
- ***Z. Xiaohui,*** Fault kinematics and structural evolution of the Amos-Malartic transect in the Abitibi and Pontiac Subprovinces, Quebec, Canada

- 17:00 – 18:00 h ***CTG Council Meeting***
- 18:00 – 23:00 h ***CTG Banquet and CFES Award to Herb Helmstaedt***

Sunday Sept 30th – Field Trip

STOP 1: The La Guadeloupe fault – the Big Hollow Brook section.
STOP 2: Ductile shearing in interlayered felsic and mafic lavas of the Stoke domain.
STOP 3: The Ascot Complex-Magog Group contact – is it an angular unconformity?
STOP 4: A conglomeratic marker horizon in the Magog Group.
STOP 5: Contact between felsic volcanic rocks of the Eustis domain and black phyllites.
STOP 6: The Capelton mine – historical view and structural characteristics

ABSTRACTS

Seismic interpretation of Ellesmerian, Mesozoic, and Cenozoic structural trends in the subsurface of Banks Island, NWT in support of surface geological and petroleum system mapping objectives

Atkinson, E.A.[1], King, H.M.[1], Piepjohn, K.[2], Dewing, K.E. [1], and McCarthy, W.M.[1]
[1]Geological Survey of Canada (Natural Resources Canada) 3303 33rd St. NW, Calgary, AB T2L 2A7
[2] Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Stilleweg 2, 30655, Hanover, Germany

Banks Island is located in the westernmost Canadian Arctic Islands. It is located between the Parry Islands Fold Belt to the NE and the Mackenzie Delta to the SW. The regional Geological Survey of Canada maps for the area (Miall, 1979) suggested that the exposed Cretaceous and Cenozoic deposits are relatively undisturbed. A few broad low amplitude folds were the main structures noted, and almost no faulting was mapped outside of limited Paleozoic outcrops. There was significant petroleum exploration in the 70's and early 80's, and 8 of the 11 wells were incorporated into the GSC regional mapping, but the petroleum industry seismic data and interpretation remained confidential in that era. Generally in the public scientific literature, the subsurface structures, including the Banks Graben, were only broadly outlined from the wells and gravity data.

In 2016, new field work was undertaken under the GSC's Geo-mapping for Energy and Minerals (GEM) program, in cooperation with the German BGR. In addition, there was a new mandate for regional petroleum resource assessment, as part of the Marine Conservation Targets* (MCT) initiative. In preparation for these projects, the legacy petroleum industry data were assembled in one location. Seismic data were loaded into geophysical interpretation software, as images of the data that were required to be submitted to the National Energy Board, and digital seismic data** donated from various petroleum companies. Raw field records were also donated and reprocessed to modern standards, with significant uplift in image quality. The assembled database allows new regional mapping of the subsurface structure in support of both programs.

The first mapping effort focused on the Northern Banks Graben in advance of the 2016 field work. An extensive array of (apparent) normal faults forming the graben are well imaged, and the faults were correlated with the aide of 3D visualization. Such visualization increased the confidence of fault correlation, despite the distance between seismic lines. A projected surface trace map was very successful in helping to locate surface exposures of faults for further analysis. Field work observations showed more complex movement on these structures including significant strike slip motion, only hinted at on the regional seismic images (Piepjohn et al, 2018). Both field observations and subsurface mapping (fault limited deposition and growth strata) suggest that these faults have a protracted history from the Jurassic to at least the Eocene.

Ongoing regional mapping has extended deeper in the stratigraphic section, and outlines significant constraints on Ellesmerian (Devonian) trends. Broad folding of significant amplitude is observed prior to a regional pre-Jurassic unconformity in NW Banks Island. The orientation of this folding is compatible with similar aged structures in the Parry Islands Fold Belt to the NE, and may indicate the Ellesmerian structural front is a more simple arc – an interesting observation for the tectonic history. Much additional potential for insight from further reprocessing and mapping remains.

References:

Miall, A.D., 1979. Mesozoic and Tertiary geology of Banks Island, Arctic Canada - The history of an unstable craton margin; Geological Survery of Canada Memoir 387, 235p.

Piepjohn, K., Atkinson, E., Dewing, K., Smith, R., and Galloway, J., 2018. Cenozoic structural evolution on northern Banks Island, NWT Canada; Arktos V.4, no.15, 19p.

* The Marine Conservation Targets (MCT) initiative provides targeted funding to Environment and Climate Change Canada (represented by the Parks Canada Agency), Fisheries and Oceans Canada (DFO), and Natural Resources Canada (NRCan) as part of the Government of Canada's commitment to conserve 10% of Canada's marine and coastal waters within the 200 nautical mile limit by 2020.

** The GSC thanks Suncor Energy and an anonymous petroleum company, for significant donations of digital seismic data, and permission to publish images of some of that data.

A numerical modelling investigation of outcrop-to thin section scale quartz CPO variation observed in nature: Flow field partitioning or Activation of slip system?

Bhandari, A., Jiang, D.
Department of Earth Sciences, Western University, London, Ontario, Canada.
abhand3@uwo.ca

Variation in quartz CPO textures such as rotated peripheral c-axis maximum in outcrop to thin section scale mylonites have been attributed qualitatively to flow field partitioning. Despite decades of research on quartz CPO, there exists no quantitative analysis on the influence of partitioned flow field on quartz CPO formation. Here, we apply a multi-scale approach that couples the self-consistent flow partitioning model (Jiang, 2016, 2014) known as Multi-Order Power Law Approach (MOPLA) with the Visco-plastic self consistent (VPSC) model of CPO formation (Lebensohn and Tomé, 1993). We regard quartz aggregates as a rheologically distinct element (RDE) embedded in a heterogeneous macroscale medium. The latter is represented by a Homogeneous Equivalent medium (HEM) that has effective rheology obtained self-consistently from the constituent materials, in this case, feldspar and mica grains. This arrangement is representative of the natural mylonites where quartz aggregates occur as heterogeneous inclusions in the feldspar-mica matrix. Partitioning equations from the generalized Eshelby solutions and developed numerical implementations of MOPLA provide the partitioned flow in the RDE, which is used as a boundary condition for quartz CPO texture development by VPSC model. We show that flow partitioning cannot explain the commonly observed variation of rotated peripheral c-axis maximum in quartz aggregates in the outcrop to thin section scale mylonites. Rotation of peripheral c-axis maximum is found to occur only when a different slip-system configuration is applied in the VPSC model. This is in contrast with the qualitative assessment of quartz CPO textures, where rotated peripheral c-axis maximum is attributed to the dominant basal <a> slip system activity influenced by flow field partitioning. This rotated peripheral c-axis maximum does not represent a change in the local shear sense. We suggest that such rotation of peripheral c-axis maximum is due to a change in slip-system activity from basal <a> slip to a combined slip system activity with more dominant rhomb <a>, prism <a>, or prism <c> slip. This result questions the widely used assumption of temperature-dependent slip system activity, since variation in quartz CPO are observed at single thin section to outcrop scale, most likely to occur at a constant temperature. A change in slip-system activity could possibly be due to its dependence on other factors such as accumulated strain or recrystallization mechanism as reported in recent experimental deformation studies.

Jiang, D., 2016. Viscous inclusions in anisotropic materials : Theoretical development and perspective applications. Tectonophysics 693, 116–142. https://doi.org/10.1016/j.tecto.2016.10.012

Jiang, D., 2014. Structural geology meets micromechanics: A self-consistent model for the multiscale deformation and fabric development in Earth's ductile lithosphere. J. Struct. Geol. 68, 247–272. https://doi.org/10.1016/j.jsg.2014.05.020

Lebensohn, R.A., Tomé, C.N., 1993. A self-consistent anisotropic approach for the simulation of plastic deformation and texture development of polycrystals: Application to zirconium alloys. Acta Metall. Mater. 41, 2611–2624. https://doi.org/10.1016/0956-7151(93)90130-K

Phase velocity variations in southeastern Canada and the northeast USA

Omid Bagherpur Mojaver[1], Fiona Darbyshire[1]
[1]Centre de recherche Geotop, Université du Québec à Montréal.

The formation and evolution of continental lithosphere is not yet well understood, and studying eastern Canada might illuminate ways to address some fundamental questions about evolving continents. Our study region includes the Phanerozoic Appalachian belt, and eastern Grenville province. The resolution of available seismic velocity models in this area, especially in the eastern part, is still not adequate due to lack of sucient data. The ultimate goal of this study is to present a more detailed look at the northern part of the Appalachian lithosphere and eastern edge of the Grenville province. To this end, Rayleigh wave phase velocity variations at 20 period passbands from 20 s to 200 s are computed using a two-plane-wave (TPW) approach which takes into account multipathing, scattering, and finite frequency effects. In this study, we are able to resolve smaller-scale velocity heterogeneities due to better azimuthal coverage than earlier studies and the inclusion of additional data from the recent temporary deployment of the QM-III network. We selected and processed data from 46 earthquakes occurring between summer 2013 and summer 2015 with a minimum magnitude of 6.0 and recorded by 71 broadband stations from 6 seismograph networks to use in the TPW inversion. From the nodal points of the resulting phase velocity maps, 1D dispersion curves are extracted and then combined to produce 2D phase velocity maps at different periods. Finally, we discuss the results in terms of tectonics and plausible origins of the observed anomalies.

Cordilleran mantle massifs of the Cache Creek terrane, British Columbia and Yukon, Canada – Evidence of oceanic extensional core complexes

Bogatu, A.[1], Bédard, J. H.[2], Labrousse, L.[3], Tremblay, A.[1], Zagorevski, A.[2]
[1]Université du Québec à Montréal (UQAM); [2]Geological Survey of Canada (GSC); [3]Sorbonne Université (SU)

The Carboniferous to Jurassic Cache Creek terrane (CC) of the Canadian Cordillera is dominated by oceanic mantle rocks, submarine lavas, chert, limestone and rare plutonic rocks. CC is bounded by the Quesnel and Stikine arc terranes, which together were accreted to North America and deformed by the Middle Jurassic. CC ophiolitic rocks occur as large, thrust-bounded massifs. Well-preserved sections of the CC mantle-crust transition are locally exposed in northern British Columbia (BC) and southern Yukon. In the Atlin area (BC), mantle harzburgite and minor dunite are in structural contact with a crustal sequence comprising slivers (~400 m) of gabbro, and a composite volcano-sedimentary sequence dominated by depleted arc tholeiites, calc-alkaline lavas and dykes, and rare alkali basalts. The mantle-crust contact is a ~100 m wide, SW-dipping serpentinite shear zone that contains cm- to m-scale fragments of mantle and crustal rocks. These are interpreted to be thrust-related structures as asymmetric fragments and C-S structures show reverse motions. Small structural windows expose the mantle rocks beneath the crust on Union Mt. Shears in these windows are shallowly SE-dipping and C-S structures show a normal motion. Such fabrics could represent syn-oceanic, extensional structures as they are affected by a SW-dipping spaced cleavage. An excellent example of an extensional shear contact occurs near Squanga Lake (Yukon), where a shallowly SE-dipping, serpentinite shear zone separates a dominantly lherzolitic mantle from massive gabbro (cut by dykes), basalts, chert, and limestone. Raman spectroscopy data on serpentines sampled at the mantle-crust contact in both studies areas are presented and discussed. The occurrence of extensional, syn-oceanic, low-angle serpentinite shear-zones between mantle and crust, when considered with the scarcity of lower crustal rocks, the lack of lateral stratigraphic continuity, and the brecciated aspect of many CC supracrustal sequences, together suggest common structural exhumation of the CC mantle prior to its accretion to N America.

Craton stabilization and supercontinent cycles recorded by Lu-Hf garnet chronology on orogenic peridotite

Cutts, J.A.[1] and Smit, M.A.[1]
[1]Department of Earth, Ocean, and Atmospheric Sciences, University of British Columbia, 2020-2207 Main Mall, Vancouver, Canada, V6T 1Z4.

Voluminous lithospheric mantle is postulated to have been extracted from the asthenosphere in the Archean and may have acted as a stable buoyant root for the rapidly growing continental crust, ultimately sustaining the secular transition to modern plate tectonics. Despite the importance of the sub-continental lithospheric mantle (SCLM) for the emergence and sustenance of continental crust and plate tectonics, its age record is difficult to investigate. Age data from mantle peridotites are limited to Re-Os sulphide dates and various types of model ages. These methods do not provide direct age constraints on rock-forming mineral assemblages and are often biased towards the most recent tectonothermal event in the host craton. The latter also applies to Sm-Nd garnet dates, which mostly provide cooling rather than crystallization ages in mantle rocks. To provide new insights into the protracted evolution of the SCLM, we performed Lu-Hf garnet chronology on five samples of orogenic peridotite from the Western Gneiss Complex, Norway. These spectacularly preserved fragments of the Laurentian (Greenlandic) SCLM represent a range of pyrope-bearing lithologies, each reflecting various degrees of melt depletion and metasomatism. Mineral chemistry and chronology results from depleted dunite samples records high degrees of deep melting during its extraction from the asthenosphere, which occurred during a prominent interval of global crustal growth in the Neoarchean. In contrast, the crystallization of fertile lithologies, which represent ponded melts or metasomatic products, was coeval with supercontinent break-up intervals in the Meso- to Neoproterozoic. Together, the new Lu-Hf ages indicate that buoyant SCLM extracted in the Neoarchean has persisted beneath—and likely contributed to the preservation of—the Archean core of Laurentia. The ancient SCLM remained largely passive except for episodic melting that occurred in sync with supercontinent cycles.

Lithospheric structure across eastern Canada

Darbyshire, F.A.
Centre de recherche GEOTOP, Université du Québec à Montréal, CP 8888 succursale Centre-Ville, Montréal, QC, H3C 3P8.

In the last 10-15 years, coverage of broadband seismograph stations across central and eastern Canada has increased substantially, thanks to a number of initiatives such as the POLARIS (Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity) project and its offshoots, and the US-Canada EarthScope project. Thanks to these denser seismograph networks, we are able to image the internal structure of the continental lithosphere and upper mantle in unprecedented detail, taking advantage of a broad range of data analysis techniques applied to the incoming seismic waves from large global earthquakes. The structure of the crust and upper mantle is characterised through variations in seismic wave speed, which correlate to compositional and temperature variations, and through seismic anisotropy, which provides information about large-scale structural alignments. Using these models, we can map out the thickness of the continental crust and lithosphere as well as exploring the internal structure from the near-surface to several hundred kilometres' depth.

Eastern and central Canada preserve over 3 billion years of Earth's geological history, including Archean cratons, Proterozoic mobile belts and Phanerozoic orogenic structures. This natural laboratory allows us to explore fundamental questions such as the initial formation of the continental lithosphere, its evolution and assembly over time, and the role of plate-tectonic processes in different periods of Earth history. We can explore how large-scale lithospheric structures relate to the tectonic boundaries visible at the surface, and how the crust and continental lithosphere change with age, in response to both plate tectonics and hotspot-lithosphere interaction.

We see that, in general, the Precambrian portions of the continent are characterised by thick (often >200 km) lithosphere whose fast seismic wave speeds can be explained by cold temperatures and a highly-depleted composition. Wave speed variation provides new clues to the assembly of the central and eastern Canadian Shield via ancient continental collisions. Similarly, the structure of the crust appears to have changed over geological time; in particular, we observe a distinct difference between Archean crust, with a simple structure, sharp Moho and felsic compositions, and crust associated with Proterozoic mobile belts. The latter shows a systematically deeper and more complex Moho transition, highly-variable composition, and internal structures reminiscent of the present-day Himalayan collision zone. The deep seismic structure of the continent thus supports the hypothesis that modern-style plate tectonics was already active at least as far back as the Paleoproterozoic.

Modelling the Formation of Fault Mirrors in Arenite Sandstones

Erin Eves[1] and James Kirkpatrick
[1]McGill University

Coseismic slip across faults is sometimes preserved in the rock record as fault "mirrors." In silicate rocks, these are nanocrystalline layers that form along the fault's slip surface. It has also been proposed that these layers are made up of a hydrated silica which lubricates the slip surface and thus facilitates dynamic weakening. Understanding the formation of these structures is necessary to understanding earthquake-scale deformation in the Earth's brittle crust, particularly in varied lithologies with different physical properties. The mirror surfaces are particularly smooth and highly polished. Can they develop in small-offset faults that did not accommodate large earthquakes? This study focuses on the microstructures of 10 faulted sandstone samples collected normal faults located in the San Rafael Desert in Utah, USA. The faults cut well-sorted, highly porous quartz arenites and were active at 1-4 km depth. The 10 studied samples contain slip surfaces with displacements that range from 0.26m to 53m. The initial stage of faulting is marked by the development of cataclasite and ultra-catclasite domains, which deformed simultaneously and mixed. Discontinuous, bifurcating slip surfaces separate the domains in samples with tens of cm of slip. Through-going slip surfaces develop at slip of around 1 m. Scanning electron microscope back-scatter electron images show that the angularity and the compaction of the matrix in ultra-cataclasite slip surfaces progressively increases with slip, while maximum grain size decreases. Similar characteristics of the cataclasite domain do not change significantly past 10-20m displacement. Melt patches, truncated grains, and dip-slip slickenlines were observed on slip surface faces using the secondary electron detector. Synthesis of observations shows that highly polished, smooth slip surfaces form in porous sandstones after around 1 m of slip due to cataclasis, grain crushing, and local melting and possibly plasticity on the slip surfaces.

Structural control on gold mineralization at the Éléonore mine and the Cheechoo showing, Eeyou Istchee Baie James, Superior Province, Québec

A. Fontaine[1], B. Dubé[2], M. Malo[1], V. McNicoll[3], S. Jackson[3], N. Prudhomme[4], J. Turcotte[5], D. Doucet[5]
[1] Institut national de la recherche scientifique, Centre Eau Terre Environnement, Québec, Québec
[2] Geological Survey of Canada, Québec, Québec,
[3] Geological Survey of Canada, Ottawa, Ontario
[4] Goldcorp Inc., Mine Éléonore, Rouyn-Noranda, Québec
[5] Sirios Resources, Montréal, Québec

The Éléonore mine, in the municipality of Eeyou Istchee James Bay, is a world-class gold deposit with reserves of 4.57 Moz, measured and indicated resources of 0.93 Moz, and inferred resources of 2.35 Moz Au. Mainly hosted by <2675Ma sedimentary rocks, the deposit is located 1.5 km south of the interpreted tectonometamorphic contact between the Opinaca (paragneiss to migmatite) and La Grande subprovinces (volcano-sedimentary belts and syn- to late-tectonic intrusions). The Cheechoo gold showing is a significant discovery located at 15 km southeast of the Éléonore mine. Structural control on gold mineralization is discussed here by defining stratigraphic relationships as well as structural, metamorphic and magmatic events relative to the establishment of auriferous hydrothermal system. This approach is based on extensive detailed surface and underground mapping, core logging, 3D modelling, and U-Pb geochronology. Ore zones at Éléonore have a diversity of mineralization styles including: i) stockwork of quartz, dravite veinlets with microcline, phlogopite replacement zones with pyrrhotite, arsenopyrite, and löllingite (5050 and 5010 zones); ii) quartz, actinolite, diopside, hedenbergite, muscovite, schorl, arsenopyrite-löllingite-pyrrhotite veins, hydrothermal breccia and amphibolite-biotite schist (6000, 7000, 8000 and hangingwall zones); and iii) more atypical metamorphosed high-grade ore in paragneissic rocks (e.g. 494 zone) and lower grade replacement zones and pegmatite dykes (North zone). Gold mineralization at Cheechoo is characterized by a network of sheeted quartz±(feldspar) veins with variable amounts of phlogopite, actinolite, diopside and scheelite that are related to calc-silicate and potassic alteration halos, mainly developed in vein selvages. High-grade gold veins and their selvages generally contain less than 5 % of disseminated sulphides (arsenopyrite, pyrrhotite ± pyrite) and have a coarse pegmatitic texture with local visible gold (similar to the Moni prospect). Metallic signatures including Au-As-B-Sb (±Bi-W-Te-Sn-Mo-Se) for Éléonore and a Bi-W-As (±Te-Se-Pb) for Cheechoo were identified. The ubiquitous presence of gold-rich löllingite inclusions within arsenopyrite overgrowths, as well as pyrrhotite, actinolite, diopside, hedenbergite, biotite and microcline, and post-ore deformation indicate that the bulk of gold mineralization at Éléonore has recorded prograde metamorphism and coeval deformation followed by retrograde metamorphism. The structural characteristics of the auriferous system at Cheechoo are best explained by a model of syn-tectonic emplacement of the Cheechoo intrusion and related leucogranitic dykes and gold-bearing veins networks. The Éléonore mine and Cheechoo showing area records i) long-lived Au-bearing hydrothermal activity associated with regional metamorphism, coeval deformation, reduced magmatism (~2612 Ma Cheechoo granodiorite/tonalite), and injection of numerous leucogranite and pegmatite veins and dykes, coeval with ii) polyphase deformation recorded by sedimentary rocks next to a major tectonic contact with a migmatitic domain. In this context, gold mineralization share analogies with hypozonal orogenic gold deposits as well as reduced intrusion-related gold systems.

