ANATOMY OF AN ORDOVICIAN VOLCANIC ARC AND FOREARC BASIN IN THE SOUTHERN QUÉBEC APPALACHIANS

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INTRODUCTION

This field trip focuses on the lithological characteristics and structural features of an Ordovician forearc basin sequence, the Magog Group, and adjacent volcanic arc, the Ascot Complex, from the oceanic domain (Dunnage Zone) of the southern Québec Appalachians. A particular emphasis will be put on stratigraphic relations within and between both units, which will serve as a template in order to better understand volcanic and sedimentation processes that has been coeval with the Taconian orogeny. We will visit key outcrops in the Sherbrooke area of southern Québec.

The fieldtrip incorporates numerous discussions with scientists involved in the geology of southern Québec over the last 30 years. I wish to express my gratitude to the late P. St-Julien for introducing me to the area and sharing his knowledge during earlier field seasons, P. Cousineau for his sedimentological expertise on the Magog Group, and to the southern Québec Appalachians team of graduate students (B. Lafrance, S. Castonguay, S. Schroetter, P. Pagé, C. Daoust, S. de Souza, P.-E. Mercier and M. Perrot) for their passion for field geology. It must be remembered, however, that this document represents my own vision of the southern Québec Appalachians, and that other interpretations exist. I hope that this short fieldtrip will be a forum for discussion of volcanic arc and related sedimentary basins genesis along the margins of active collision zones.

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, covering approximately 75,000 km^2, which corresponds to ca. 25% of the whole surface area of the Northern Appalachians (Figure 1). 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 (on the surface) 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 overlain by Upper Silurian and Devonian rocks of the Gaspé Belt (Figure 2).

The Humber Zone is subdivided 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

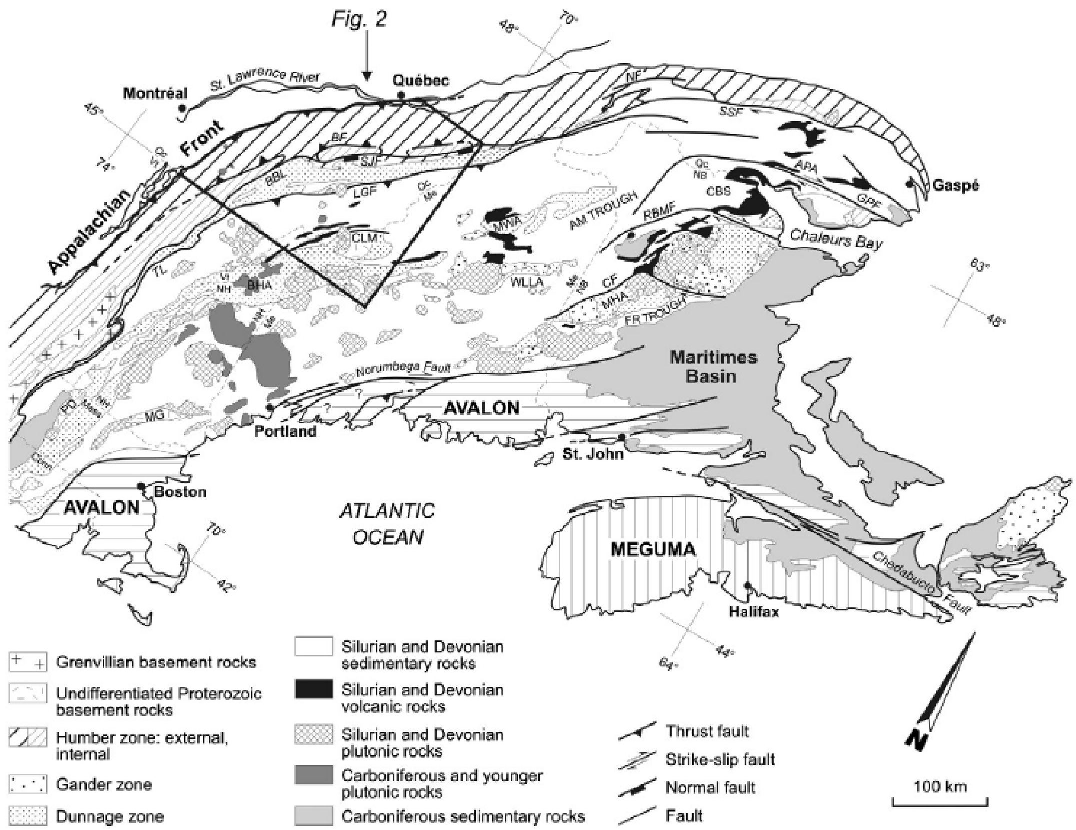

Figure 1. Simplified geological map of the Northern Appalachians of mainland Canada and New England showing the major lithotectonic elements of the region. Modified from Williams (1978). Basement rocks:CLM—Chain LakeMassif;MG—Massabesic Gneiss and PD—PelhamDome.Major anticlinoria and synclinoria:APA—Aroostook–Percé anticlinorium; CBS—Chaleurs Bay synclinorium; BHA—Bronson Hill Anticline;MHA—Miramichi Highlands Anticline;MWA—Munsungun–Winterville Anticline andWLLA—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—Massachussets; Me—Maine; NB—New Brunswick; NH—New Hamshire; 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).

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 doubly-plunging dome structures (i.e. the Sutton Mountains and Notre-Dame Mountains anticlinoria; Figure 2). 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 & Castonguay, 2002; Figure 2).