Quartz crystallographic fabrics and P-T constraints on the Creighton-Victoria mylonite zone, Southern Province

Généreux, C.-A.[1], Lafrance, B.[1], and Tinkham, D.K.[1]
[1]Harquail School of Earth Sciences, Laurentian University, Sudbury, Ontario P3E 2C6

Structural geologists have long used crystallographic preferred orientation (CPO) of quartz in the study of shear zones, first to characterize strain and, more recently, to estimate the temperatures of deformation. CPO fabrics can also help identify foliations that are indiscernible to the human eye, especially in rocks lacking platy minerals such as micas. The Creighton-Victoria deformation zone includes a layered mylonite zone that deforms the southern boundary of the Superior craton near Sudbury, Ontario. It is characterized by a steep foliation that contains a steeply plunging quartz stretching lineation. To the east, C'-type shear bands indicate oblique dextral (simple) shearing that is consistent with the orientation of the stretching lineation. To the west, the mylonite zone contains the same quartz stretching lineation, but a chlorite phyllonite unit displays C'-type shear bands that indicate (horizontal) dextral shear. The goal of this study is to determine if the quartz stretching lineation and the dextral shear sense indicators, recorded by chlorite and muscovite, formed during a single transpressive event, or if they are the results of two separate, overprinting events. Detailed structural mapping was combined with the study of microstructures and quartz crystallographic fabrics using electron back-scatter diffraction on a scanning electron microscope (SEM-EBSD). Recrystallized quartz grains display c-axes that form slightly asymmetric type I crossed girdles and a-axes maxima, thus confirming that quartz recorded a vertical shearing component. The opening angle of the crossed girdle is ~68°, which suggests that quartz deformed at temperatures between 500 and 700°C. This is consistent with phase equilibria modeling of syn-tectonic staurolite-chloritoid-bearing metapelites, which indicates that regional metamorphism associated with the mylonite zone reached ~500-600°C and ~2.5-6kbar. The horizontal shear sense indicators defined by chlorite therefore are interpreted to correspond to a post-peak metamorphic dextral event, which did not exceed 300°C and overprints the oblique-dextral shearing event recorded by quartz crystallographic fabrics.

The Montagne d'Or auriferous volcanogenic massive sulphide deposit, French Guiana, South America: Towards a polyphase mineralization event.

J Guiraud[1], M Jébrak[1], A Tremblay[1], and R Lefrançois[2]
[1] Département des Sciences de la Terre, Université du Québec à Montréal, Montréal, Québec, Canada, guiraud.james@courrier.uqam.ca ;
[2] Compagnie Minière Montagne d'Or SAS, Rémire-Montjoly, Guyane Française, France ;

In French Guiana, the "Montagne d'Or" gold deposit (5 Moz Au at 1.5 g/t), a property of "Compagnie Minière Montagne d'Or", is hosted by the northern branch of the Proterozoic Paramaca Greenstone Belt (PGB). The PGB is interpreted as the remnant of a volcanic island-arc sequence formed between 2.18 to 2.13 Ga during the Transamazonian orogeny. The sulphides deposit is hosted by a bimodal volcanic and volcaniclastic, south-facing sequence that is affected by a penetrative E-W striking and south-dipping regional foliation. The volcanic stratigraphy is dominated by calc-alkaline felsic lithologies to the west, interbedded and interdigitated with tholeiitic mafic rocks to the east. The mineralization consists of two main sulphide horizons, the UFZ and LFZ, surrounded by two subsidiary zones known as the FWZ and HWZ. Three distinct facies characterize the sulphide mineralization, (1) stratiform disseminations, (2) stockworks-veinlets, and (3) structurally-transposed layers of semi-massive sulphides. The Au mineralization is associated with pyrite, pyrrhotite and chalcopyrite with minor sphalerite, magnetite and arsenopyrite within chlorite-sericite-rich alteration halos. Metal distribution and alteration zoning suggest a volcanogenic massive sulphide system with magmatic affinity. The chemo-stratigraphic variations of metal and alteration propose a two-step replacement process, (1) a primary low-temperature Zn-Pb rich hydrothermal fluid input within the LFZ-FWZ, and (2) the superimposition of secondary high-temperature fluids impregnating the upper part of the sequence forming the Cu Au rich UFZ-HWZ orebodies. The last mineralization event results of sulphide remobilization by metamorphism and deformation, as suggested by the deformed ore textures and late quartz-chlorite-carbonate-sulphides veins with Cu±Au±Bi±Te±Sb±As mineralization. Lead isotopes confirm that this vein-type mineralization is attributed to *in situ* remobilization rather than to external additions. Understanding metals and alterations behaviors allow constraining all mineralization events of the Montagne d'Or deposit with the primary hydrothermal system and its remobilization during metamorphism.

Implications of a 'millefeuille' lithospheric strength model for mineral exploration in Archean terrains

Harris, L.B.[1], Cleven, N. [2,3], Guilmette, C. [2]
[1] INRS-ETE, 490 de la Couronne, Québec (QC), G1K 9A9
[2] Géologie et de génie géologique, Université Laval, Québec (Qc), G1V 0A6
[3] Present address: Geological Survey of Canada, Vancouver, BC

In the two end-member lithospheric strength profiles: (i) the crème-brûlée analog where a strong, uppermost brittle crustal layer overlies weak lower crust and upper mantle and (ii) the jelly sandwich model, where lithospheric strength resides in both the elastic-ductile subcontinental lithospheric mantle (SCLM) and brittle-elastic upper crust (Burov and Watts, 2006; DOI: 0.1130/1052-5173 (2006)016<4:TLTSOC >2.0.CO;2), the mid- and lower crust are shown as ductile. Similarly, discrete faults in the upper crust are commonly portrayed as broadening with depth into brittle-ductile shear zones then mylonites; the lower crust is depicted as undergoing pervasive ductile deformation, especially in Archean terrains. It is difficult to reconcile these ideas of ductile mid- to lower-crust with those of many economic and tectonic researchers and exploration geologists, and as illustrated by recent magnetotelluric (MT) profiling in South Australia (Wise and Thiel, 2018; DOI: 10.1071/ASEG2018abM2_2G), that long-lived deep crustal structures: (i) exert primary controls on cratonic architecture and the localization of mineral deposits, (ii) are commonly linked with SCLM discontinuities and focus the flow of mantle-sourced fluids and igneous intrusions, and (iii) localize host structures for mineralization in the mid- to upper-crust when reactivated.

Enhancements of NRCan and MERN aeromagnetic data of the NE Superior Province in Quebec to highlight deep crustal features (viz. long wavelength components and derived pseudogravity images; see Harris, this volume) highlight deep domain boundaries that are oblique to trends in the upper crust and to lithostratigraphic boundaries derived from surface mapping. In the La Grande and Opinaca subprovinces, where ca. N-S trends of the NE Superior change to a generally E-W orientation, high resolution enhanced short wavelength aeromagnetic data portray regional distributed ductile deformation of amphibolite to granulite facies gneisses during E-W dextral transpression. Images highlighting underlying (i.e. deep crustal) features, however, portray several discrete E-W dextral shear zones that displace the initially N-S margins of an elongate, semi-rigid block (ca. 170 km from N to S). Localized shearing in the lower crust of the NE Superior Province is attributed to the presence of strong, anhydrous felsic granulites. Elsewhere (e.g. central Abitibi), gravity data show that discrete E-W shear zones offsetting the N-S margins of mafic rocks similarly underlie broad ductile shear zones. Strong deep, as well as upper crustal and SCLM layers, with intervening ductile layers, hence resemble a millefeuille instead of a jelly sandwich. These deep crustal discontinuities, and discrete shear zones and faults localized by them, in the NE Superior and central Abitibi are spatially related to Au, polymetallic, VMS, IOCG and REE occurrences in the overlying crust. Our research shows that mapping boundaries and structures developed in strong, deep crustal layers from enhanced geophysical images is thus important in mineral exploration.

Deep structures in the Pilbara Craton, Western Australia: relationship to overlying deformation, mineralization and kimberlite emplacement

Harris, L.B.
INRS-ETE, 490 de la Couronne, Québec (QC), G1K 9A9

Enhanced pseudogravity images provide an excellent means to distinguish between different tectonostratigraphic domains or terranes and to highlight deep crustal features. Calculation of pseudogravity involves (i) the vertical integration of reduced to the pole total magnetic intensity data and (ii) the conversion from a dipolar magnetic field to gravity-like polar behaviour using Poisson's relation (the correlation between the magnetic potential and the gravitational potential). In regional structural studies, pseudogravity images provide valuable information, complementary to that provided by standard treatments of aeromagnetic and gravity data, which aids mineral exploration targeting.

Pseudogravity images of Archean granite-greenstones of the Pilbara Craton, Western Australia support Hf isotope studies (Gardiner et al., 2017; http://doi.org/10.1016/j.precamres.2017.05.004) which show that the eastern part of the East Pilbara Terrane (EPT) is a geologically distinct block, separated from the rest of the EPT by the sinistral transpressional Lalla Rookh–Western Shaw structural corridor. Overlying the edge-enhanced short wavelength aeromagnetic image on pseudogravity portrays the relationships between upper and deep crustal features, allowing one to ‘look through’ the diapiric granite-gneiss domes of the EPT to see the underlying, basement blocks, that in part control their form, and deep crustal faults. That deep crustal features showing evidence of horizontal tectonics and accretion can be mapped beneath the archetypal Pilbara diapirs supports the results of numerical modeling where a mafic to ultramafic lower crust is preserved beneath a diapiric overturn, i.e. Rayleigh-Taylor instability, affecting overlying middle granitic and upper mafic layers (Robin and Bailey, 2009; https://doi.org/10.1130/G25519A.1).

In the N Pilbara, conjugate ductile transcurrent shear zones both cross and occur on the margins of basement blocks. Most Au and other mineral occurrences in Pilbara Craton greenstones occur on the margins of the deep N-S elongate blocks that underlie the granite-gneiss domes, commonly at their intersection with NNW to NNE-striking faults. Paleoproterozoic Brockman kimberlite dykes in the Pilbara Craton ca. 50 km NNW of Nullagine occur on a N-S structure that can be traced on pseudogravity images to link with the contact between the Youanmi and Eastern Goldfields terranes in the Yilgarn Craton. Diamondiferous Nabberu kimberlites and ultramafic lamprophyres on the N margin of the Yilgarn Craton also intrude this structure, suggesting Paleoproterozoic reactivation and northwards propagation of this lithospheric structure from the Yilgarn to cross the Pilbara Craton.

Structural and Tectonic Considerations in Deciphering the Evolution of Primary Diamond Deposits

Herb Helmstaedt
Queen's University, Kingston ON, Canada, helmstaedt@queensu.ca

The evolution of most primary diamond deposits is multi-stage and intricately linked to the tectonic histories of their host cratons and their lithospheric and sublithospheric underpinnings. Yet the integration of the surface geological record of diamondiferous cratons with the complexities observed within the diamond and xenolith populations of their primary igneous hosts (kimberlites, lamproites, etc.) remains a major challenge for both diamond explorers and tectonicians interested in craton formation. A comparison of primary diamond deposits on different cratons shows that whilst processes leading to the formation of such deposits have operated worldwide, the timing of individual diamond-forming events and transport to the surface are craton specific. A recurring theme emerging from such comparisons involves five broad stages, referred to here as **Life Cycle of Diamondiferous Cratons** (see Table below). For an economic primary diamond deposit to form and survive to be mineable, the balance between diamond-friendly and diamond-unfriendly events during all stages of this cycle should be in favor of diamond survival. However, judging from the relatively small number of "high-grade" primary diamond mines worldwide, this was not the rule. Comparing the life cycles of different cratons, integrating geological evolution and geophysical settings with studies of the upper mantle sample from many deposits, brings out similarities and differences and helps to better understand the effects of terrane accretion, regional "granite blooms", rifting and plume events on the diamond potential of the cratons. This leads to more realistic diamond deposit models for area selection and provides important feedback for tectonic models of craton evolution. A case can be made that the tectonic history of most diamondiferous cratonic nuclei is compatible with the survival of Paleo- to Mesoarchean depleted lithospheric roots retaining at least some harzburgitic P-type diamonds.

Stage 1	**Earliest subcontinental lithosphere development** with depleted roots and harzburgitic P-type diamonds. Proto-continental nuclei.	>3 Ga
Stage 2	**Amalgamation of early nuclei** and formation of first eclogitic (E-type) diamonds. First detrital diamonds appear in sedimentary record and primary igneous rocks. Early roots must survive accretion of Neoarchean greenstone terrains, various "granite blooms" and other diamond-unfriendly events. **Cratonization**, greatest extent of Archean cratons.	~3 Ga ~2.5 Ga
Stage 3	**Post-Archean break-up of Archean cratons,** fragments become involved in Proterozoic (and Phanerozoic) orogenic events and supercontinent cycles. Archean craton roots are affected again by various mantle root-friendly or unfriendly tectonic and magmatic events, either diminishing diamond content of lithospheric source rocks or enhancing it by the addition of Proterozoic E-type or, more rarely, by lherzolitic P-type diamonds.	<2.5 Ga
Stage 4	**Archean cratons may be intruded by one or more generations of kimberlites or lamproites.** Such events may be accompanied or preceded by metasomatic alterations within or below the diamondiferous lithospheric roots. They may also be preceded by growth of late-stage amber or fibrous diamonds (type Ib). Sub-lithospheric diamonds may be picked up by kimberlites at this stage.	kimberlite or lamproite emplacement
Stage 5	Includes all geological **factors controlling the preservation of diamondiferous kimberlites or lamproites** and the dispersal of indicator minerals.	Post-emplacement

Cooling history of Southern Rae craton: spatio-temporal evolution from mobile crust to tectonic quiescence

Kellett, D. A.[1], Regis, D.[2] and Pehrsson, D.[2]
[1]Geological Survey of Canada, 1 Challenger Dr., Dartmouth, Nova Scotia, Canada, B2Y 4A2; dawn.kellett@canada.ca
[2]Geological Survey of Canada, 601 Booth St., Ottawa, Ontario, Canada K1A 0E8

Archean cratons in the interior of the Canadian Shield experienced a dynamic tectonic regime during the Archaen and Proterozoic involving craton formation and multiple reworking events within mobile crustal domains. Since that time, rocks now exposed at the surface have remained at shallow crustal levels indicating long-term tectonic quiescence. This evolution from dynamic tectonism to tectonic quiescence is recorded in the rock record as Archean to Proterozoic peak metamorphic and cooling ages, hence temperature-time (T-t) histories can be used to identify the spatio-temporal pattern of the transition. Here, we examine 65 new $^{40}Ar/^{39}Ar$ ages for hornblende and biotite from the southern portion of the Rae craton, which, in conjunction with new and emerging peak pressure-T-t data from the same area, allow us to reconstruct the transition to long term stable crust for this region of the Canadian Shield.
Preliminary analysis of this dataset indicates that stabilization of the crust of Southern Rae was progressive and domainal. Early stabilization of the westernmost Porter domain occurred by ~2.2 Ga, and latest stabilization occurring by ~1.75 Ga, with major structural breaks separating domains with contrasting cooling patterns. The main cooling and stabilization event during 1.85-1.80 Ga involved widespread moderate (~4 C/myr) to rapid (>20 C/Ma) cooling across several crustal domains. This timing supports previous interpretations that stabilization of southern Rae crust was triggered by the farfield Trans-Hudson Rae orogeny during which time Rae occupied an interior position within Nuna.

Structural modification of VMS deposits

Lafrance, B.[1], Gibson, H.L.[1], Stewart, M.S.[2]
[1]Mineral Exploration Research Centre, Harquail School of Earth Sciences, Laurentian University, Ramsey Lake Road, Sudbury, Ontario, Canada P3E 2C6. Email: blafrance@laurentian.ca
[2]Department of Earth and Environmental Sciences, University of Ottawa, 25 Templeton Street, Ottawa, Ontario, Canada K1N 6N5

Metal Earth Contribution Number: MERC-ME-2018-041

Ancient volcanogenic massive sulfide (VMS) deposits formed in extensional geodynamic environments and were deformed during later convergent accretionary events. How tectonic structures form in VMS deposits is influenced by their primary features. During deformation, strain is typically taken by the weaker sulfide lenses and their footwall alteration envelopes. The sulfide lenses and alteration envelopes act as shear zones, undergo hinge thickening and limb attenuation during folding and are deformed into elongate bodies parallel to regional fold hinges and stretching lineations. A tectonic foliation forms as a sulfide banding in the interior of VMS lenses due to deformation of primary textural and compositional heterogeneities, and as a banded silicate-sulfide tectonic foliation along the margins of VMS lenses due to transposition and shearing of primary silicate (exhalites)-sulfide layers. Cusps, piercement cusps and veins, and durchbewegung structures (sulfide breccias) are other structures that form as a result of the strong competency contrast between the sulfide lenses and their host volcanic rocks.

Some features of VMS deposits may have both primary and tectonic components. One example is the vertical stacking of VMS lenses, which may be primary and due to rapid burial of sulfide lenses by volcanic and sedimentary deposits during long-lived upflow of hydrothermal fluids, or tectonic and due to thrusting and isoclinal folding of VMS lenses. A second example is the elongation of VMS lenses, which may have a primary component due to the deposition and coalescence of sulfide lenses along linear syn-volcanic faults, as well as a tectonic component due to remobilization of sulfides parallel to linear structural features in the host volcanic rocks. Careful mapping of volcanic lithofacies and structures associated with mineralization is necessary to distinguish between primary and tectonic structures and assess the structural evolution of VMS deposits.

Promontory collision and the early Paleozoic Wuyi-Yunkai orogeny in South China

Shoufa Lin
Department of Earth and Environmental Sciences, University of Waterloo, ON N2L 3G1, Canada

Continental margins, especially passive margins, commonly exhibit promontories and reentrants. Where this is the case, collision between two continents is expected to start at a promontory or between two promontories. This leads to some unique geological processes at the site of promontory collision, including potentially deep subduction and burial of the continental crust of the promontory on the lower plate. A similar situation is where a small continent on the lower plate collides with a major continent, as in the case of India colliding with Eurasia.