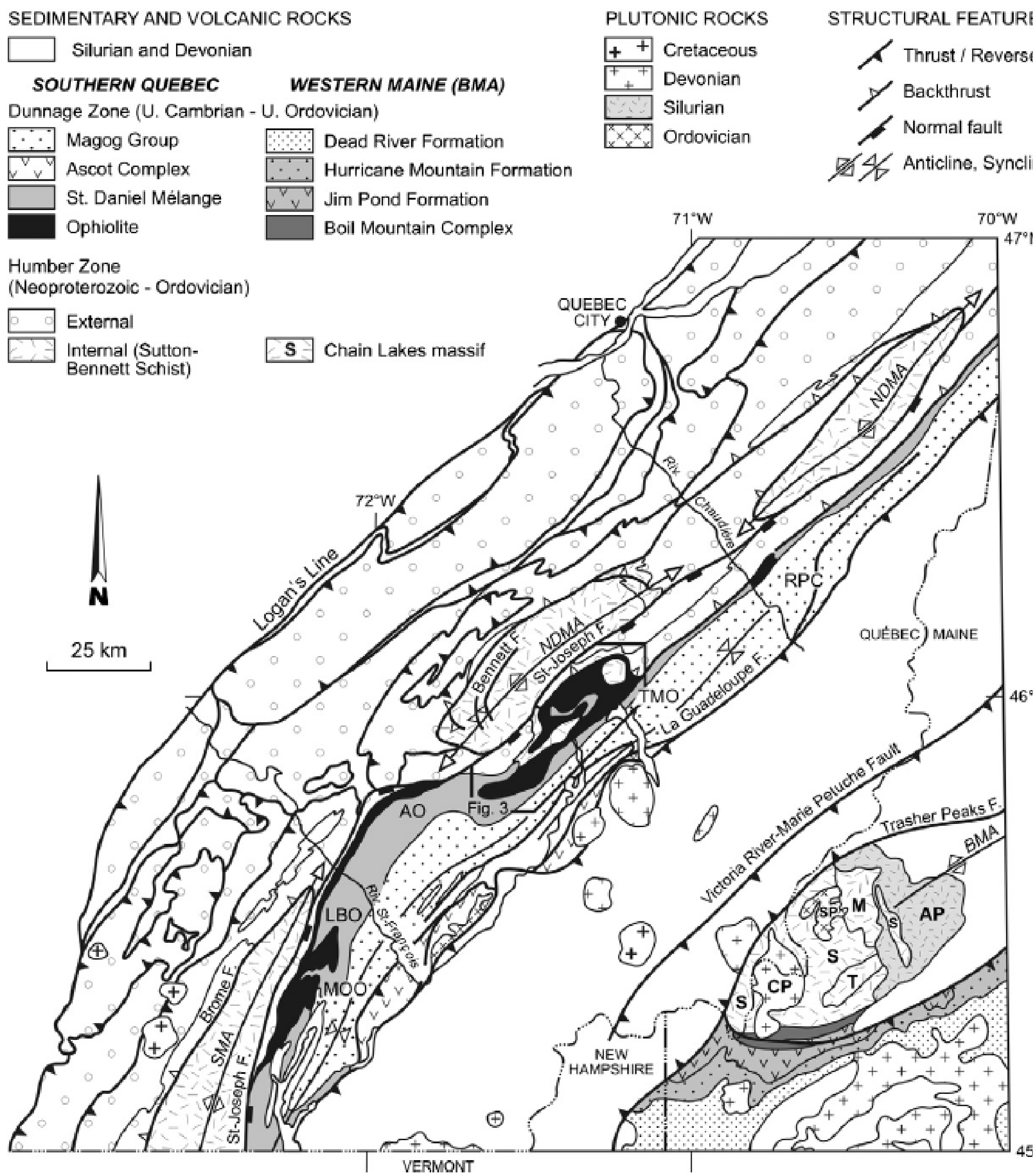

Figure 2. Geological map of the southern Quebec and western Maine Appalachians (modified from de Souza and Tremblay, 2010). BMA—Boundary Mountains anticlinorium; SMA—Sutton Mountains anticlinorium; NDMA—Notre-Dame Mountains anticlinorium; MOO—Mont-Orford ophiolite; LBO—Lac-Brompton ophiolite; AO—Asbestos ophiolite; TMO—Thetford-Mines ophiolite; RPC—Rivière-des-Plante ultramafic Complex; SP—Skinner pluton; AP—Attean pluton; CP—Chain of Ponds pluton; CLM—Chain Lakes massif: S—Sarampus Falls facies; T—Twin Bridges facies; M—McKenney Stream facies. See Fig. 1 for location.

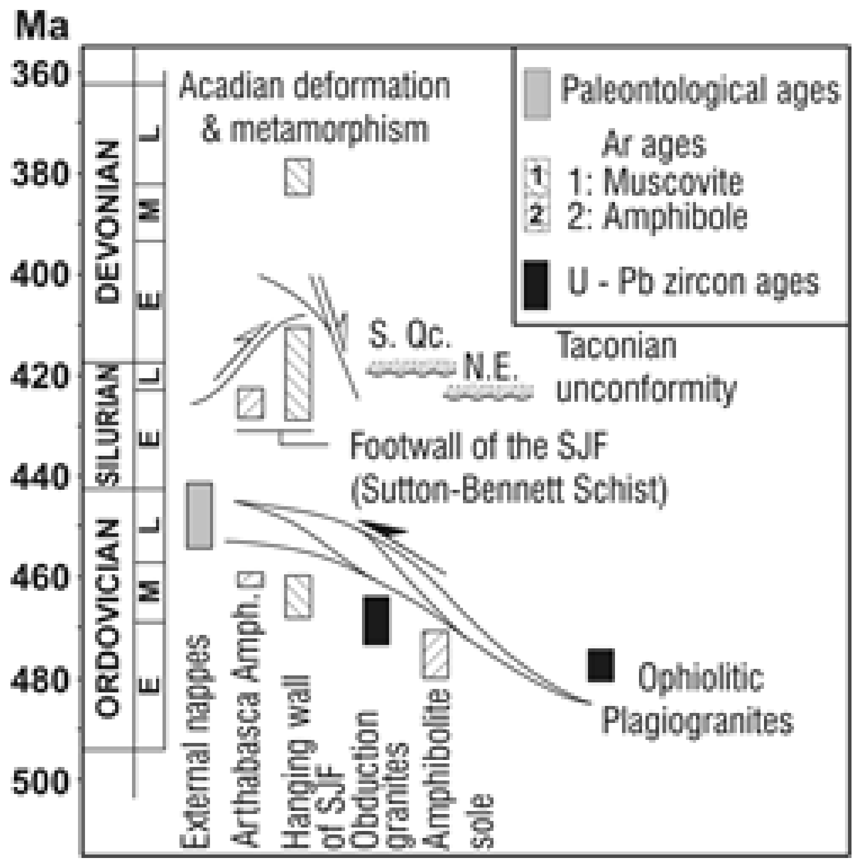

Figure 3. Diagram summarizing age constraints for deformation and metamorphism in the southern Québec Appalachians.

Amphibole and mica $^{40}Ar/^{39}Ar$ ages from the internal Humber Zone vary between 431 and 410 Ma (Figure 3). Ordovician high-temperature step ages (462-460 Ma) suggest that the geochronologic imprint of typical Taconian metamorphism is only 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 (Figure 2). 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) 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 Québec 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 ophiolites of the Thetford-Mines and Asbestos areas 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, 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, 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 continental 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 yielded by metamorphic fragments of basal debris flows of the Saint-Daniel mélange (Schroetter et al., 2006; Tremblay et al., 2011). This is within the age range of regional metamorphism in rock units structurally below the ophiolites 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. 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 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., 2015; Perrot, in progress).

Ascot Complex. The Ascot Complex (Figure 2) is interpreted as the remnant of a 460 $\pm$ 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 Ordovician peri-Laurentian volcanic arc sequences in the Quebec Appalachians. Correlative volcanic rocks are lacking in Temiscouata and Gaspé Peninsula, either because the inferred arc massif(s) did not developed there or has 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 3; 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.

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 any 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 & Castonguay (2002). The Taconian stage (ca. 480 to 445 Ma) involved the stacking of northwest-directed thrust nappes (Figure 4). 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 5a), hence preserving Ordovician isotopic ages, parts of which are now preserved below the ophiolite in the downthrown side of the St-Joseph-BBL fault system.

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 D3 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.

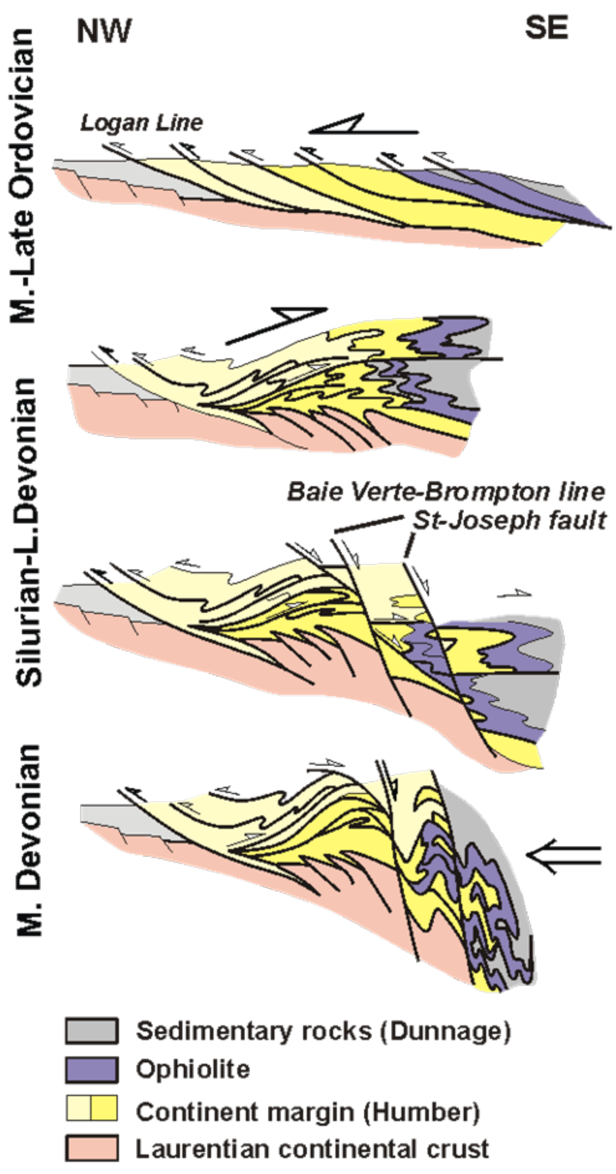

Figure 4. Schematic model for structural evolution of Laurentian margin in southern Quebec. 1- Grenvillian rocks, 2- St. Lawrence Lowlands platform, 3- External Humber Zone, 4- Internal Humber Zone, 5-6- ophiolites and sedimentary rocks of Dunnage Zone, respectively.