We suggest that West Cathaysia in South China was (part of) a promontory on the lower plate in the early Paleozoic. It collided with the upper plate in late Cambrian-Ordovician. The collision and the resulting slower subduction rate turned off arc magmatism at the site of collision and potentially elsewhere as well. Subduction of the remaining oceanic lithosphere in the adjacent reentrant(s) led to continued convergence between the two plates and subduction and progressive burial of the West Cathaysia continental crust at the promontory. The buried West Cathaysia crust reached upper amphibolite-granulite facies metamorphic conditions with partial melting occurring in late Ordovician-Silurian, generating S-type granites. Since conductive heating of large slabs of cold crust buried by thrusting is a slow process and heating up to upper amphibolite and granulite conditions can take tens of millions of years, the model readily explains that peak metamorphism and partial melting took place tens of millions of years after onset of collision. In this model, the late Ordovician-Silurian Wuyi-Yunkai orogeny was a continuation of the Cambrian-Ordovician (Kunngan/Yu'nan?) collisional orogeny that took place at the late stage of Gondwana assembly. The model explains the unique features of West Cathaysia in the context of Gondwana assembly. It offers a solution to the biggest puzzle concerning South China in the early Paleozoic, that is, a major tectono-thermal event in South China, with characters of a collisional orogeny, took place tens of millions of years after the Gondwana supercontinent had been assembled and collision appeared to have been over.

The strength of polyphase rocks and the rheology of continental lithosphere

Lucy X. Lu, Dazhi Jiang
Department of Earth Sciences, Western University, London, Ontario, Canada N6A 5B7 (xlu245@uwo.ca ; djiang3@uwo.ca)

Earth's continental lithosphere is made of polyphase rocks in which each phase may exhibit distinct rheological properties. The overall strength of a polyphase rock depends on the strengths of its rheologically heterogeneous constituents, their concentrations, and their geometric arrangement, all of which change with progressive deformation. Therefore, an effective approach to evaluate the "average" rheological properties of a polyphase rock from the properties of its rheologically distinct phases is required to understand the rheology of the heterogeneous continental lithosphere. The Voigt and Reuss averages of an elastic composite material corresponding respectively to the uniform strain and uniform stress situations provide the upper and lower limits of the composite material property. Unfortunately, the range between the upper bound and lower bound is too broad to constrain the rheological properties of polyphase rocks effectively. An empirical approach cannot be extrapolated to conditions of natural deformation. In particular, the approach cannot account for rheological anisotropy, which is common and significant in the continental lithosphere. We apply micromechanical homogenization, based on our established self-consistent Eshelby formalism, to evaluate the overall rheological properties of polyphase rocks. Available experimental data on the strength of calcite-halite aggregates and quartz-mica aggregates are used to verify our approach. We demonstrate that for a polyphase aggregate, the anisotropy of its constituents, their orientations, and deformation mechanisms play a critical role in the overall rheological behavior of the material. The successful verification of our approach implies that it can be confidently extrapolated to real rocks under natural deformation conditions and to follow the evolution of rheological properties of rocks as fabrics and hence rheological anisotropy develop in them.

Detrital zircon U-Pb geochronology of the Magog Group, southern Québec – Stratigraphic and tectonic implications for the Québec Appalachians

Perrot, M.[1], Tremblay, A.[1], and David, J.[2]
[1]Université du Québec a` Montréal-Geotop, Département des sciences de la Terre et de l'atmosphère, Case postale 8888, Succursale Centre-ville, Montréal, Québec, H3C 3P8, Canada. Email : perrot.morgann@courrier.uqam.ca
[2]Bureau d'Exploration Géologique du Québec-Geotop, Ministère de l'Énergie et des Ressources Naturelles, Université du Québec è Montréal, 201 av Président-Kennedy, Montréal, Québec, H3C 3P8, Canada

In the Quebec Appalachians, the Laurentian continental margin (Humber Zone) and adjacent oceanic domain (Dunnage Zone) were amalgamated during the Ordovician Taconian orogeny. The Dunnage Zone includes ophiolites and overlying synorogenic deposits of both the Saint-Daniel Mélange and Magog Group. The latter consists of a *ca.* 3 km-thick pile of sandstone, felsic volcaniclastic rocks and graphitic slate at the base (Frontière, Etchemin and Beauceville formations) overlain by a *ca.* 7 km-thick turbiditic flysch sequence, constituting the Saint-Victor Formation. The maximum upper age limit of the Magog Group was considered to be Darriwilian based on graptolite fauna. This was proven consistent with a $462^{+5}/_{-4}$ Ma (U-Pb ID-TIMS) from a felsic tuff of the Beauceville Formation but contradicts a detrital zircon U-Pb age of 424 ± 6 Ma recently measured in the Saint-Victor Formation. A new detrital zircon U-Pb geochronology study (HR-LA-ICP-MS and ID-TIMS), focused on the Saint-Victor Formation, yields young detrital populations that suggest that the Saint- Victor Formation is not exclusively Ordovician and extends into the Silurian, as indicated by a maximum age of sedimentation around 430 Ma. Detrital zircon U-Pb geochronology associated with fossil age constraints and stratigraphic correlations in adjacent areas attest that the Saint-Victor Formation should be considered as an upper Magog Group sequence that is separated from lower units (the Frontière-Etchemin-Beauceville formations) by an unconformity corresponding to a sedimentary hiatus of < 10 m.y. Regional tectonic considerations imply that the Magog Group evolved from a syn-Taconian forearc basin in Middle-Late Ordovician time to a syn-Salinic peri-continental basin in early Silurian time. Several NW and SE erosional sources are invoked for the sedimentation of the Magog Group, evolving from the erosion of both the southern Quebec ophiolites and adjacent sedimentary rocks of the Laurentia margin to the NW, and volcanic arc rocks of the Ascot Complex, Shelbourne Falls and Bronson Hill massifs to the SE. Potential sources for *ca*. 430 Ma zircons found towards the top of the Saint-Victor sequence are the Silurian Frontenac Formation and the East Inlet granitic pluton, both located in the vicinity of the Quebec-Maine border.

Diachronic structural and metamorphic evolution of orogenic basins – the Connecticut Valley-Gaspé trough, Northern Appalachians.

Morgann Perrot[1]; Alain Tremblay[1]; Gilles Ruffet[2]; Labrousse Loic[3] ; Gervais Félix[4] ; Fabien Caroir[3]
[1] Université du Quebec à Montréal-Geotop, Département des sciences de la Terre et de l'atmosphère, Case postale 8888, Succursale Centre-ville, Montréal, Quebec, H3C 3P8, Canada. Email : perrot.morgann@courrier.uqam.ca
[2]CNRS (CNRS/INSU), Université de Rennes 1, Géosciences Rennes. 263 av. du général Leclerc, Rennes Cedex, 35042 France.
[3]Institut des Sciences de la Terre de Paris, University of Paris 06-CNRS, UMR 7193, F-75005, Paris, France.
[4]Département des Génies Civil, Géologique et des Mines, École Polytechnique de Montréal, C.P. 6079, succursale Centre-Ville, Montréal, Quebec H3C 3A7, Canada.

In Québec and New England, the Connecticut Valley-Gaspé (CVG) trough is an orogen-scale Silurian-Devonian basin of the Northern Appalachians. From Gaspé peninsula to southern New England, the CVG trough has experienced contrasting metamorphic and structural evolution during the Acadian orogeny. From north to south, it is characterized by increasing (1) deformation and polyphased structures, (2) intensity of regional metamorphism, i.e. from very low-grade to upper amphibolite facies, and (3) abundance of crosscutting ~ 390 to 370 Ma granitic intrusions. In southern Quebec and northern Vermont, a series of NW-SE transects in the CVG trough have been studied to better understand the along-strike structural and metamorphic variations. Detailed structural analyses, combined with phase equilibria modeling, Raman spectrometry and muscovite $^{40}Ar/^{39}Ar$ dating highlight a progressive incremental deformation involving a close timing and spatial north-south diachronism.

In southern Québec, regional deformation is characterized by D_1-related NW-verging folds. Towards the Québec-Vermont border, D_2 fabrics progressively appears as evidenced by SE-verging F_2 folds associated with a S_2 crenulation cleavage that wraps around granitic intrusions. D_2 structures are locally overprinted by a late-stage crenulation cleavage (S_3). Temperature of regional metamorphism (M_1) has been determined from Raman spectrometry. It gradually increases toward the south, from ~ 370°C to 420°C, whereas IPDS suggest that M_1 pressure reached ~ 4 Kb. At the Quebec-Vermont border, the M1 temperature gradient was partially obliterated by the heat released from granitic intrusions. In Vermont, D_2 and D_3 structures are more pervasive and IPDS suggest that P-T conditions reached at least ~ 5 Kbar and 500°C. In Southern Québec, $^{40}Ar/^{39}Ar$ ages of metamorphic muscovites indicate that the D_1 -M_1 greenschist-facies event, peaked at ~ 380–375 Ma. However, in Québec-Vermont border and northern Vermont, ~ 369-355 Ma and ~ 355-335 Ma metamorphic muscovite from upper greenschist/amphibolite facies rocks reflects cooling, and thus minimum ages for the D_2 and D_3 events, respectively. Alleghanian metamorphic ages (~ 300 Ma) are found in easternmost part of the Vermont, in the footwall of the Monroe Fault.

These results can be attributed to spatial and temporal partitioning of compressive deformation during the Acadian orogeny where a differential burial of more than 10km between southern Québec and Vermont during D_1 was followed by a proportional differential exhumation along the strike of the CVG trough. This suggest the presence of a major crustal indenter toward the New England segment of the Acadian orogeny, which is associated to the Bronson Hill Arc Massif.

Sedimentary Provenance of the Elliot Lake and Hough Lake groups, Huronian Supergroup, Sudbury Area.

Josee A. Menard [1]

[1] Department of Earth and Environmental Sciences, University of Waterloo, 200 University Ave W, Waterloo, ON N2L 3G1
ja2menard@uwaterloo.ca

The Huronian Supergroup (HSG) was deposited between 2.2 to 2.4 Ga in a continental rift basin along the southern margin of the Superior Province in Ontario, Canada. This Master's project builds and aims to better understand the results of an undergraduate thesis conducted by the author (Menard, 2017). Previous work in the Huronian Supergroup was limited in areal reach and focussed on the fluvial formations. The preliminary results of five additional samples of the lower Huronian Supergroup in the Sudbury and Elliot Lake area have been analyzed using LA-ICP-MS.

A total of 603 zircon grains with <20% discordance were analyzed: 1) 118 zircons from the Ramsay Lake Formation conglomeratic sandstone, McKim Township, 2) 99 zircons from the McKim Formation, turbidite sequence, siltstone, McKim Township, 3) 188 zircons from the Mississagi Formation, quartz arenite, Drury Township, 4) 91 zircons from the Matinenda Formation, quartz arenite, Drury Township, and 5) 107 zircons from the Ramsay Lake Formation, Joubin Township. This presents the first detrital zircon ages of the McKim Formation turbidite sequence.

The resulting $^{207}Pb/^{206}Pb$ ages were used to create Probability Density Distribution Diagrams and compared against the Ontario Geological Survey Geochronology Database and the Geological Survey of Canada Geochronology for the Superior Province. The vast majority of zircon ages for the Superior Province in these databases fall between 2740 Ma – 2690 Ma. Whereas sediments from the Lower Huronian Supergroup tend to have major peaks between 2690 Ma – 2640 Ma. This observation illustrates a discrepancy between the Huronian Supergroup sediment and the current exposure of the Superior Province. The Timiskaming Assemblage in the Abitibi Subprovince have a maximum depositional age 2679 Ma – 2669 Ma and resedimentation of the Timiskaming could account for some of the 2669 Ma and older ages (Frieman et al., 2017). Given that zircon ages younger than 2690 Ma are uncommon in the currently exposed Superior Province, it is possible for the source terranes of the Huronian Supergroup sediments to have been completely eroded.

Frieman, B. M., Kuiper, Y. D., Kelly, N. M., Monecke, T., & Kylander-Clark, A. (2017). Constraints on the geodynamic evolution of the southern Superior Province: U-Pb LA-ICP-MS analysis of detrital zircon in successor basins of the Archean Abitibi and Pontiac subprovinces of Ontario and Quebec, Canada. Precambrian Research, 292, 398–416.

Water Concentrations in Quartz from Recrystallized Metapelites in the Lower Crust

Nucciarone, M.
Department of Earth and Planetary Sciences, McGill University, Montreal, Canada.

The Lower Fish River Onseepkans Shear Zone (LFROSZ) is a crustal scale tectonic boundary within the central Namaqua-Natal Province located in South Africa. It is interpreted to be a suture zone during collision of the Richtersveld and Grunau provinces (~1200 Ma) that was reactivated in extension (~1100– 1040 Ma). The high grade deformation features of the meta-pelites occurred during reactivation. We examine a protomylonite and an ultramylonite from a pelitic gneiss (quartz-plagioclase-garnet-sillimanite-rutile) exhumed from a lower crustal shear zone (T = ~700°C). This is done using Fourier Transform Infrared (FTIR) spectroscopy and spectral analysis. The ultramylonite has an average water concentration level of 63 ± 3 PPM and the protomylonite has an average water concentration level of 73 ± 4 PPM. The quartz is abundant in the samples, therefore the rheology of the samples is close to quartz. The quartz's water content is low compared to water contents from the literature of naturally and experimentally deformed and undeformed quartz, consequently we may use flow laws of dry rock to estimate its strength. Grain boundary migration is present in the samples, but it does not correlate with water content.

Why do subduction thrusts lock?

Christie D. Rowe, Noah J. Phillips, James D. Kirkpatrick
Earth & Planetary Sciences Department, McGill University.

Solution creep as a deformation mechanism is very efficient in most rocks at low to moderate temperatures, where water is plentiful. Plate boundary faults in subduction zones lie in the pressure-temperature region where solution creep should be able to accommodate strain, potentially keeping up with far-field plate tectonic motions if the deforming zone is sufficiently large. This is particularly true within the (thermally defined) seismogenic zone (~150 – 400°C) where locking must occur because large earthquakes nucleate and propagate through this zone, releasing elastic energy. If solution creep is so efficient, why would these faults ever lock or accumulate elastic strain?

The answer to this paradox must be in the decay in the rate of solution creep by the development of unfavorable conditions at the grain scale. Solution creep is facilitated by interconnected networks of pore water where dissolved minerals can flush through from high-stress dissolution sites to areas of low stress. Limiting the amount of pore water or the connectivity of the fluid network may shut down solution creep. Solution creep redistributes mineral cements to reduce pore space and cement pore throats. Thus, solution creep is an inherently self-limiting deformation mechanism that results in a decay in creep rate on timescales of 10s-100s of years in typical subduction thrust rocks, similar to the timescales of locking inferred for active megathrusts. Once the potential strain rate has decayed below the tectonically imposed plate rate, the plate boundary fault must broaden or will start to develop a slip deficit resulting in the accumulation of elastic strain. The timescale of solution creep self-shut down therefore may be a major control on recurrence interval of megathrust earthquakes.

The Formation of L-tectonites: A Multiscale Numerical Investigation

Rui Yang[1,2], Dazhi Jiang[2,1]
[1]Department of Geology, Northwest University
[2]Department of Earth Sciences, Western University (yangruivv@163.com; djiang3@uwo.ca)

Rocks having a well-developed lineation but weak or no foliation are commonly called L-tectonites. Previous models for L-tectonite formation cannot explain the occurrence of L-tectonites as isolated inclusions in a matrix of S-tectonites or LS-tectonites. In this investigation, a multi-scale numerical modeling approach is followed. We regard the isolated domains containing L-tectonites as heterogeneous Eshelby inclusions embedded in a heterogeneous matrix. The latter consists of rheologically heterogeneous elements. Generalized Eshelby Inclusion Solutions (GEIS) for power-law viscous materials are used for a self-consistent multiscale approach called the MOPLA. In MOPLA the heterogeneous matrix surrounding a rheological inclusion is replaced by a hypothetical homogeneous-equivalent matrix (HEM) whose rheological properties are obtained by homogenization. GEIS are used to obtain the partitioned flow field in an inclusion as well as for homogenization. We examine the set of conditions for the partitioned flow in a heterogeneous inclusion to be favorable for L-tectonite formation. We found that only in inclusions rheologcally stronger than HEM will L-tectonites develop. Strong inclusions with initial prolate, oblate, and sphere shapes were considered. The initial orientation of the strong inclusion also affects the development of constrictional strain under any given boundary condition. Prolate and oblate inclusions under bulk simple shearing flow could easily develop L-tectonites. In a plane-strain general shear with a minor pure shear component (convergence angle $\alpha \approx 10°$), L-tectonites can form within any strong inclusions regardless of their initial shapes. However, in a transpressional zone with biaxial stretching boundaries (e.g., along strike and dip directions), L-tectonites are rarely developed in strong inclusions. As the convergence angle increases to $\alpha > 30°$, no L-tectonites will develop within any strong inclusions. Therefore, the occurrence of L-tectonites allows us to constrain both the rheological properties and the tectonic boundary conditions of the deformation.

Regional folding, quartz veining and gold mineralization in a successor basin in the Abitibi greenstone belt, Malartic, Quebec

Samson, B., Lafrance, B., and Zhou, X.
Mineral Exploration Research Centre, Harquail School of Earth Sciences, Laurentian University, 935 Ramsey Lake Road, Sudbury, Ontario, Canada P3E 2C6

Metal Earth Contribution Number: MERC-ME-2018-055

The Larder Lake–Cadillac deformation zone in the Abitibi greenstone belt is a major crustal-scale deformation zone hosting numerous world-class gold deposits. The Malartic segment is a NW-SE trending bend of this overall E-W trending deformation zone. A sedimentary successor basin, adjacent to the Malartic segment, is comprised of two sedimentary groups: (1) the Cadillac Group (<2686 Ma), which consists of turbiditic sandstone with minor iron formation, and (2) the Timiskaming Group (2677–2672 Ma), which includes polymictic conglomerate, sandstone and minor turbidites. Regional folding has affected these sedimentary rocks causing WNW striking isoclinal folds moderately plunging to the ESE. An axial planar cleavage, oriented anticlockwise to north-younging beds and clockwise to south-younging beds, is expressed as a continuous slaty cleavage in mudstone, as a spaced disjunctive cleavage in sandstone, and by the flattening and elongation of clasts in conglomerate. A mineral stretching lineation defined by biotite porphyroblasts in turbidite and sandstone, and by the elongation of clasts in conglomerate, plunges moderately to the ESE, parallel to the regional fold axes. The folds, cleavage and lineation are interpreted as the earliest generation of deformation structures within the successor basin.

Four generations of quartz veins are present in the basin. V1 veins formed as en echelon arrays in sandstone beds and are oriented anticlockwise to bedding. V2 veins are Z-shaped sigmoidal tension gashes that are oriented and that formed sub-perpendicular to the mineral stretching lineation. V3 veins are S-shaped sigmoidal en echelon veins that were emplaced during sinistral shearing parallel to bedding. V4 veins are gold-bearing (1.7–41 g/t Au), tightly S-folded, extensional veins oriented at a low angle anticlockwise to bedding on both limbs of regional folds. Their S-shaped geometry suggests that they formed during the same deformation, albeit later, as the V3 veins. Their consistent orientation anticlockwise to bedding on both limbs of regional folds suggests that they were emplaced and gold mineralization was deposited late during or after regional folding.