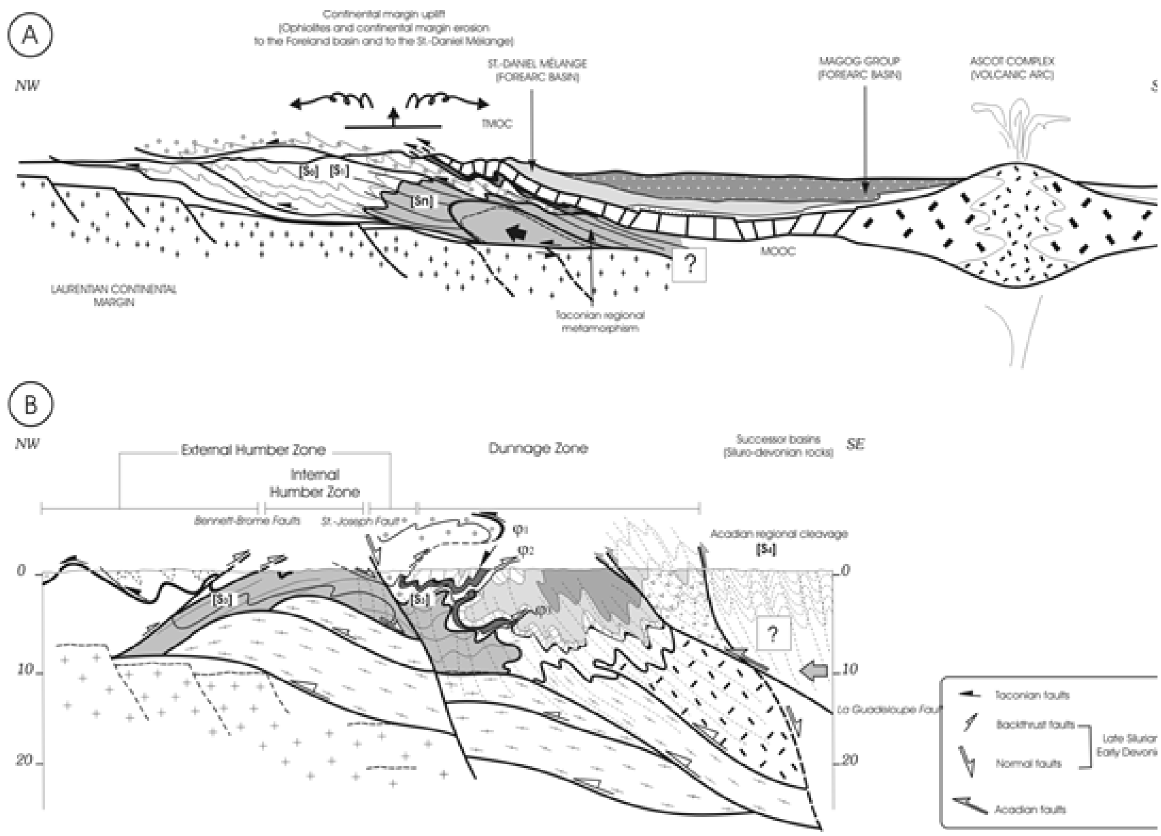

Figure 5. A) Inferred regional tectonic setting of the Southern Québec Appalachians during the Taconian orogeny, and schematic sedimentary and tectonic evolution of the Saint-Daniel Mélange and the Magog Group. B) Schematic composite structural profile across the Laurentian margin and the adjacent oceanic domain. From Schroetter et al. (2005).

GEOLOGY OF THE SHERBROOKE AREA

The Sherbrooke area (Figure 6) 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 each unit with, however, a particular emphasis on the Ordovician rocks series.

The Ascot Complex has been divided into three lithotectonic domains separated by mélange-type phyllites, the Sherbrooke, Eustis, and Stoke domains (Tremblay, 1992b; Figure 6). 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).

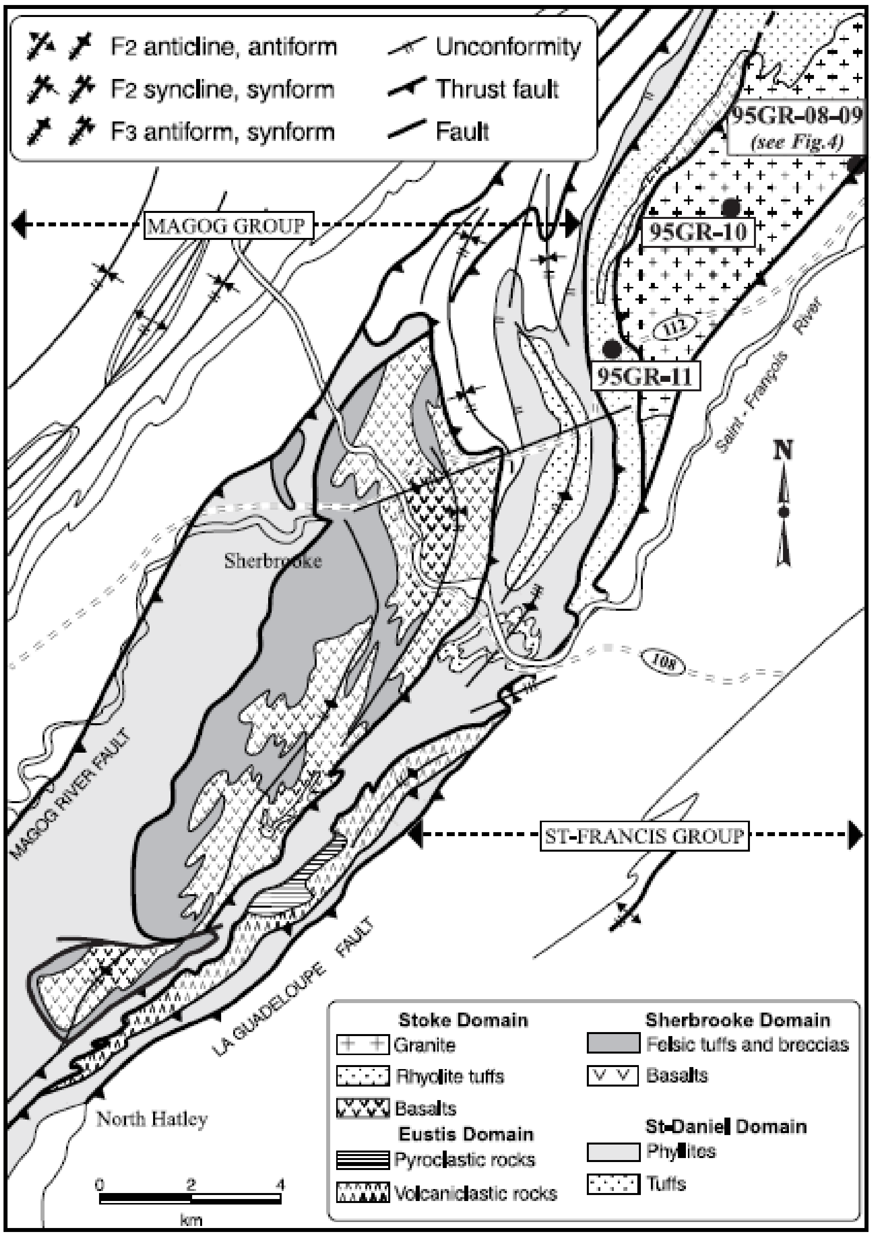

Figure 6. Geology of the Sherbrooke area. From Tremblay et al. (2000).

The Magog Group occupies the core of the St-Victor synclinorium (Figures 2 and 6), 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 feldpathic 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 St-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., 2015; in progress), which is incompatible with the age of the Beauceville Formation (see above), and suggests that both the lower and upper units belong to the St-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 6), where they occupy the core of the Gaspé-Connecticut Valley 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 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 zircon age of 396 ± 5 Ma recently measured in the upper part of the Milan member (de Souza et al., 2014). 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).

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 MAGOG GROUP AND THE ASCOT COMPLEX

The meeting point for departure is the parking lot of the *Bureau en Gros* store, at the intersection between Jean-Paul-Perrault Street and Portland Blvd (in front of the Portland Mall).

STOP 1.1: The uppermost fine-grained sequence of the Magog Group.

Location: Take Jean-Paul-Perrault Street, and drive to HGW 410N. Follow HGW 410N for approximately 1 km and take the exit to HGW 10W (toward Montreal). Drive for ca. 7 km and take Exit 133 to St-Rock Road. Turn left on St-Rock Road, and then right on the exit back to HGW 10E. Park along the access ramp, the outcrop is the roadcut along both sides of the ramp.

Field description: This outcrop exposes a well-bedded sequence of siltstone and black slate that are typical of the uppermost stata of the St-Victor Formation in southern Québec. Relationships between the bedding and the regional schistosity indicate that this exposure is located along the hinge of a major regional fold that is the St-Victor synclinorium.

The source of the St-Victor Formation is believed to be siliciclastic and fine-grained felsic volcanic rocks (Cousineau, 1990). Detrital chromite and serpentinite indicate an ultramafic component in the source area (St-Julien, 1987). Cousineau (1990) concluded that this deposit originated from two sources: an uplifted accretionary prism (the St-Daniel mélange) to the West, and a volcanic arc (the Ascot Complex) to the East.

Figure 7. Field example of the Magog Group conglomerate showing a boulder-size granitic block.

STOP 1.2: The conglomeratic marker horizon.

Location: Drive back to HGW 10E toward Sherbrooke. Follow the highway for ca. 8 km and take Exit 141 for Monseigneur-Fortier Blvd (next exit after HGW 410S). 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 6). 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 7). Volcanic rocks fragments are predominant. This conglomerate forms a metres-thick lenticular horizon within feldspathic sandstones. The conglomerate and sandstone belong to the former lower Silurian (?)

Sherbrooke Formation which was interpreted as a basal unconformity by St-Julien (1963), but has been since re-interpreted and included into the Magog Group by St-Julien et al. (1972) and St-Julien and Hubert (1975). Preliminary results of a regional U-Pb detrital zircon dating study suggest, however, that it effectively belongs to the Silurian (Perrot et al., 2015; Perrot, in progress).

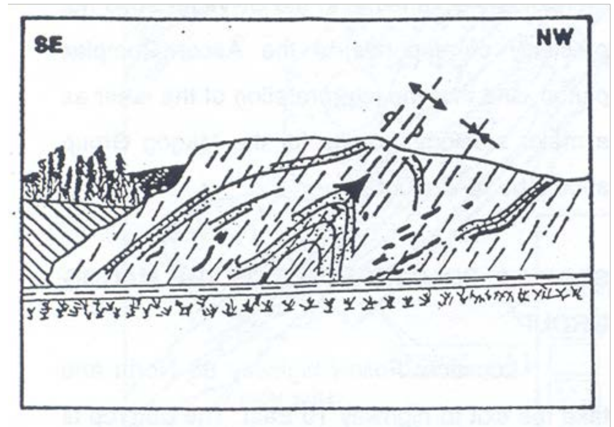

Figure 8. Field sketch of the antiformal structure exposed at Stop 1.3.