Late dextral bedding-parallel shearing overprint all veins and host rocks as indicated by: (1) the clockwise rotation of the tips of V1 veins, (2) Z-shaped folding of V2 veins, (3) extension (boudinaged) and overprinting of V4 veins by dextral shear bands, (4) the presence of Z-shaped flanking folds adjacent to V4 veins, and (5) asymmetrical strain shadows surrounding granitoid clasts within conglomerate. These structures are observed across the basin, suggesting that dextral shearing was a regional event after the regional folding.

Carboniferous Ainslie Detachment of Atlantic Canada: is it everywhere a salt weld?

John W.F. Waldron[1]
Department of Earth & Atmospheric Sciences, University of Alberta, Edmonton AB T6G2E3. John.waldron@ualberta.ca

The Maritimes Basin of Atlantic Canada is a large (over 400 km diameter) and deep (>12 km) sedimentary basin underlying large parts of the Gulf of St. Lawrence and Prince Edward Island, and portions of New Brunswick, Nova Scotia, and Newfoundland. The basin fill is predominantly late Paleozoic (Devonian-Permian) non-marine clastic sedimentary rocks, which display a consistent group-level stratigraphy over most of the basin, but the Viséan Windsor Group, and the correlative Codroy Group of Newfoundland, contain substantial evaporites, including gypsum and anhydrite, halite, and potash. Laterally correlative limestone-evaporite-shale cycles have been traced throughout the middle and upper parts of the Windsor Group.

The role of rising evaporite diapirs derived from the Windsor Group in the tectonics of the Maritimes Basin has long been recognized. In addition to these features generated by primarily vertical tectonics, the Maritimes Basin displays extensive low-angle deformation surfaces characterized by anomalous breaks in the basin-wide stratigraphic succession. These breaks were originally interpreted as thrust faults, but later investigations, noting substantial omission of stratigraphy, led to their re-interpretation as a single regional low-angle detachment surface, the Ainslie Detachment.

Analysis of seismic profiles allows the timing of salt movement to be resolved. In the western Cumberland sub-basin, for example, the famous Joggins Pennsylvanian succession was rapidly deposited in accommodation space created by salt expulsion, showing that Windsor Group salt had remained in place until the late Bashkirian before rapidly moving into diapiric salt walls. In contrast, in the eastern Cumberland sub-basin, evaporite expulsion was already controlling sedimentation during late Viséan to Serpukhovian deposition of the Mabou Group, and probably during deposition of the underlying Windsor Group. Field relations in other parts of the Maritimes Basin, where the Mabou and upper parts of the Windsor Groups show striking thickness variations, suggest that this history of early evaporite expulsion is more usual.

These observations suggest a new interpretation, in which movement of a thick lower Windsor evaporite layer began within a few million years of its deposition. Feedback between halokinesis and sedimentation occurred from mid-Viséan onward. Multiple minibasins active during deposition of the middle and upper Windsor Group were simultaneously flooded by eustatic sea-level rises, related to glacial cycles on Gondwana, accounting for the laterally continuous limestones. Differences in the overlying stratigraphic successions are best explained, therefore, by deposition above a changing configuration of moving evaporite bodies that culminated in complete expulsion of salt beneath some minibasins, and not by excision at a basin-wide normal fault. The 'Ainslie Detachment' can therefore be reinterpreted as an evaporite weld.

Diachronous development of the Taconian pro-arc foreland basin in the northern Appalachian Orogen

White, Shawna E.[1] and Waldron, John W.F. [2]
[1]Mineral Exploration Research Center, Laurentian University, Sudbury
[2]Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton

The Anticosti Basin includes foreland basin successions that record distinct tectonic loading events associated with Middle Ordovician to Early Devonian evolution of the northern Appalachian Orogen. Due to the fact that the basin is largely hidden beneath the Gulf of St. Lawrence, with few exposures on small islands and along the western coast of Newfoundland, we reply heavily on geophysical data to map these successions. An absence of wells drilled offshore means that 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, it is possible to tie onshore outcrops to seismic reflections.
Seismic isochron maps of the Ordovician foreland successions show important differences in geometry, and imply that orogenic loading varied through time in amount, distribution and location. The geometry and subsidence rates of the Middle Ordovician foreland succession imply formation in a pro-arc setting associated with loading from the Newfoundland portion of the Appalachian Orogen. These results are consistent with east-dipping subduction of the Laurentian margin beneath obducted allochthons and microcontinents. In Newfoundland, subduction polarity reversal at 460 Ma placed the Laurentian Craton on the upper plate, implying that the Upper Ordovician Long Point Group was deposited in a retro-arc basin. However, high subsidence rates are consistent with development in a pro-arc setting and basin geometry suggests that loading of the Laurentian margin by Taconian allochthons in Quebec was responsible for generating this Upper Ordovician foreland basin. These observations are consistent with continued allochthon emplacement onto the downgoing Laurentian plate until at least 450 Ma in the Quebec Embayment, the age of the youngest flysch units incorporated into allochthons. Subduction polarity reversal immediately followed, as constrained by the 450 Ma age of the oldest forarc sediments unconformably overlying Taconian allochthons in Quebec. The 10 Myr delay in polarity reversal in Quebec (with respect to Newfoundland) positioned the Long Point Group in a unique tectonic setting, a combined retro-arc and pro-arc setting. This basin setting is analogous to the current tectonic setting of the northern Australian Plate near Papua New Guinea and is a direct consequence of the irregular margin shape.

A Weighted Least Square Particle-in-cell Solver for Nonsteady Multiphase Geological Flow

Qihang Wu, Shoufa Lin
Department of Earth and Environmental Sciences, University of Waterloo.

Numerical simulations of geological flows are frequently faced with the following difficulties: 1) large finite strain accumulated through prolonged period of deformation; 2) complex interactions between materials with drastically different rheological properties. The former requires a computational mesh that retains its quality under large deformation, while the latter requires an accurate tracking algorithm for material interfaces. To solve these two problems, we generate a set of marker particles (or material points) to represent geological material, alongside with a structured computational mesh. At the start of each computational cycle, the material properties and dynamic information stored on the material points are projected onto the computational mesh. The governing equations, in this case the incompressible Navier-Stokes equations, are then discretized and solved on the computational mesh by the finite element method. The updated dynamic parameters are interpolated back to material points to propel advection. To ensure the accuracy of the projection from material point to the computational mesh and smooth out the numerical noise, a weighted least square framework is implemented on the computational mesh by minimizing a weighted error norm. In addition to the material points, we use a front-tracking algorithm based on a set of interface particles. The advection velocity of the interface particles are also interpolated from the computation mesh so that particle inter-penetration does not happen. The solver is tested on Newtonian and power-law flow models and demonstrates good fit with analytical solutions or solutions from established fluid solvers. The solver is applied to model rotating porphyroclast under a simple shear regime and the formation of sigma- and delta-type tails is successfully simulated.

Fault kinematics and structural evolution along the Amos-Malartic transect in the Southern Abitibi and Pontiac Subprovinces, Quebec, Canada

Zhou, X. and Lafrance, B.
Mineral Exploration Research Centre, Harquail School of Earth Sciences, Laurentian University, 935 Ramsey Lake Rd, Sudbury, Ontario, P3E 2H6. Email: xzhou1@laurentian.ca

Metal Earth Contribution Number: MERC-ME-2018-047

The Superior Province is the largest exposed Archean craton in the world. It consists of generally east-striking metavolcanic-granitoid subprovinces (e.g. Abitibi, Uchi) separated by subprovinces (e.g., Pontiac, English River) dominated by metasedimentary and gneissic rocks. Numerous world-class gold, volcanogenic massive sulfide, and less-known magmatic nickel-copper deposits are spatially associated with east-striking, subvertical, crustal-scale deformation zones along subprovince boundaries (e.g., Larder Lake-Cadillac Deformation Zone), or along contact zones (Porcupine-Destor-Manneville Deformation Zone) between metavolcanic and metasedimentary rocks within subprovinces. These province-scale faults exert key controls on the formation of deposits since they act as conduits for the flow and migration of ore-forming fluids.
Detailed geological mapping was carried out in the highly metal-endowed Amos-Malartic transect area. A geometric and kinematic analysis was done on crustal scale deformation zones, namely the Porcupine-Destor-Manneville, the Larder Lake-Cadillac and the less-known Chicobi deformation zones. Notwithstanding early S_1 fabrics locally preserved in foliated xenoliths in plutons or in gneissic clasts in deformed polymictic conglomerate along the deformation zones, all three deformation zones show a strong penetrative west-to-northwest–striking subvertical (S_2) cleavage, which is axial planar to regional, upright, isoclinal to tight, F_2 folds. A stretching (L_2) lineation lies on the S2 cleavage and typically plunges steeply near the contact between metavolcanic terranes and sedimentary basins, and becomes moderately-plunging toward the centre of these basins. Shear sense indicators suggest that the older volcanic terranes move upward with respect to the sedimentary basins. The main (S_2) cleavage is folded by late (F_3) Z or M folds and kink band cleavage. Recognizing the similarities and differences between major ore-hosting deformation zones is the first step towards understanding the regional structural control on mineralization, which is one of the major goals of the Metal Earth project.

Structure of the Ascot Complex Volcanic Arc and Magog Group Basin, southern Québec Appalachians
- CTG 2018 Field Trip Guidebook -

Alain Tremblay and Morgann Perrot
Département des Sciences de la Terre et de l'Atmosphère
Université du Québec à Montréal
Montréal, Qc, H3C 3P8

INTRODUCTION

This field trip focuses on the lithological characteristics and structural features of an Ordovician volcanic arc, the Ascot Complex, and adjacent forearc basin sequence, the Magog Group, from the oceanic domain (Dunnage Zone) of the southern Québec Appalachians. A particular emphasis is made on the structural characteristics of the Ascot Complex, which is used as a template for Middle Devonian Acadian metamorphism and deformation in southern Quebec. We will visit key outcrops in the Sherbrooke area.

THE SOUTHERN QUÉBEC APPALACHIANS

The Appalachian belt is the result of the closure of oceanic basins (Iapetus and Rheic oceans and smaller marginal oceanic domains) and collisions of Laurentia, Baltica and Gondwana-derived continental blocks during the Paleozoic. The Québec Appalachians represent a 1000 km-long segment of that mountain belt (Figure 1), covering approximately 75,000 km^2, which corresponds to ca. 25% of the surface area of the Northern Appalachians. The southern Québec Appalachians comprise three lithotectonic assemblages (Figure 2): the Cambrian-Ordovician Humber and Dunnage zones (Williams, 1979), and the Silurian-Devonian successor sequence of the Gaspé Belt (Bourque et al., 2000). The Humber and Dunnage zones are remnants of the Laurentian continental margin and of the adjacent oceanic domain, respectively. The Humber-Dunnage boundary corresponds to a zone of dismembered ophiolites and serpentinite slices known as the Baie Verte-Brompton line (BBL; Williams & St-Julien, 1982). The Dunnage zone is unconformably overlained by Upper Silurian and Devonian rocks of the Gaspé Belt (Figure 2).

The Humber Zone is divided into external and internal zones (Tremblay & Castonguay, 2002). The external Humber Zone consists of very low-grade sedimentary and volcanic rocks deformed into a series of northwest-directed thrust nappes. The internal Humber Zone is made of greenschist- to amphibolite-grade metamorphic rocks that represent distal facies of the external Humber Zone units.

The highest-grade metamorphic rocks occur in the core of dome structures (i.e. the Sutton Mountains and Notre-Dame Mountains anticlinoria; Figure 2) within the internal Humber Zone. Regional deformation includes a S_{1-2} schistosity and syn-metamorphic folds and faults, which have been overprinted by a penetrative crenulation cleavage (S_3 of Tremblay & Pinet, 1994) axial-planar to hinterland-verging (southeast) folds and ductile shear zones rooted along the northwestern limb of the internal Humber Zone (Pinet et al., 1996; Tremblay & Pinet, 2016; Figure 3).

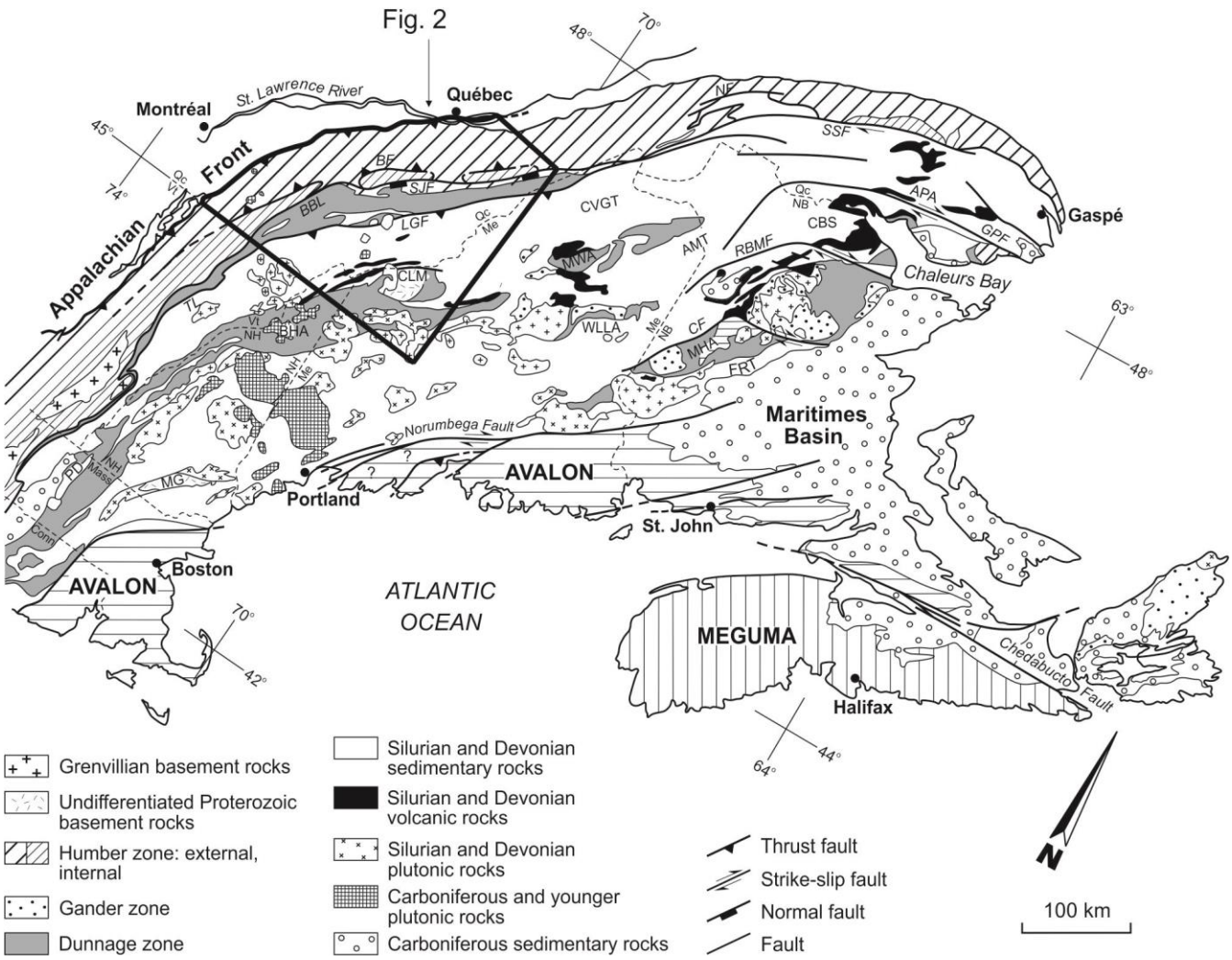

Figure 1. Simplified geological map of the Northern Appalachians of mainland Canada and New England showing the major lithotectonic elements of the region. Modified from Williams (1978). Basement rocks: CLM—Chain Lake Massif; MG—Massabesic Gneiss and PD—Pelham Dome. Major trough, anticlinoria and synclinoria: AMT—Aroostook–Matapedia trough; CVGT—Connecticut Valley-Gaspé trough; FRT—Fredericton trough ; APA—Aroostook–Percé anticlinorium; CBS—Chaleurs Bay synclinorium; BHA—Bronson Hill Anticline; MHA—Miramichi Highlands Anticline; MWA—Munsungun–Winterville Anticline and WLLA—Weeksboro–Lunksoos Lake Anticline. Major faults: BBL—Baie Verte–Brompton Line; BF—Bennett fault; SJF—Saint-Joseph fault; LGF—La Guadeloupe fault; TL—Taconic Line; NF—Neigette fault; SSF—Shickshock-Sud fault; GPF—Grand Pabos fault; RBMF—Rocky Brook–Millstream fault and CF—Catamaran fault. State boundaries: Conn—Connecticut; Mass—Massachusetts; Me—Maine; NB—New Brunswick; NH—New Hampshire; Qc—Quebec and Vt—Vermont. Note that the boundary between Medial New England (Gander zone) and Composite Avalon is approximate; see text for discussion. Modified from Tremblay and Pinet (2005).

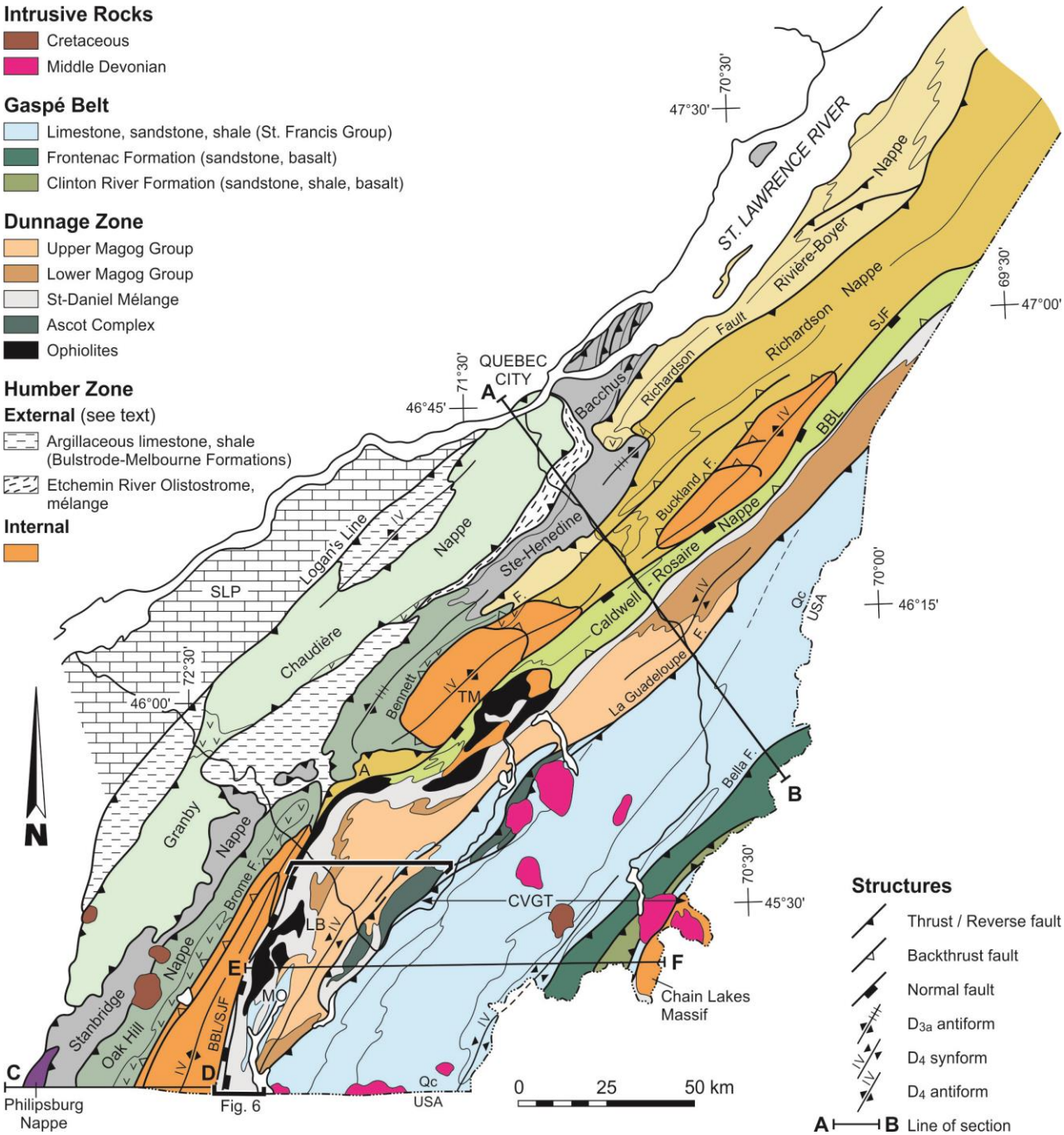

Figure 2. Geological map of the southern Quebec Appalachians (from Tremblay & Pinet, 2016). BBL, Baie Verte-Brompton line; CVGT, Connecticut Valley-Gaspé Trough; SJF, Saint-Joseph fault; SLP, St. Lawrence Platform. Ophiolites: A, Asbestos ophiolite; LB, Lac Brompton ophiolite; MO, Mount Orford ophiolite; TM, Thetford Mines ophiolite. «v» pattern in the external Humber Zone nappes is for mafic volcanic rocks. Me, Maine; NH, New Hampshire; Vt, Vermont. Structural profiles A–B and C–D–E–F are show in Fig. 3. From Tremblay and Pinet (2016).