STOP 1.3: Typical sandstone-rich turbidites of the Magog Group.

Location: Drive back to HGW 10E (55N) and follow the exit for HGW 610E. Drive ~ 2 km and take Exit 3, right after crossing the river, to St-François Street. Turn left. There is a parking lot at ca. 100 metres, park there. The outcrop is a huge roadcut along the access ramp to HGW 610E.

Field description: This is an exposure of the typical sandstone-rich turbidites of the Magog Group. It comprises interbedded quartzo-feldpathic sandstone, siltstone and mudslate. Sandstone beds are characterized by various primary structures such as graded-bedding, cross-laminations and ripples. Intraformational breccias are locally visible. The outcrop corresponds to the hingeof an overturned anticline (Figure 8). Fold-related faults are found and the presence of bedding-parallel shear zones indicates that flexural-slip folding was dominant.

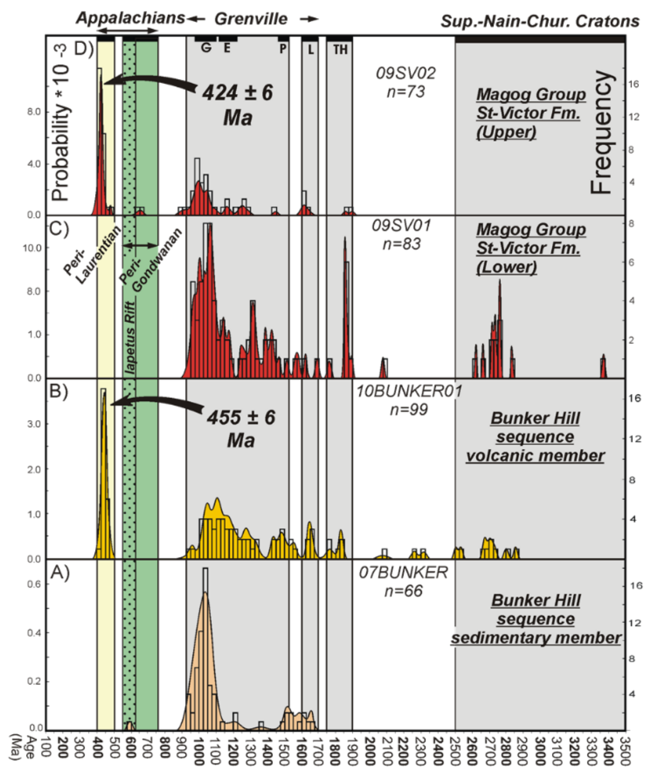

Figure 9. Probability density distribution–frequency diagrams of detrital zircon ages for samples of (A) the Bunker Hill sequence sedimentary member—07BUNKER; (B) volcanic member —10BUNKER01; and Magog Group (C) 09SV01, (D) 09SV02. The age–probability density distribution plots shown in the insets of (B) and (D) are for the youngest age clusters from which were calculated weighted mean ages.

This outcrop is at the same stratigraphic level than the 09SV02 sample of de Souza et al. (2014), which yielded the following age results by U-Pb zircon dating: 41% of the zircons yielded two Ordovician ages (480 ± 12 Ma; 459 ± 23 Ma) and 31% yielded Silurian to Early Devonian ages (Figure 9D). Nine of these analyses yielded Silurian-Early

Devonian concordant ages ca. 90 percent to 105 percent, determining an age cluster from which was calculated a weighted mean $^{238}U/^{206}Pb$ age of 424 ± 6 Ma (Figure 9D).

STOP 1.4: The lowermost sequence of the Magog Group and the contact with the Ascot Complex phyllites.

Location: Drive back to HGW 610E and follow it until the intersection with Road 112 (approximately 7 km). At the intersection with Road 112, turn around the traffic circle and drive back 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 lower most stratigraphic unit of the Magog Group is made up of volcanic conglomerate and sandstone. On the basis of regional mapping, it was interpreted as unconformably overlying the sedimentary rocks of the Ascot Complex (Tremblay, 1992b). This outcrop is a new roadcut that exposes this contact. We will walk the section from East to West (from the Ascot Complex phyllites toward the contact with the Magog Group).

Figure 10. Volcanic conglomerate of the lowermost stratigraphic unit of the Magog Group in the Sherbrooke area.

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 seen. 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?

Stratigraphically higher (westward) along the section, the outcrop exposes a volcanic, polygenic conglomerate (Figure 10) 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 same sequence unconformably overlies the felsic volcanic rocks of the Stoke domain (Mercier, 2013), and yielded preliminary U-Pb detrital zircon ages of ca. 435 Ma (Perrot, in progress).

STOP 1.5: The Ascot Complex – interlayered felsic and mafic lavas of the Stoke domain.

Location: Continue on HGW 610W and take Exit 7 to 12e Avenue. Turn left onto 12e Avenue and then back onto HGW 610E. Drive the highway until Road 112. Turn right on Road 112, and then left on Gastin Street after 150-200 metres. Turn left on Bibeau Road until the end (ca. 300 metres) and park. The outcrop is an abandoned access ramp, ca. 100 metres to the 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 6). In terms of REE profiles (Figure 11), the 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 (Figure 11).