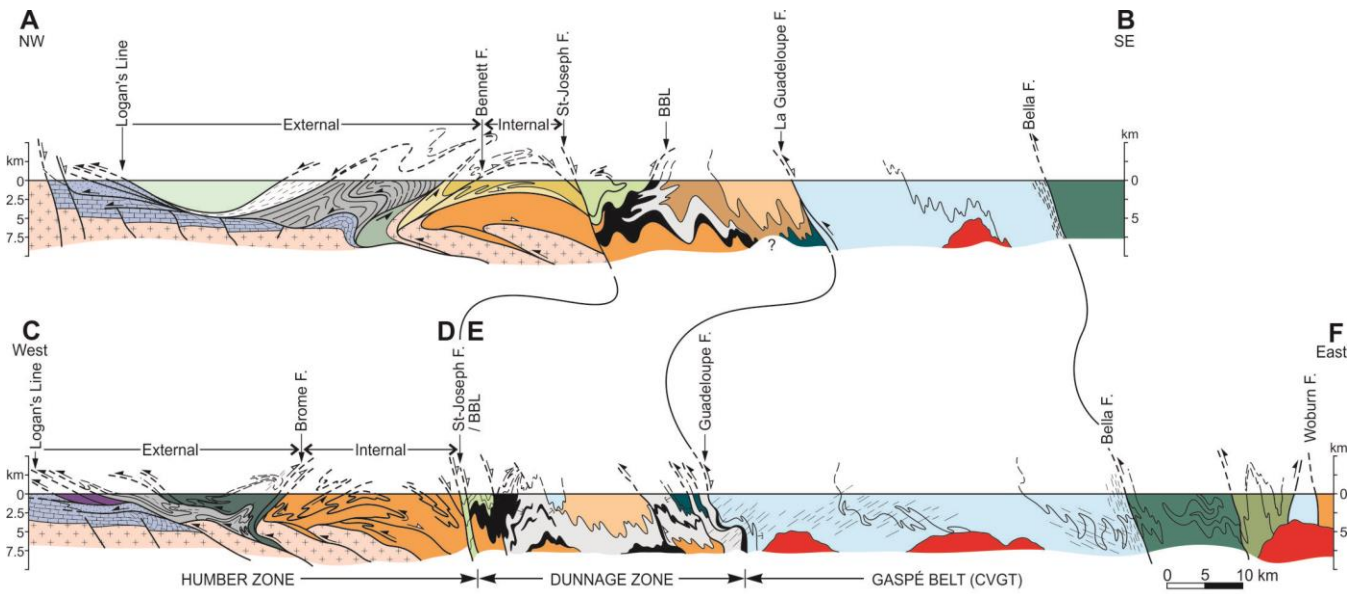

Figure 3. Structural profiles A–B and C–D–E–F of the southern Quebec Appalachians. Same lithological symbols as Figure 2. Cross pattern for Grenvillian basement rock. See Figure 2 for location. From Tremblay and Pinet (2016)

Amphibole and mica $^{40}Ar/^{39}Ar$ ages from the internal Humber Zone of southern Quebec vary between 431 and 410 Ma (Figure 4). Ordovician high-temperature step ages (462-460 Ma) suggest that the geochronologic imprint of typical Taconian metamorphism is locally preserved (Castonguay et al., 2001; 2007; Tremblay & Castonguay, 2002). To the southeast, the internal Humber Zone is bounded by the Saint-Joseph fault (Pinet et al., 1996) and the BBL, which form a composite east-dipping normal fault system marking a boundary with less metamorphosed rocks in the hanging wall (Figures 2 and 3). East of the Saint-Joseph-BBL fault system, continental metamorphic rocks, which yielded Middle Ordovician $^{40}Ar/^{39}Ar$ muscovite ages (469-461 Ma; Whitehead et al., 1995; Castonguay et al., 2001; Figure 4) are locally exposed in the core of antiformal inliers.

THE SOUTHERN QUÉBEC DUNNAGE ZONE

The Dunnage Zone occurs in the hanging wall of the Saint-Joseph-BBL fault system and comprises ophiolites, mélanges, volcanic arc sequences, and marine flysch deposits. In southern Quebec it is made up of four lithotectonic assemblages (Figure 2): (1) the Southern Quebec ophiolites, mainly represented by four massifs, the Thetford-Mines, Asbestos, Lac-Brompton and Mont-Orford ophiolites; (2) the Saint-Daniel Mélange; (3) the Magog Group forearc basin; and (4) the Ascot Complex volcanic arc (see Tremblay et al., 1995 for a review).

Ophiolites. The Thetford-Mines and Asbestos ophiolites are characterized by well-preserved mantle and crustal sections, whereas only the mantle and a dissected part of the oceanic crust are exposed in the Lac-Brompton ophiolite. U/Pb zircon dating from felsic rocks of the Thetford-Mines and the Asbestos ophiolites yielded ages of 479 ± 3 Ma and 478-480 $^{+3}/_{-2}$ Ma, respectively (Dunning et al., 1986; Whitehead et al., 2000). These three ophiolitic massifs are dominated by magmatic rocks with boninitic affinities (and subordinate tholeiites), a feature which has been attributed to their genesis either in a forearc environment (Laurent & Hébert, 1989; Hébert & Bédard,

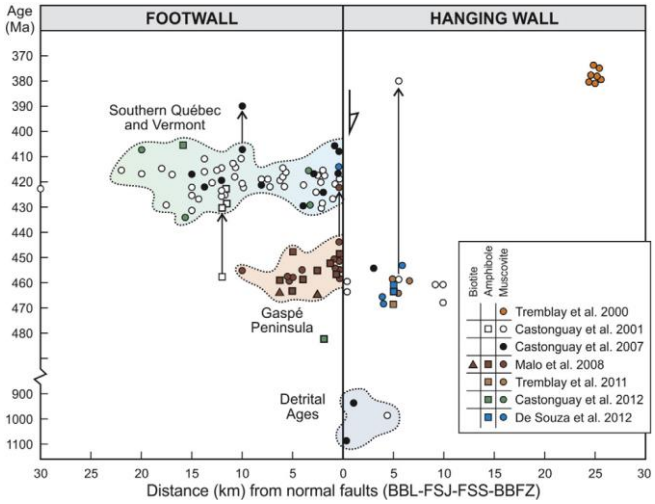

Figure 4. Compilation of $^{40}Ar/^{39}Ar$ plateau and sub-plateau ages for metamorphic rocks of the hanging wall and footwall of the BBL-Saint-Joseph fault (SJF) and correlative structures of northern Vermont (Burgess Branch fault zone, BBFZ) and Gaspé Peninsula (Shickshock-Sud fault, SSF). The x-axis indicates the approximative distance (in km) of analysed samples from these faults (as measured perpendicular to the trace of faults). Black arrows are for samples showing spectra with younger thermal disturbances. Note the contrast of metamorphic age distribution on both sides of the BBL-SJF-BBFZ and the occurrence of Grenvillian ages in the hanging wall. Some dots may represent several single age results. From Tremblay and Pinet (2016).

2000; de Souza et al., 2008), and/or in a backarc setting (Oshin & Crocket, 1986; Olive et al., 1997). In contrast, only the crustal section is present in the Mont-Orford ophiolite (Figure 2), which contains a greater diversity of magma types, interpreted in terms of arc-backarc (Harnois & Morency, 1989; Laurent & Hébert, 1989; Hébert & Laurent, 1989) or arc-forearc to backarc environments (Huot et al., 2002). The Mont-Orford ophiolite has a maximum age of 504 ± 3 Ma (David & Marquis, 1994).

Amphibolites from the dynamothermal sole of the Thetford-Mines ophiolite and adjacent micaschists yielded $^{40}Ar/^{39}Ar$ ages of 477 ± 5 Ma (Whitehead et al., 1995) and 471-461 Ma (Figure 4; Castonguay et al., 2001; Tremblay et al., 2011), respectively, suggesting that intra-oceanic detachment of the ophiolite (ca. 475-470 Ma) occurred immediately after oceanic crust formation (ca. 480 Ma); with emplacement against continental margin rocks and associated metamorphism occurring afterwards (ca. 470-455 Ma; Tremblay et al., 2011).

Saint-Daniel Mélange. The Saint-Daniel mélange (Figure 2) is a Middle Ordovician (Darriwilian) lithostratigraphic unit that represents the lowermost series of the western (present coordinates) part of a forearc basin that lies on a partly-eroded ophiolite basement and which is mainly represented by the Magog Group (Schroetter et al., 2006). The lower contact of the mélange represents an erosional unconformity marking the base of the forearc basin. The processes that formed the chaotic and breccia units of the mélange were the successive uplift, erosion, and burial by heterogeneous and localized debris flows of different parts of the ophiolite and of the underlying metamorphic rocks during the emplacement of the ophiolite. $^{40}Ar/^{39}Ar$ muscovite ages between 467 and 460 Ma were yield by metamorphic fragments of basal debris flows of the Saint-Daniel mélange (Schroetter et al., 2006; Tremblay et al., 2011; Tremblay & Pinet, 2016). This is within the age range of regional metamorphism in rock units structurally below the ophiolites (Figure 4) and implies that the exhumation of these metamorphic rocks occurred during or shortly after the emplacement of the ophiolite onto the continental Laurentian margin.

Magog Group. The Magog Group (Figure 2; Cousineau & St-Julien, 1994) unconformably overlies both the Saint-Daniel Mélange and the Ascot Complex (Figure 5). It is made up of four units: (i) lithic sandstones and black shales of the Frontière Formation; overlain by (ii) purple-to-red shales, green siliceous siltstones and fine-grained volcaniclastic rocks of the Etchemin Formation; overlain by (iii) pyritous black shales and volcaniclastic rocks of the Beauceville Formation; overlain by (iv) sandstones, siltstones and shales with occurrences of tuff and conglomerate

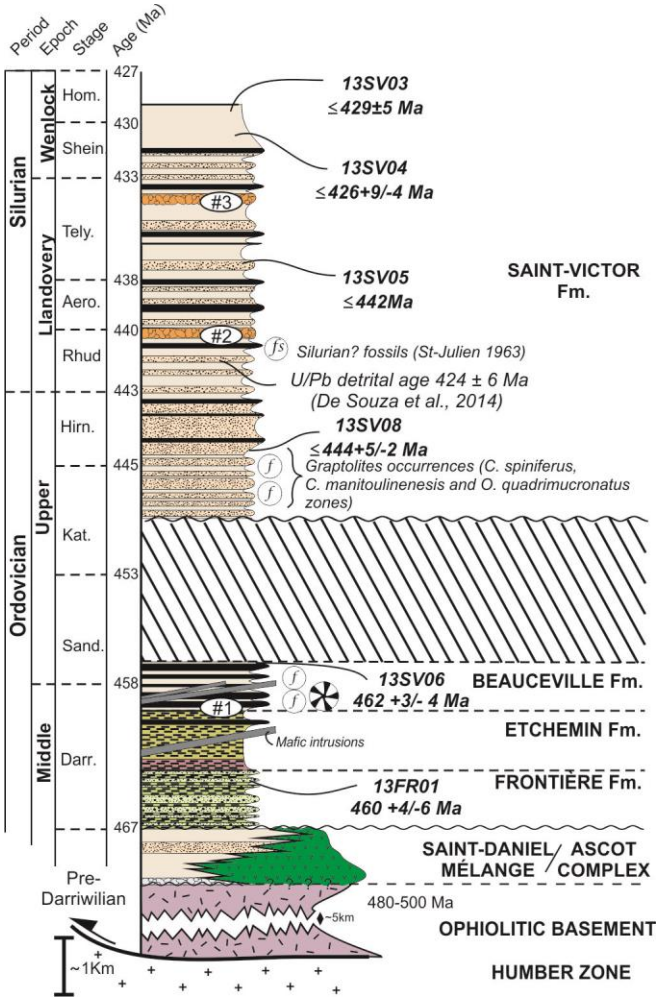

Figure 5. Stratigraphy of the Magog Group and underlying units as revised by Perrot et al. (2017). Chronostratigraphic limits (in Ma) and subdivisions are from Cohen and others (2013). The diagonal lines pattern refers to a sedimentary hiatus between the lower (Frontière, Etchemin and Beauceville formations) and upper part (Saint-Victor Formation) of the Magog Group.

constituting the Saint-Victor Formation, which makes up over 70% of the thickness of the Magog Group.

Graptolites, *Nemagraptus gracilis*, found in the Beauceville and Saint-Victor formations are Late Llandeilian to Early Caradocian (Middle Ordovician). However, the age of the Saint-Victor Formation has been recently put into question by detrital U-Pb zircon ages of 435 to 420 Ma measured in its medial and uppermost strata (de Souza et al., 2014; Perrot et al., 2017; Figure 5).

Ascot Complex. The Ascot Complex (Figures 2 and 6) is interpreted as the remnant of a 460 ± 3 Ma volcanic arc sequence (Tremblay et al., 1989a; Tremblay et al., 2000). It is made up of various metavolcanic rock series, in inferred fault contact with laminated and pebbly phyllites that have been correlated with the Saint-Daniel Mélange (Tremblay & St-Julien, 1990). The Ascot Complex is the sole occurrence of an Ordovician peri-Laurentian volcanic arc sequence in the Quebec Appalachians. Correlative volcanic rocks are lacking in Temiscouata and Gaspé Peninsula, either because the inferred arc massif(s) did not develop there or have been buried beneath the Silurian–Devonian cover rocks of the Gaspé belt. Roy (1989) suggested that Middle Ordovician volcanic rocks of the Winterville-Munsungun formations of northeastern Maine correlate with the Ascot Complex but van Staal and Barr (2012) argued that the they rather belong to the Gander margin, a peri-Gondwanan terrane of the Northern Appalachians.

Structure and metamorphism. In the southern Québec Dunnage Zone, regional deformation and metamorphism are related to the Middle Devonian Acadian orogeny (Tremblay 1992a; Cousineau & Tremblay, 1993). Peak metamorphism varies from greenschist grade in the south (i.e., in the vicinity of the Québec-Vermont border), to prehnite-pumpellyite grade in the Chaudière river area (Figure 2). $^{40}Ar/^{39}Ar$ dating of greenschist-grade metamorphic rocks of the Ascot Complex yielded 380-375 Ma (Figure 4; Tremblay et al., 2000). The Magog Group is characterized by tight regional folds, generally overturned to the NW. Folds plunge gently or moderately to the SW or the NE. Evidence for intense Ordovician (Taconian) metamorphism and deformation is absent.

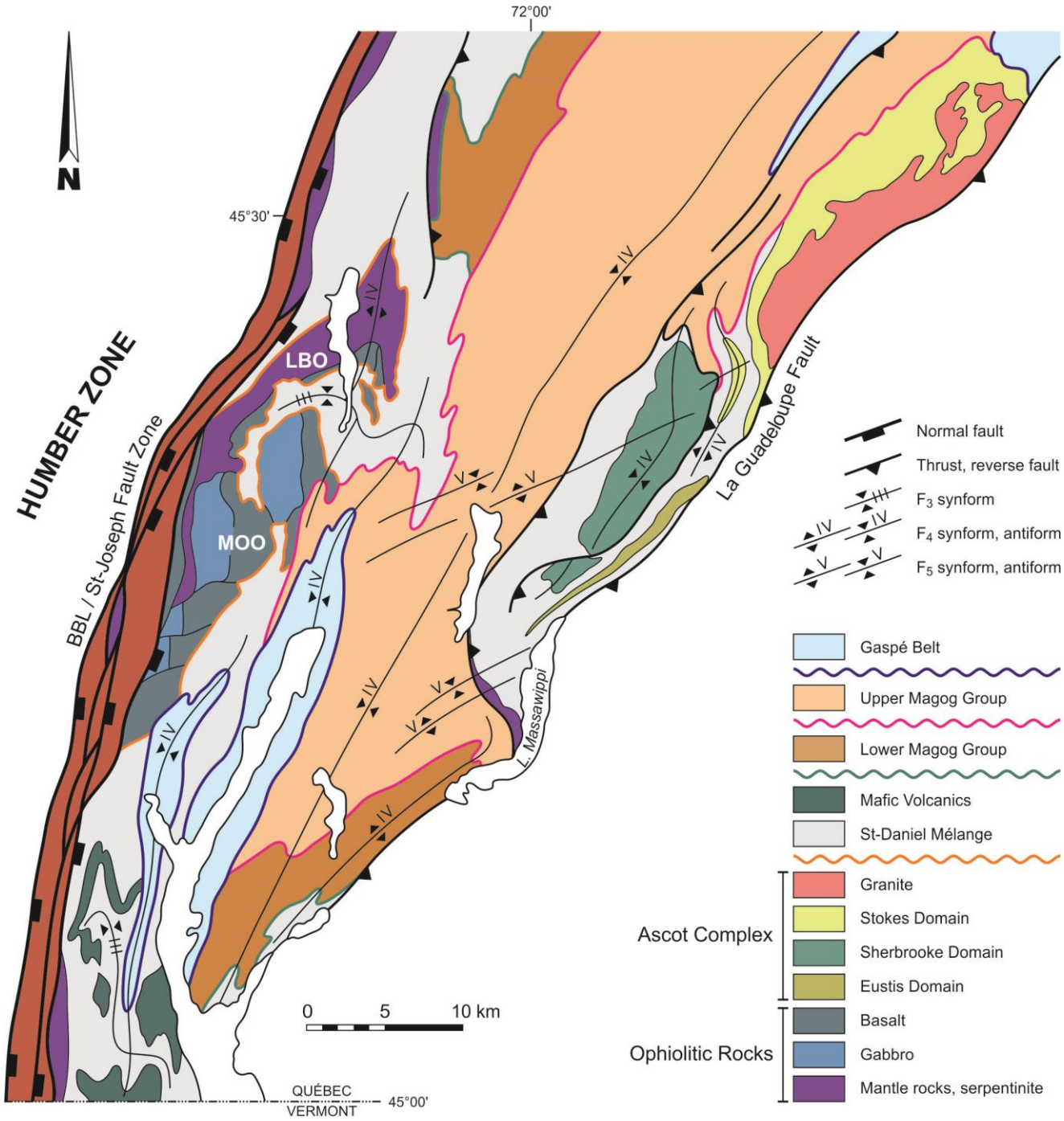

Figure 6. Geological map of the Sherbrooke-Magog area showing the distribution and relationships between the various unconformities separating units of the Dunnage Zone. Sh, Sherbrooke. LBO, Lac-Brompton ophiolite. MOO, Mont-Orford ophiolite. See Figure 2 for location. From Tremblay and Pinet (2016).

TECTONIC EVOLUTION

In the Northern Appalachians, the Taconian orogeny was historically interpreted as the result of a collision between Laurentia and an island arc terrane that was formed over an east-facing subduction zone (Osberg, 1978; Stanley & Ratcliffe 1985). The Acadian orogeny is viewed as the consequence of the accretion of terrane(s) from the east by either a renewed tectonic convergence (Osberg et al., 1989) or by polarity flip of the Taconian subduction zone (van Staal et al. 1998).

On the basis of age data for arc volcanism and ophiolite genesis in southern Québec, as well as the similar lithological and structural setting of ophiolites of southern Québec and western Maine, Pinet and Tremblay (1995) proposed an alternative hypothesis for the Taconian orogeny. In their model, the Taconian deformation and metamorphism of the Laurentian margin is attributed to the obduction of a large-scale ophiolitic nappe that predates collisional interaction with the volcanic arc.

The structural evolution of the Laurentian continental margin and adjacent Dunnage Zone of southern Québec has been summarized by Tremblay and Pinet (2016). The Taconian stage (ca. 470 to 450 Ma) involved the stacking of northwest-directed thrust nappes (Figure 7). That deformation, known as D_{1-2} (Tremblay & Pinet, 1994), progressed from east to west, from ophiolite emplacement and related metamorphism in the underlying margin in the early stages of crustal thickening, to the piggyback translation of accreted material toward the front (west side) of the accretionary wedge. Obducted oceanic crust remained relatively undeformed except for minor tectonic slicing. Underplating of the overridden margin and the foreland (westward) translation of metamorphic rocks due to frontal accretion have led to progressive exhumation of deeper crustal levels of the orogeny (Figure 7), hence preserving Ordovician isotopic ages. Parts of those Ordovician ages are now preserved below the ophiolite in the downthrown side of the St-Joseph-BBL fault system (Figure 4).

D_3 deformation began in latest Early Silurian time (ca. 430 Ma) and lasted until the Early Devonian (ca. 410 Ma; Figure 4). $^{40}Ar/^{39}Ar$ age data suggest that D_3 first consisted of ductile shear zones defining a major upper plate-lower plate (UP-LP) boundary, i.e. the Bennett-Brome fault, and culminated with normal faulting along the St-Joseph fault and the Baie Verte-Brompton line (Figure 4). The upper plate is made up of a folded stack of D_{1-2} nappes of deformed and metamorphosed rocks of the Taconian accretionary wedge and includes metamorphic rocks that retain Ordovician ages. Low- and high-angle normal faulting was probably activated in Late Silurian-Early Devonian time (Figure 4) and crosscut the UP-LP boundary, which led to the juxtaposition of metamorphic rocks from different crustal levels on both sides of the St-Joseph-BBL fault system. East of the St-Joseph-BBL fault system, the D_3 event thus accounts for the presence of external-zone rocks, their juxtaposition with ophiolites or underlying metasedimentary rocks, and the presence of SE-verging recumbent folds (originally interpreted as gravity nappes by St-Julien & Hubert, 1975).

Acadian compression resulted in the folding of D_{1-2} and D_3 structures and in the passive rotation and steepening of high-angle normal faults (Figure 4), which conducted to the current geometry of the belt (Figure 5b). Tectonic inversion of normal faults has probably occurred.

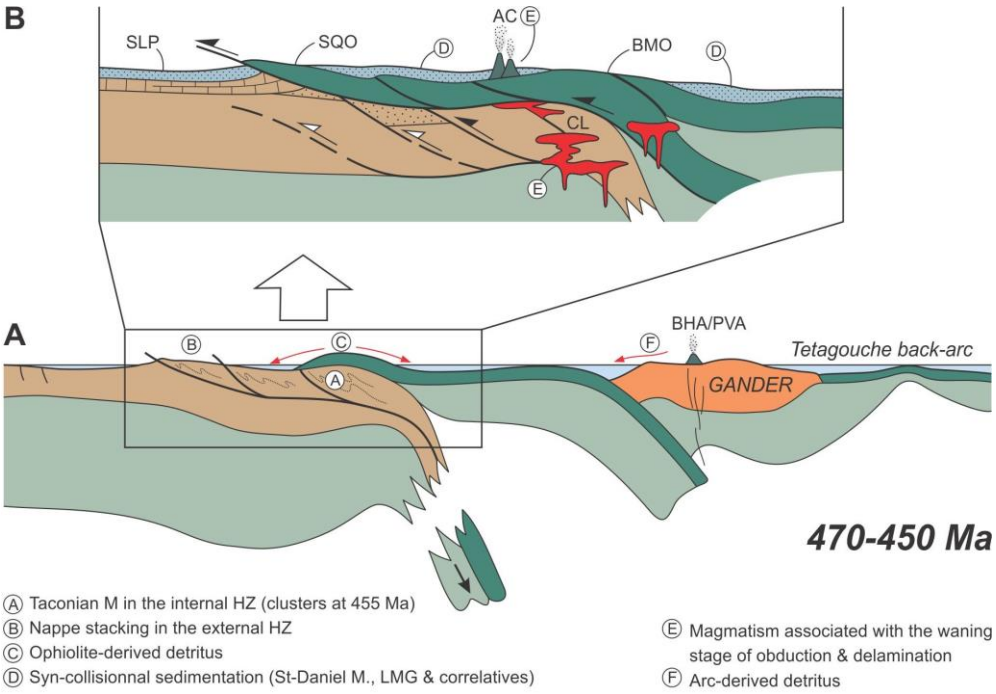

Figure 7. (A) Geodynamic setting of the Northern Appalachians during the Middle to Late Ordovician Taconian orogeny in mainland Canada and adjacent New England. BHA/PVA, Bronson Hill and Popelogan-Victoria arcs. (B) Details on the tectonic setting and structural evolution of the Quebec Appalachians. AC, Ascot Complex; CL, Chain Lakes Massif; SLP, St. Lawrence platform; SQO, Southern Quebec ophiolites. Brown pattern, Grenvillian basement. From Tremblay and Pinet (2016).

GEOLOGY OF THE SHERBROOKE AREA

The Sherbrooke area (Figure 8) exposes three major units of the southern Québec Appalachians, from base to top, the Ascot Complex, the Magog Group and the St. Francis Group, which are briefly described below. During this field trip, we will visit representative outcrops of the two first units with, however, a particular emphasis on the Ascot Complex.

The Ascot Complex has been divided into three lithotectonic domains separated by mélange-type phyllites, the Sherbrooke, Eustis, and Stoke domains (Tremblay, 1992b; Figure 8). The Sherbrooke domain consists of felsic and mafic volcanic rocks. Felsic rocks are pyroclastic breccias, crystal and aphanitic tuffs, and foliated equivalents. U-Pb zircon dating of a rhyolite from the Sherbrooke domain yielded 441 $^{+7}/_{-12}$ Ma (David and Marquis, 1994). Mafic rocks are vesicular to amygdaloidal, massive and pillowed basalts, chlorite schists, and a lesser amount of mafic tuffs. The Eustis domain is mainly characterized by quartz-plagioclase-sericite-chlorite schists originating from coarse-grained to conglomeratic volcaniclastic rocks. In the Stoke domain, felsic rocks predominate over mafic volcanic rocks. Felsic rocks are homogeneous, porphyritic to fine-grained pyroclastic rocks of rhyolitic composition. Mafic volcanics are pillowed basalts and chlorite schists. The volcanic rocks are intruded by a granitic massif, the Ascot Complex pluton, interpreted as an equivalent of the extrusive sequence (Tremblay et al., 1994). The Ascot Complex pluton lacks isotopic dating but $^{40}Ar/^{39}Ar$ high-temperature muscovite ages of 462 Ma has been measured (Tremblay et al., 2000). This is consistent with U/Pb dating of a rhyolite of the Stoke domain, at 460 ± 3 Ma, with a significant proportion (~25%) of inherited zircons of Precambrian and Archean ages (David and Marquis,

1994). The phyllites of the Ascot Complex are laminated argillite and graphitic pebbly mudstone, the latter containing clasts of shale, dolomitic siltstone, and black sandstone. Tectonic slivers of serpentinite occur near major faults such as the La Guadeloupe fault (Tremblay et al., 1989b) and the Massawippi Lake fault zone (Tremblay and Malo, 1991).

The Magog Group occupies the core of the Saint-Victor synclinorium (Figures 2 and 8), which consists of northeast- and southwest-plunging, open to tight folds, commonly overturned to the northwest. In the Sherbrooke area, Tremblay (1992b) subdivided the Magog Group into two units; (i) a lower unit of volcanic conglomerate and feldspathic sandstone with interlayered rusty slates attributed to the Beauceville Formation, and (ii) an upper unit of conglomerate, turbiditic sandstone-shale assemblage and black slates forming the Saint-Victor Formation. In the Stoke Mountains area, north of Sherbrooke, the lower unit of the Magog Group unconformably overlies the Ascot Complex (Mercier, 2013). U-Pb detrital zircon dating in rocks of this lower unit yielded lower Silurian ages (ca. 435 Ma; Perrot et al., 2017), which is incompatible with the age of the Beauceville Formation (see above) and suggests that both the lower and upper units belong to the Saint-Victor Formation. The upper unit is a typical flysch-dominated series, which consists of a lower sandstone-rich and an upper slate-rich turbidite sequences that are separated by a regional stratigraphic marker horizon of channel-facies arkosic sandstone and conglomerate.

The Silurian and Devonian rocks of St. Francis Group crop out east of the Ascot Complex, in the hanging wall of the La Guadeloupe fault (Figure 8), where they occupy the core of the Connecticut Valley -Gaspé trough, a major sedimentary basin that extends from New England to Gaspé Peninsula (Bourque et al., 2000; Tremblay and Pinet, 2005). In the Sherbrooke area, it consists of the Ayer's Cliff and Compton formations. The Ayer's Cliff Formation is a homogeneous sequence of impure

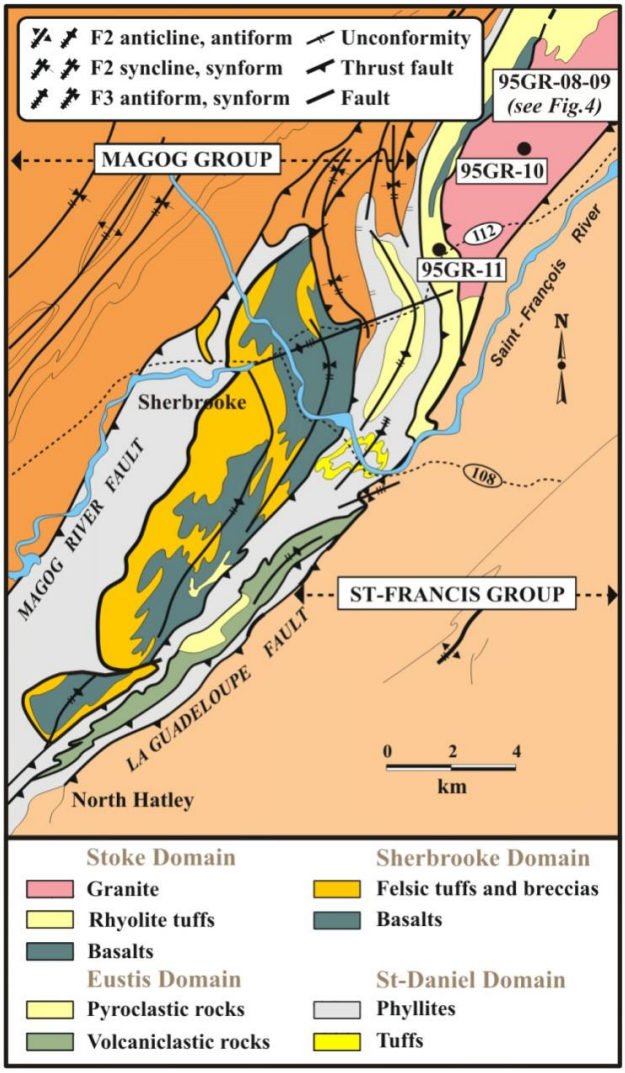

Figure 8. Geological map of the Sherbrooke area. Modified from Tremblay et al. (2000).

limestone and calcareous shale characterized by abundant syn-sedimentary deformation. The contact with the overlying Compton Formation is gradual over several tens of metres. The Compton Formation is a thick sedimentary sequence that has been subdivided into three members (Lebel and Tremblay, 1993), the Milan, Lac-Drolet, and Saint-Ludger members. The Milan member forms a typical turbidite sequence characterized by abundant sedimentary structures. It contains *Chitinozoan* microfauna (van Grootel et al., 1995) and fossil

plants (Hueber et al., 1990) suggesting Upper Silurian-Lower Devonian and Lower Devonian ages, respectively, which is consistent with a U-Pb detrital zircon age of 415 ± 12 Ma recently measured in the upper part of the Milan member (Perrot et al., in press). The Lac-Drolet and Saint-Ludger members are dominated by typical feldspathic wackes and black mudstone, respectively, recording a progressive deepening of the sedimentary basin due to the west-directed progression of the Acadian orogenic front (Bradley et al., 2000). The Lac-Drolet member yielded a U-Pb detrital zircon age of 413 ± 7 Ma (Perrot et al., in press).

Structural relationships between Ordovician and post-Ordovician rocks of southern Québec indicate that regional deformation is related to the Acadian orogeny (Cousineau and Tremblay, 1993). From the Québec-Vermont border to east of Québec city (Figure 2), the La Guadeloupe fault has been recognized as a northwest-directed, high-angle reverse fault (Tremblay et al., 1989b; Labbé and St-Julien, 1989; Cousineau and Tremblay, 1993), and is associated with greenschist-grade, quartzofeldspathic and calc-silicates mylonites observed in adjacent units from both sides (Tremblay et al., 1989b; Labbé and St-Julien, 1989; Tremblay et al., 2000). In the Sherbrooke area, regional folds are F_2 folds that trend parallel to down-dip stretching lineations along the La Guadeloupe fault. D_2 folds are locally affected by southeast-verging, F_3 open folds with an axial-planar, northwest-dipping crenulation cleavage (Tremblay and St-Julien, 1990), which clearly postdate the La Guadeloupe fault and associated F_2 folds. These F_3 folds correlate with the «easterly features» of Osberg et al. (1989) in New England, which are refolded by late north-trending folds (Hatch and Stanley, 1988) corresponding to the dome-stage deformation of Armstrong et al. (1992).

FIELD TRIP ROAD LOG

The meeting point for fieldtrip departure is the CTG meeting site, the Camp Beauséjour on lake Sunday, near the town of St-Martyrs-Canadiens in southern Quebec.

STOP 1: The La Guadeloupe fault – the Big Hollow Brook section.

Location: From Camp Beauséjour, drive back to Road 161 and turn left (to the south). Drive for ca. 10 km and turn right on Road 112. Drive Road 112 for approximately 40 km. Approaching East-Angus, take the exit towards the town (St-Jean street). Turn right on St-Jean street. After ca. 600 metres, turn right on Goddard-East Road. Drive for ca. 600 metres and take the first private road on your left (chemin du Mont Élan). Drive to the parking lot (c. 400 metres) and park. The outcrop is a section in the river bed, known as Big Hollow Brook, just beside the access road.

Field description: The volcanic rocks of the Stoke domain are intruded by a granitic massif, the Ascot Complex pluton, interpreted as a plutonic equivalent of the extrusive sequence (Tremblay et al., 1994). The Ascot Complex pluton is a well-foliated granite showing the same deformational style and fabrics as the adjacent volcanic rocks. It is a coarse-grained rock (4-7 mm in diameter) of deformed crystals of quartz, plagioclase, K-feldspar, chlorite, muscovite and epidote with minor amounts of biotite, sphene, zircon, calcite and pyrite. K-feldspar is only locally visible. Granophyric texture is common. Chlorite/muscovite ratios are variable and are mostly the product of metamorphic recrystallization and alteration of primary minerals.

The La Guadeloupe fault is a high-angle reverse fault along which Silurian and Devonian rocks of the Gaspé Belt were transported over the Humber/Dunnage zones. It is marked by greenschist-grade quartzo-feldspathic and calc-silicate mylonites with down-dip stretching lineations and shear-sense indicators consistent with NW-directed transport (Figure 9; Tremblay et al., 1989b; Labbé and St-Julien, 1989).

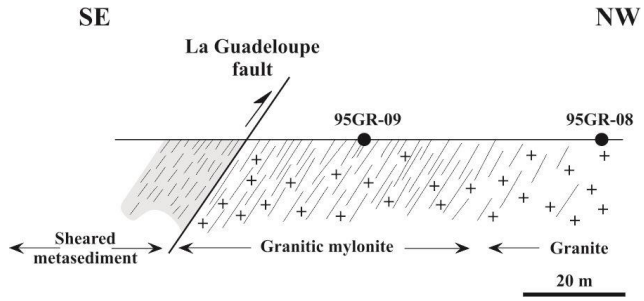

Figure 9. Schematic profile of the La Guadeloupe fault at Big Hollow Brook, and location of samples 95GR-08 and 95GR-09. See Figure 10 for $^{40}Ar/^{39}Ar$ results. From Tremblay et al. (2000).

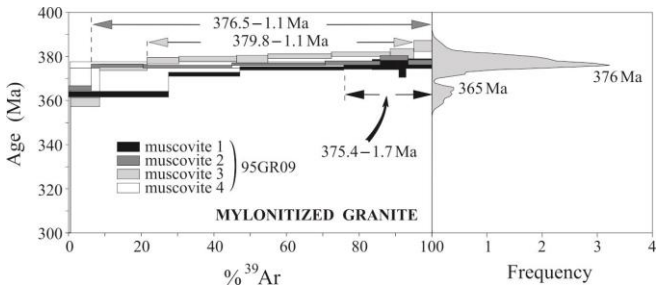

Figure 10. $^{40}Ar/^{39}Ar$ spectra of muscovites from mylonitized granite of the Big Hollow Brook section (see Fig. 4). The apparent age frequency diagram is also shown. See Figure 8 for location. From Tremblay et al. (2000).

In the Stoke Mountains area, the progressive development of granitic mylonites related to the La Guadeloupe fault is superbly exposed in the Big Hollow Brook section (Tremblay et al., 2000), which has been used as a type locality for the $^{40}Ar/^{39}Ar$ dating of the regional Acadian metamorphism. Isotopic analyses of sheared rocks of the Big Hollow Brook section clearly demonstrated that Acadian peak metamorphism in the southern Québec Appalachians can be tightly constrained at 380-375 Ma (Figure 10).