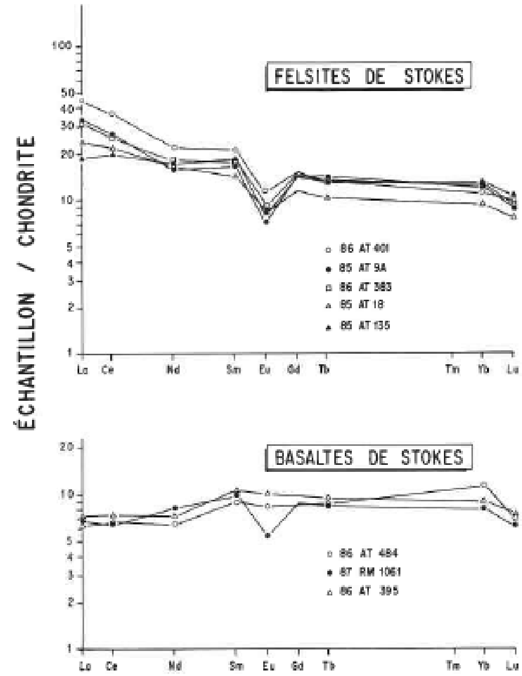

Figure 11. REE patterns for rhyolitic and basaltic lavas of the Stoke domain. From Tremblay et al. (1989a).

On the outcrop, 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 in the vicinity of this outcrop (along road 122) yielded plateau ages of ca. 379 Ma (Figure 12), which corresponds to the age of regional metamorphism (Tremblay et al., 2000).

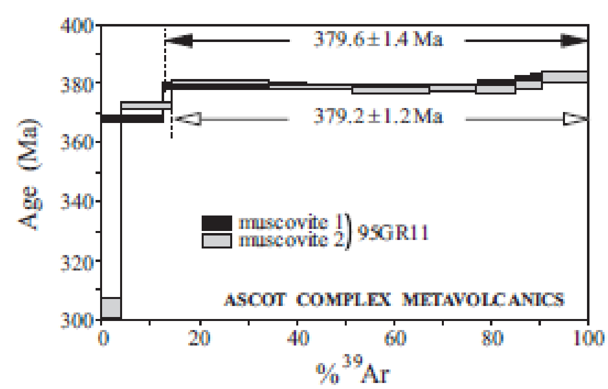

Figure 12. $^{40}Ar/^{39}Ar$ spectra of muscovites from felsic metavolcanic rocks of the Stoke domain; sample 95GR-11. Modified from Tremblay et al. (2000).

STOP 1.6: The Ascot Complex – the granitic synvolcanic intrusion.

Location: Drive back to Road 112 and turn right. Drive for 1.2 km and park on your right.

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 granitic rock 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.

In a comparative geochemical study between granitic boulders found in conglomerates (Stop 1.2) of the Magog Group and the Ascot Complex intrusive rocks, Tremblay et al. (1994) have shown that both are quite similar (Figure 13), and that their petrographical and geochemical characteristics suggest that both types of granitoids are peraluminous, anatectic granitic magmatic pulses originating from destructive plate magmatism.

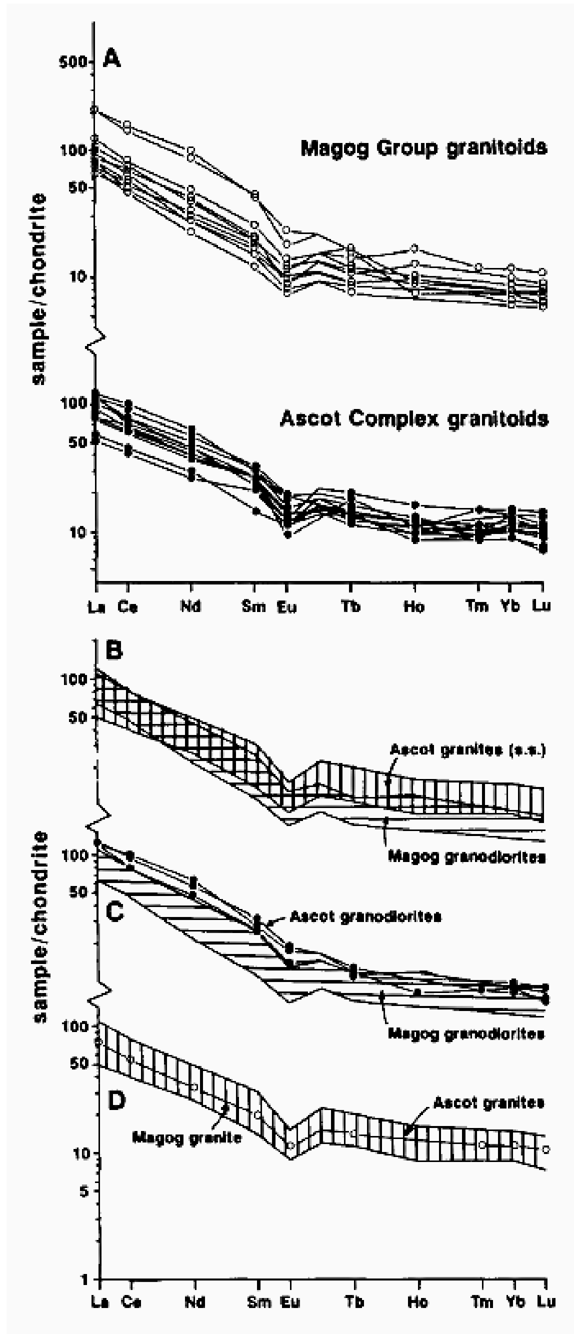

Figure 13. Chondrite-normalized REE data for the Magog Group and Ascot Complex granitoids. From Tremblay et al. (1994).