STOP 2: Ductile shearing in interlayered felsic and mafic lavas of the Stoke domain.

Location: Drive back to road 112 West towards Sherbrooke. Drive for approximately 12 km. At the junction with HGW 610, stay on Road 112 at the traffic circle and, after ca. 150-200 metres, turn left on Gastin street. Turn left on Bibeau Road until the end (ca. 300 metres) and park. The outcrop is an abandoned access ramp, ca. 100 metres east of the parking lot.

Field description: This outcrop nicely exposes a series of felsic and mafic volcanic rocks and schists of the Stoke domain (Figure 8). In terms of REE profiles, these felsic volcanics are very homogeneous; they are LREE-enriched and show a typical negative Eu anomaly that is attributed to the fractionation of plagioclase (Tremblay et al., 1989a). The mafic rocks are tholeiitic basalts with a typical MORB-type REE composition.

On the outcrop (Figure 11), the volcanic rocks are strongly sheared and hydrothermalized. The northern wall of the ramp exposes a ca. 5-10 metres-wide ductile shear zone marked by sericite-rich «paper» schist on the hanging wall, and chlorite-carbonate laminated schist on the footwall. $^{40}Ar/^{39}Ar$ muscovite dating of a felsic schist close to this outcrop (along road 122) yielded plateau ages of ca. 379 Ma, which corresponds to the age of regional metamorphism (Tremblay et al., 2000).

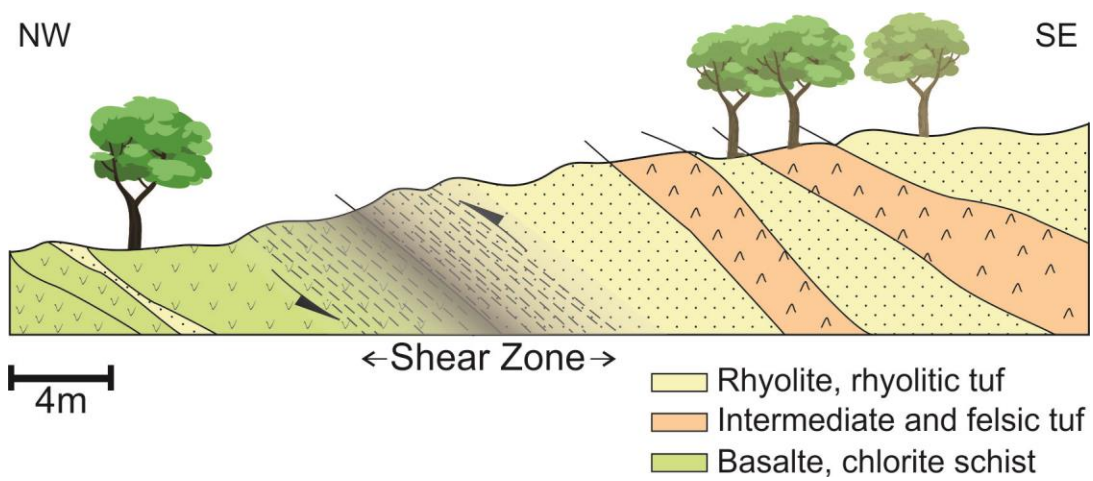

Figure 11. Field sketch of Stop 2.

STOP 3: The Ascot Complex-Magog Group contact – is it an angular unconformity?

Location: Drive back to Road 112 and turn right. Turn around the traffic circle and take HGW 610 toward the West. Drive approximately 800 metres and park (there is a service road on your right). The outcrop consists in a series of roadcuts along the highway.

Field description: In the Sherbrooke area, the lowermost stratigraphic unit of the Magog Group is made up of volcanic conglomerate and sandstone. Based on field relationships, it has been originally interpreted as unconformably overlying the sedimentary rocks of the Ascot Complex (Tremblay, 1992b). This outcrop is a new roadcut that exposes the Magog-Ascot contact. We will walk the section from East to West (from the Ascot Complex phyllites toward the contact with the Magog Group).

The phyllites of the Ascot Complex consist here of black and rusty argillite with occasional but typical, cm-sized nodules of pyrite. The deformation

of these rocks is complex; three generations of folds and fabrics can be observed. The contact with the Magog Group corresponds to a diffuse zone, approximately 1 metre-wide, in which well-bedded sandstone strata (typical of the Magog Group) progressively appear. The main point to examine here is the deformational contrast between the Ascot phyllites and the Magog Group strata: is there a missing structural fabric in the latter?

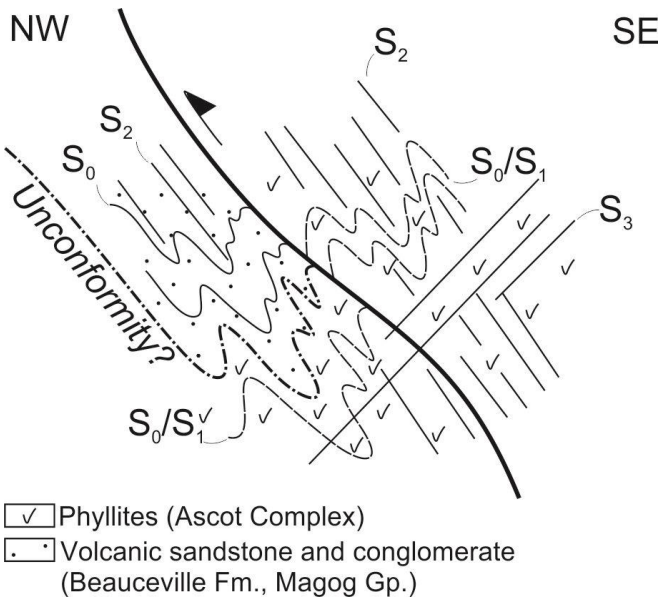

Figure 12. Interpretative field sketch of the Magog-Ascot contact as exposed at Stop 3.

Stratigraphically higher (westward) along the section, the outcrop exposes a volcanic conglomerate, attributed to the Beauceville Formation, which constitutes more than 50% of the basal unit of the Magog Group in the Sherbrooke area (Tremblay, 1992b). Cm-scale clasts consist of felsic volcanic and pyroclastic rocks, less commonly of pelite, granite and siltstone. Regionally, this sequence is interlayered with quartz-feldspar sandstone and lithic tuff. In the Stoke Mountains area (approximately 10 km to the northeast), this sequence unconformably overlies felsic volcanic rocks of the Stoke domain (Mercier, 2013), and yielded U-Pb detrital zircon ages of 462 $+^{7}/-_{5}$ Ma (Perrot et al., 2017), which is consistent with the Marquis's and others (2001) U-Pb crystallization age of 462 $+^{5}/-_{4}$ Ma measured in the Beauce area.

STOP 4: A conglomeratic marker horizon in the Magog Group.

Location: Continue on HGW 610W until HGW 10W (which is also HGW 55S). Take HGW 10W and then the first exit (Exit 141) on your right for Monseigneur-Fortier Blvd. Turn left on Monseigneur-Fortier Blvd, right on Lionel-Groulx Blvd and then right again on Arnold-Pryce Road. Drive approximately 100 metres and park (there is a private road to the right). The outcrop is a roadcut on your right along the bike path.

Field description: This outcrop is a typical exposure of conglomerate and arkosic sandstone that make a stratigraphic marker horizon in the Sherbrooke area (Figure 8). The conglomeratic facies constitutes ca. 50% of this unit. It contains cm- to dc-sized, subangular to well-rounded clasts and blocks of volcanic, granitic and sedimentary rocks. Some granitic blocs can be up to 1 metre in diameter (Figure 12). Volcanic rocks fragments are predominant. This conglomerate forms metres-thick lenticular horizons within feldspathic sandstones. The conglomerate and sandstone belong to the former lower Silurian (?) Sherbrooke Formation, which were interpreted as marking an unconformity by St-Julien (1963) but have been since re-interpreted and included into the Magog Group by St-Julien et al. (1972) and St-Julien and Hubert (1975). The results of regional U-Pb detrital zircon analyses suggest, however, that it effectively belongs to the Silurian (de Souza et al., 2014; Perrot et al., 2017).

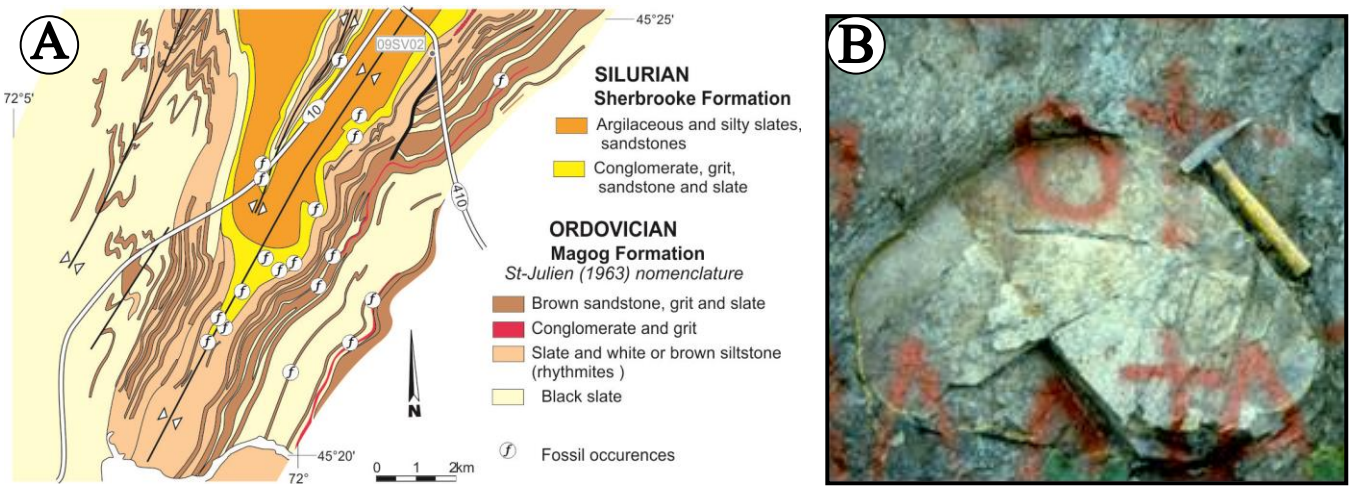

Figure13. A. Geological map of the Lake Magog area (after St-Julien 1963) showing the former Sherbrooke Formation and location of Silurian (?) fossil occurrences. B. Field example of decimetre-sized rounded clasts of granitoid in the conglomerate.

STOP 5: Contact between felsic volcanic rocks of the Eustis domain and black phyllites.

Location: Drive back to HGW 10W. Take HGW 410E and drive for approximately 12 km, until the intersection with Road 108. Keep right at the traffic circle and take the first road on your right (Haskett Hill Road). Drive it for ca. 200 meters and park. The outcrop is a roadcut on both sides of the Haskett Hill Road and is part of a huge roadcut exposure along HGW 410 at the traffic circle.

Field description: This is a new outcrop that exposes the northwestern contact between the volcanic rocks of the Eustis domain and the laminated phyllites of the Ascot Complex. Based on contrasting lithological facies and on geochemical characteristics of the volcanic rocks, the contact between the different domains of the Ascot Complex and the surrounding sedimentary rocks has been originally interpreted as faults (Tremblay, 1992b). However, such a contact is superbly exposed on this outcrop (Figure 13) and, obviously, it does not correspond to a tectonic contact but is rather depositional, and probably represents a disconformity between a «basement» made up of a heterogeneous series of volcanic rocks (i.e. the various volcanic domains of the Ascot Complex) and a sequence of manganiferous, fine-grained siltstone grading up into deep-marine mudstone representing *in situ* seafloor sedimentation. If correct, such an interpretation raises important questions regarding the origin and the accretionary history of the Ascot Complex.

On this outcrop, cm-thick layers of brown-coloured siltstone and sandstone, and more rarely, limestone are visible in the phyllites. Locally preserved cross-laminations and gradded-bedding structures indicate that stratigraphy is overturned, and that the phyllites overly the volcanic rocks. Fabrics and structures visible in the phyllites are quite complex and three generations of folding are visible (Figure 20). This structural complexity has been attributed to the proximity of the La Guadeloupe fault (Tremblay and St-Julien, 1990) which is located less than a hundred metres to the SE (see Figure 8).

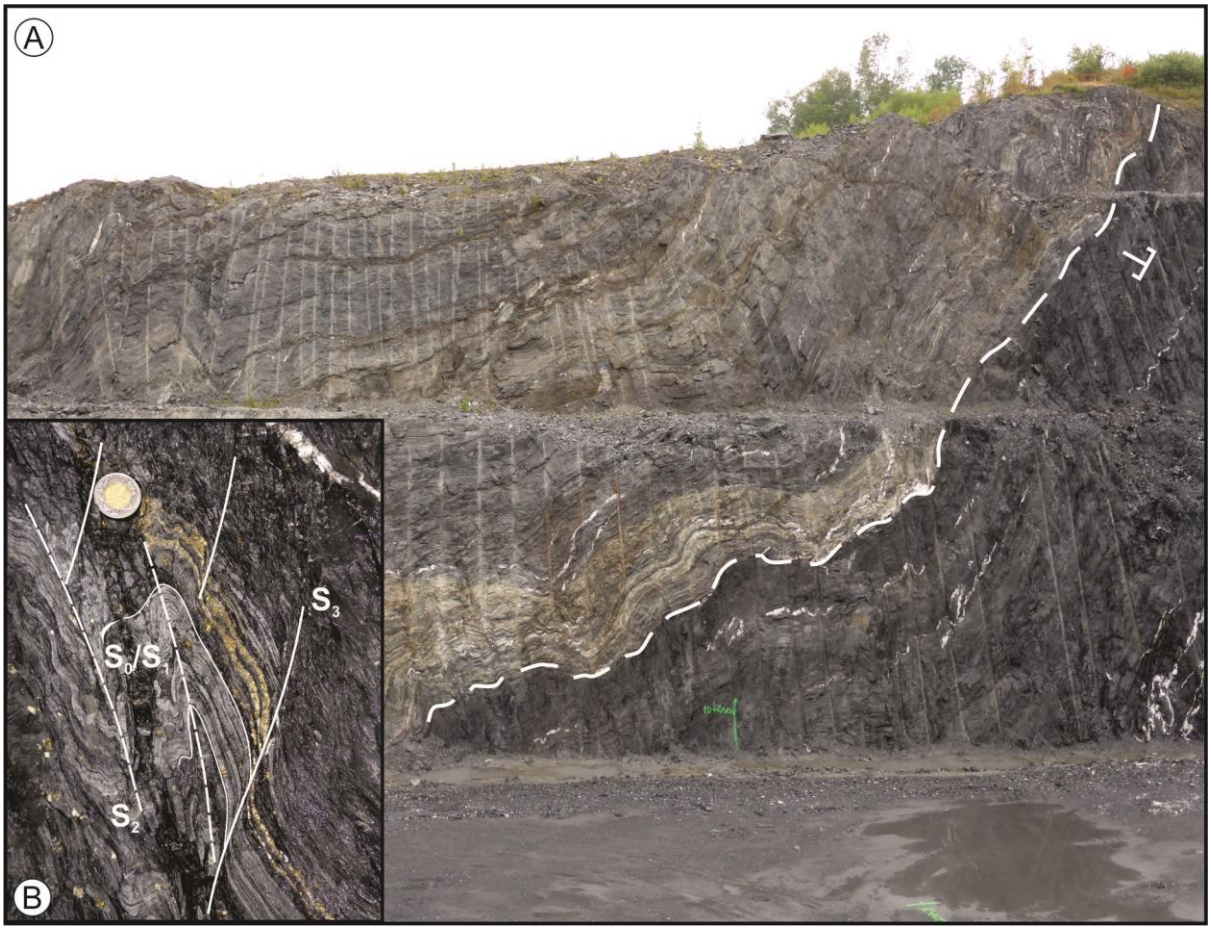

Figure 14. Field photographs of the contact between felsic volcanic rocks of the Eustis domain and black phyllites of the Ascot Complex at Stop 5.

STOP 6: The Capelton mine – historical view and structural characteristics.

Location: Drive back to Road 108 and turn right. Drive for ca. 4 km and turn right towards North Hatley. Just after the bridge over Massawippi River, turn left in the parking lot of the *L'épopée de Capelton* where we close the fieldtrip with a visit of the old Capelton mine, a strongly-deformed VMS deposit hosted by the volcanic rocks of the Ascot Complex.

Mining history: The Capelton mine (1863-1907) is part of the historical mining district of the Sherbrooke area (1863-1939), including the well-known Eustis mine, which was open in 1865 and close in 1939, after more than 70 years of almost continuous mining. At the closing of mining activity, it was known as the oldest Cu mine in Canada. In 1995, a local business started a tourist attraction at the site of the Capelton mine, and adapted the 3 uppermost levels of the mine and made them accessible to the public. This was the first time that the Capelton mine re-opened since its closure. The underground visit of the mine will be led by a local guide but we will first examine a typical exposure of felsic schists and sulphide mineralization.

Field description: Just at the mine entrance (Figure 14), there is an exposure of typical intermediate and felsic schists that host the

sulphide mineralization. Felsic schists are interpreted as an interlayered sequence of rhyolite crystal tuffs and blocks and lapilli tuffs, whereas the intermediate to mafic schists probably represents crosscutting mafic dykes or sills. The felsic schists locally show well-developed, SE-plunging stretching lineations defined by elongated clasts. A cm-thick, almost continuous horizon of massive sulphide (mostly pyrite) is present and clearly preserves 2 generations of folds, F_2 and F_3. F_2 axes are plunging SE, subparallel to the stretching lineation. F_3 are open folds marked by axial-planar NW-dipping crenulation cleavages.

D_2 deformation records a higher strain in the Eustis domain than elsewhere in the Ascot Complex. S_2 schistosity is a mylonitic foliation, axial-planar to F_2 folds which are crosscut by an anastomosing pattern of ductile shear zones (Figure 15). Shear zones are marked by various types of mylonites and mylonitic schists. Moreover, kinematic indicators systematically record a NW-directed thrust/reverse fault movement (Tremblay et al., 1989). These anastomosing shear zones isolate strongly folded bodies of Eustis rocks showing S_1-S_2 relationships and minor folds indicative of F_2 hinge zones. F_2 folds plunge systematically to the SE, almost parallel with stretching lineations. These ductile shear zones are kinematically related to the La Guadeloupe fault.

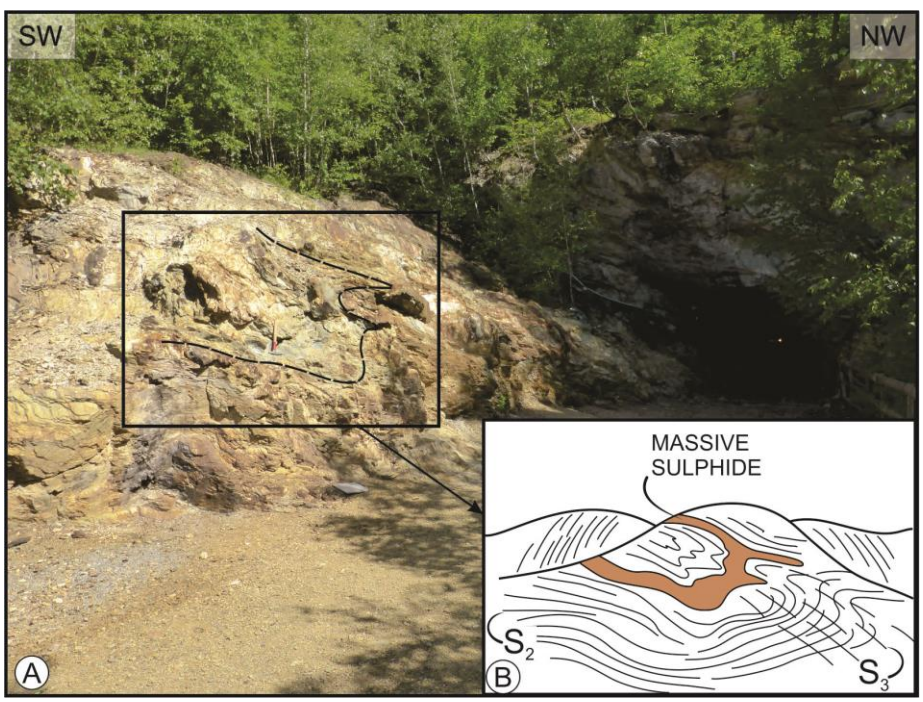

Figure 15. Field photograph and sketch of the felsic schist exposed at the entrance of the Capelton mine.

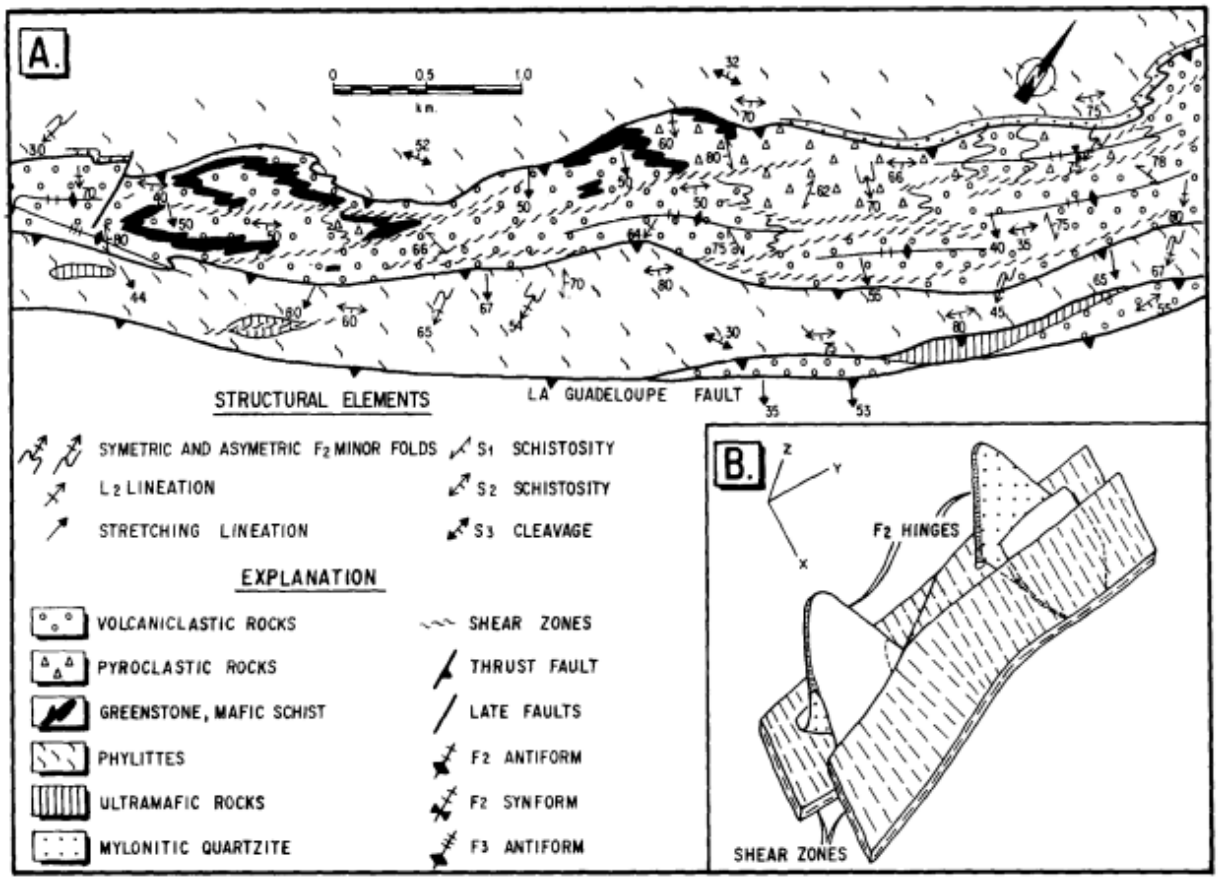

Figure 16. A. Detailed geologic map of a segment of the Eustis domain. B. Interpretation of the structural pattern shown in Figure 15A. From Tremblay and St-Julien (1990).

End of the field trip.

REFERENCES

Armstrong, T. R., Tracy, R. J. & Hames, W. E., 1992. *Contrasting styles of Taconian, Eastern Acadian and Western Acadian metamorphism, central and western New England*. Journal of Metamorphic Geology, 10: 415–426.

Bourque, P.-A., Malo, M. & Kirkwood, D., 2000. *Paleogeography and tectono-sedimentary history at the margin of Laurentia during Silurian–earliest Devonian time: the Gaspé Belt, Québec.* Geological Society of America Bulletin 112: 4–20.

Bradley, D.C., R.D. Tucker, D. R. Lux, A.G. Harris, & D.C. Mc Gregor, 2000. *Migration of the Acadianorogen and foreland basin across the Northern Appalachians of Maine and Adjacent areas.* United States Geological Survey, Professional Paper 1624, 49 pages.

Castonguay, S., Ruffet, G. & Tremblay, A. 2007. *Dating polyphase deformation across low grade metamorphic belts: An example based on 40Ar/39Ar muscovite age constraints from the southern Québec Appalachians, Canada*. Geological Society of America Bulletin, 119: 978-992.

Castonguay, S., Ruffet, G., Tremblay, A. & Féraud, G., 2001. *Tectonometamorphic evolution of the southern Quebec Appalachians: 40Ar/39Ar evidence for Ordovician crustal thickening and Silurian exhumation of the internal Humber zone*. Geological Society of America Bulletin, 113: 144-160.

Cousineau, P.A. 1990. *Le Groupe de Caldwell et le domaine océanique entre St-Joseph-de-Beauce et Sainte-Sabine.* Ministère des ressources naturelles du Québec, MM 87-02, 165 pages.

Cousineau, P.A., & St-Julien, P. 1992. *The Saint-Daniel Mélange: Evolution of an accretionary complex in the Dunnage terrane of the Québec Appalachians*. Tectonics, 11: 898-909.

Cousineau, P.A., & St-Julien, P. 1994. *Stratigraphie et paléogéographie d'un bassin d'avant-arc ordovicien, Estrie-Beauce, Appalaches du Québec.* Journal Canadien des Sciences de la Terre, 31: 435-446.

Cousineau, P.A. & Tremblay, A. 1993, *Acadian deformation in the southwestern Québec Appalachians.* Geological Society of America Special Paper 275, pp. 85-99.

David, J. & Marquis, R. 1994. *Géochronologie U-Pb dans les Appalaches du Québec: application aux roches de la zone de Dunnage.* La Revue géologique du Québec, 1: 10-15.

de Souza, S. & Tremblay, A., 2010. *The Rivière-des-Plante ultramafic Complex, southern Québec: Stratigraphy, structure, and implications for the Chain Lakes massif In* Tollo, R.P., Bartholomew, M.J., Hibbard, J.P., and Karabinos, P.M., eds., From Rodinia to Pangea: The Lithotectonic Record of the Appalachian Region: Geological Society of America Memoir 206, pp. 1–17.

de Souza, S., Tremblay, A. & Ruffet. G. 2014. *Taconian orogenesis, sedimentation and magmatism in the southern Quebec-northern Vermont Appalachians: stratigraphic and detrital mineral record of Iapetan suturing*. American Journal of Science, 314: 1065-1103.

de Souza, S., Tremblay, A., Daoust, C. & Gauthier, M. 2008. *Stratigraphy and geochemistry of the Lac-Brompton ophiolite Complex and evolution of SSZ magmatism in the southern Québec Dunnage Zone,* Canada. Canadian Journal of Earth Sciences, 45: 1-16.

Dunning, G.R., Krogh, T.E., & Pederson, R.B., 1986. *U–Pb zircon ages of Appalachian–Caledonian ophiolites*. Terra Cognita, 6, L51.

Harnois, L. & Morency, M. 1989. *Geochemistry of Mont Orford ophiolite complex, Northern Appalachians,* Canada. Chemical Geology, 77: 133–147.

Hatch, N. L., & Stanley, R. S., 1988. *Post-Taconian structural geology of the Rowe-Hawley zone and the Connecticut Valley belt west of the Mesozoic basins.* U.S. Geological Survey Professional Paper 1366, pp. C1–C36.

Hébert, R. & Laurent, R. 1989. *Mineral chemistry of ultramafic and mafic plutonic rocks of the Appalachian ophiolites, Québec, Canada*. Chemical Geology, 77: 265–285.

Hébert, R. & Bédard, J.H., 2000. *Les ophiolites d'avant-arc et leur potentiel minéral: exemple des complexes ophiolitiques du sud du Quebec*. Chroniques de la Recherche Minière, 539: 101–117.

Hueber, F. M., Bothner, W. A., Hatch, Jr., N. L., Finney, S. C., & Aleinikoff, J. N., 1990, *Devonian plants from southern Quebec and northern New Hampshire and the age of the Connecticut Valley trough.* American Journal of Science, v. 290, n. 4, p. 360–395.

Huot, F., Hébert, R., & Turcotte, B., 2002. *A multistage magmatic history for the genesis of the Orford ophiolite (Quebec, Canada): a study of the Mt.*

Chagnon massif. Canadian Journal of Earth Sciences, 39: 1201–1217.

Labbé, J.-Y. & St-Julien, P. 1989. *Évidences de failles de chevauchement acadienne dans la région de Weedon, Québec*. Journal Canadien des Sciences de la Terre, 26: 2268-2277.

Laurent, R. & Hébert, R., 1989. *The volcanic and intrusive rocks of the Québec Appalachians ophiolites (Canada) and their island-arc setting.* Chemical Geology, 77: 287–302.

Lebel, D. & Tremblay, A. 1993. *Géologie de la région de Lac-Mégantic (Estrie).* Ministère de l'Énergie et des Ressources du Québec, DV 93-04 (carte géologique), 1/50 000..

Mercier, P.-E. 2013. *Analyse stratigraphique et structurale du Groupe de Magog et de la Ceinture de Gaspé, région des Monts Stoke, Appalaches du Québec*. Mémoire de maîtrise, UQAM, 95 pages

Olive, V., Hébert, R. & Loubet, M., 1997. *Isotopic and trace element constraints on the genesis of a boninitic sequence in the Thetford Mines ophiolitic complex, Québec*, Canada. Canadian Journal of Earth Sciences, 34: 1258-1271.

Osberg, P.H. 1978. *Synthesis of the geology of Northeastern Appalachians, U.S.A. In* Tozer, E.T. and Schenk, P.E. eds., Caledonian-Appalachian orogen of the North-Atlantic region. Geological Survey of Canada Paper 78-13, pp. 137-147.

Osberg, P.H., Tull, J.F., Robinson, P., Hon, R., & Butler, J.R., 1989, *The Acadian orogen In* The Appalachian-Ouachita orogen in the United States (eds R.D.Jr. Hatcher, W.A. Thomas, and G.W. Viele), pp. 179-232, Geological Society of America., Geology of North America, v. F-2.

Oshin, O.I. & Crocket, J.H., 1986. *The geochemistry and petrogenesis of ophiolitic rocks from Lac de l'Est, Thetford Mines complex, Québec, Canada*. Canadian Journal of Earth Sciences, 23: 202-213.

Perrot, M., Tremblay, A. & David, J. 2017. *Detrital zircon U-Pb geochronology of the Magog Group, southern Quebec – Stratigraphic and tectonic implications for the Quebec Appalachians*. American Journal of Science, 317: 1049-1094.

Perrot, M., Tremblay, A., Ruffet, G., & David, J. In press. *Detrital U-Pb and 40Ar/39Ar geochronology of the Connecticut Valley-Gaspé trough, southern Quebec and northern Vermont–Transitional tectonism from Salinic to Acadian orogenic cycles*. Tectonophysics.

Pinet, N. & Tremblay, A., 1995. *Tectonic evolution of the Québec-Maine Appalachians: from oceanic spreading to obduction and collision in the Northern Appalachians*. American Journal of Science, 295: 173-200.

Pinet, N., Tremblay, A., & Sosson, M., 1996, *Extension versus shortening models for hinterland-directed motions in the southern Québec Appalachians*. Tectonophysics, 267: 239-256.

Roy, D.C. 1989. *The Depot Mountain Formation: transition from syn- to post-Taconian basin along the Baie Verte-Brompton Line in northwestern Maine*. Maine Geological Survey, Studies in Maine Geology, vol. 2, pp. 85-99.

Sasseville, C., Tremblay, A., Clauer, N. & Liewig, N. 2008. *K-Ar time constraints on the evolution of polydeformed fold-thrust belts: the case of the Northern Appalachians (southern Quebec).* Journal of Geodynamics, 45: 99-119.

Schroetter, J.-M., Tremblay, A., Bédard, J.H. & Villeneuve, M. 2006. *Syncollisional basin development in the Appalachian orogen: The Saint-Daniel mélange, southern Québec, Canada*. Geological Society of America Bulletin, 118: 109-125.

Stanley, R.S., & Ratcliffe, N.M. 1985. *Tectonic synthesis of the Taconian orogeny in western New England.* Geological Society of America Bulletin, 96: 1227-1250.

St-Julien, P., 1987, *Géologie des régions de Saint-Victor et de Thetford-Mines (moitié Est).* Ministère des ressources naturelles du Québec, MM 86-01, 66 pages.

St-Julien, P. 1963. *Preliminary report on Saint-Élie-d'Orford area, Sherbrooke and Richmond counties.* Department of Natural Resources, Québec, PR #492, 14 pages.

St-Julien, P., & C. Hubert. 1975. *Evolution of the Taconian orogen in the Quebec Appalachians*. American Journal of Science, 275-A: 337-362.

St-Julien, P., Hubert, C., Skidmore, B. & Béland, J. 1972. *Appalachian structure and stratigraphy*. Quebec XXIV: International Geological Congress, Montreal, Guidebook 56, 99 pages.

Tremblay, A. 1992a. *Tectonic and accretionary history of Taconian oceanic rocks of the Québec Appalachians.* American Journal of Science, 292: 229-252.

Tremblay, A. 1992b. *Géologie de la région de Sherbrooke*. Ministère des ressources naturelles du Québec, ET 90-02, 80 pages.

Tremblay, A. & Castonguay, S. 2002. *The structural evolution of the Laurentian margin revisited (southern Quebec): implications for the Salinian Orogeny and Appalachian successor basins.* Geology, 30: 79-82.

Tremblay, A. & Malo, M. 1991. *Significance of brittle and plastic fabrics within the Massawippi Lake Fault Zone, southern Canadian Appalachians.* Journal of Structural Geology, 13: 1013-1023.

Tremblay, A. & Pinet, N. 2016. *Late Neoproterozoic to Permian tectonic evolution of the Quebec Appalachians, Canada*. Earth-Science Reviews, 160: 131-170.

Tremblay, A. & Pinet, N. 2005. *Diachronous supracrustal extension in an intraplate setting and the origin of the Connecticut Valley-Gaspé and Merrimack troughs, Northern Appalachians*. Geological Magazine, 142 (1): 7-22.

Tremblay, A. & Pinet, N., 1994. *Distribution and characteristics of Taconian and Acadian deformation, southern Quebec Appalachians.* Geological Society of America Bulletin, 106: 1172-1181.

Tremblay, A., & St-Julien, P. 1990. *Structural style and evolution of a segment of the Dunnage zone from the Quebec Appalachians and its tectonic implications*. Geological Society of America Bulletin, 102: 1218-1229.

Tremblay, A., Hébert, R. & Bergeron, M. 1989a. *Le Complexe d'Ascot des Appalaches du sud du Québec: pétrologie et géochimie*. Journal Canadien des Sciences de la Terre, 26: 2407-2420.

Tremblay, A., Malo, M. & St-Julien, P. 1995. *Dunnage Zone - Québec*; Canadian Appalachians Region In Chapter 3 of Geology of the Appalachian/Caledonian Orogen in Canada and Greenland, Harold Williams, (co-ord.); Geological Survey of Canada, Geology of Canada, no. 6, pp. 179-197 (aussi Geological Society of America, The Geology of North America, vol. F-1).

Tremblay, A., Ruffet. G. & Bédard. J.H. 2011. *Obduction of Tethyan-type ophiolites – a case-study from the Thetford-Mines ophiolitic Complex, Québec Appalachians, Canada*. Lithos, 125: 10-26.

Tremblay, A., Ruffet, G. & Castonguay, S. 2000. *Acadian metamorphism in the Dunnage zone of southern Québec, northern Appalachians: 40Ar/39Ar evidence for collision diachronism*. Geological Society of America Bulletin, 112: 136-146.

Tremblay, A., St-Julien, P. & Labbé, J.-Y. 1989b. *Mise à l'évidence et cinématique de la faille de La Guadeloupe, Appalaches du sud du Québec.* Journal Canadien des Sciences de la Terre, 26: 1932-1943.

Tremblay, A., Laflèche, M.R., McNutt, R.H. & Bergeron, M. 1994. *Petrogenesis of Cambro-Ordovician subduction-related granitic magmas of the Québec Appalachians, Canada.* Chemical Geology, 113: 205-220.

van Grootel, G., Tremblay, A., Soufiane, A., Achab, A. & Marquis, R. 1995. *Analyse micropaléontologique du synclinorium de Connecticut Valley-Gaspé dans le sud du Québec: étude préliminaire.* Ministère des Richesses naturelles, Québec, MB 95-26, 32 pages.

van Staal, C.R. & Barr, S.M. 2012. *Lithospheric architecture and tectonic evolution of the Canadian Appalachians and associated Atlantic margin*. Chapter 2 *In* Tectonic styles in Canada: the LITHOPROBE Perspective. Edited by J.A. Percival, F.A. Cook and R.M. Clowes, Geological Association of Canada, Special Paper 49, 55 pages.

van Staal, C.R., Dewey, J.F., Mac Niocaill, C., & McKerrow, W.S., 1998. *The Cambrian-Silurian tectonic evolution of the Northern Appalachians and British Caledonides: history of a complex, west and southwest Pacific-type segment of Iapetus.* Geological Society of London Special Publication 143, 199-242.

Whitehead, J., G. R. Dunning & J. G. Spray. 2000. *U-Pb geochronology and origin of granitoid rocks in the Thetford Mines ophiolite, Canadian Appalachians.* Geological Society of America Bulletin, 112: 915-928.

Whitehead, J., Reynolds, P.H. & Spray, J.G. 1995. *The sub-ophiolitic metamorphic rocks of the Québec Appalachians.* Journal of Geodynamics, 19: 325-350.

Williams, H., 1979. *The Appalachian orogen in Canada.* Canadian Journal of Earth Science, 16: 792-807.

Williams, H., & St-Julien, P., 1982. *The Baie Verte-Brompton Line: Early Paleozoic continent ocean interface in the Canadian Appalachians In* Major Structural Zones and Faults of the Northern Appalachians (eds J. Béland, and P. St-Julien), pp. 177-208, Geological Association of Canada Special Paper 24.