STOPS 1.7 and 1.8: Hanging wall and footwall of the La Guadeloupe fault–sheared metasedimentary and granitic rocks.

Location: Continue on Road 112 for approximately 2.5 km and turn right on Biron Road. Drive it for 2.5 km and park at the intersection with Provost Street; stop 1.7 is a roadcut at that intersection. For stop 1.8, drive another 800-900 metres along Biron Road and turn right onto Mont-Blanc Street. The outcrop is on your right approximately 100 metres from the intersection with Biron Road.

Field relations: In the Stoke Mountains area, the progressive development of granitic mylonites related to the La Guadeloupe fault is nicely exposed in the Big Hollow brook section (Figure 14; Tremblay et al., 2000), which has been used as a type section for the $^{40}Ar/^{39}Ar$ dating of the regional Acadian metamorphism. Isotopic analyses of sheared rocks of the Big Hollow section clearly demonstrated that Acadian peak metamorphism in the southern Québec Appalachians can be tightly constrained in the 380-375 Ma time range (Figure 15).

These two stops illustrate the intensity of shear deformation that can be observed in metasedimentary (Stop 1.7) and granitic rocks (Stop 1.8) in the hanging wall and footwall, respectively, of the La Guadeloupe fault.

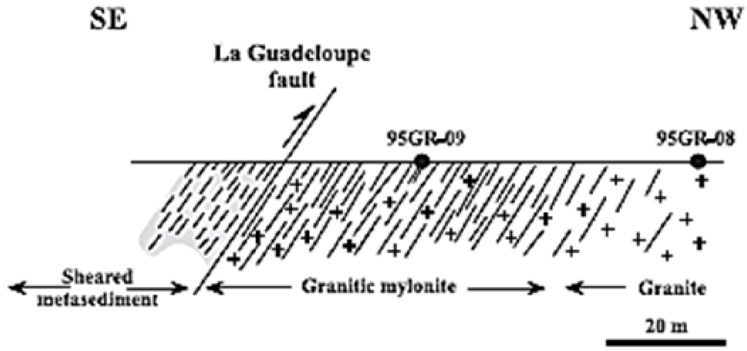

Figure 14. Schematic profile of the La Guadeloupe fault at Big Hollow Brook. From Tremblay et al. (2000).

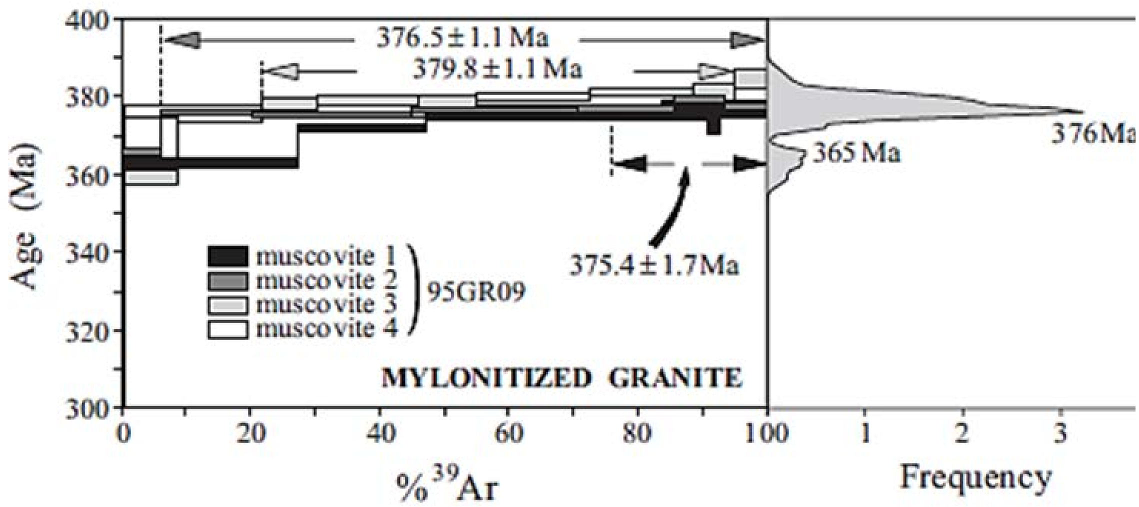

Figure 15. $^{40}Ar/^{39}Ar$ spectra of muscovites from a mylonitized granite of the Big Hollow Brook section (see Figure 14). The apparent age frequency diagram is also shown. From Tremblay et al. (2000).

STOP 1.9: Contact between felsic volcanic rocks of the Eustis domain and black phyllites.

Location: Follow Moulton Hill road until the intersection with College Street (Road 108), just after another bridge over St-François River. Turn right onto College Street and then (downtown) left on Road 143. Drive for approximately 1.5 km and park (there is a small dirt road right after the second traffic circle for safe parking). Walk back to the traffic circle, the outcrop is a huge roadcut on the left.

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 constrasting 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 16) 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 an heterogeneous series of volcanic rocks (i.e. the domains of the Ascot

Complex) and a sequence of manganiferous, fine-grained siltstone grading up into deep-marine mudstone representing an *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-colored 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 17). This structural complexity has been attributed to the proximity of the La Guadeloupe fault (Tremblay and St-Julien, 1990; see next Stop) which is located less than a hundred metres to the SE.

Figure 16. Field photograph of the contact between the felsic rocks of the Eustis domain (pale-colored rocks on the left side) and the black phyllites of the Ascot Complex. Looking south.

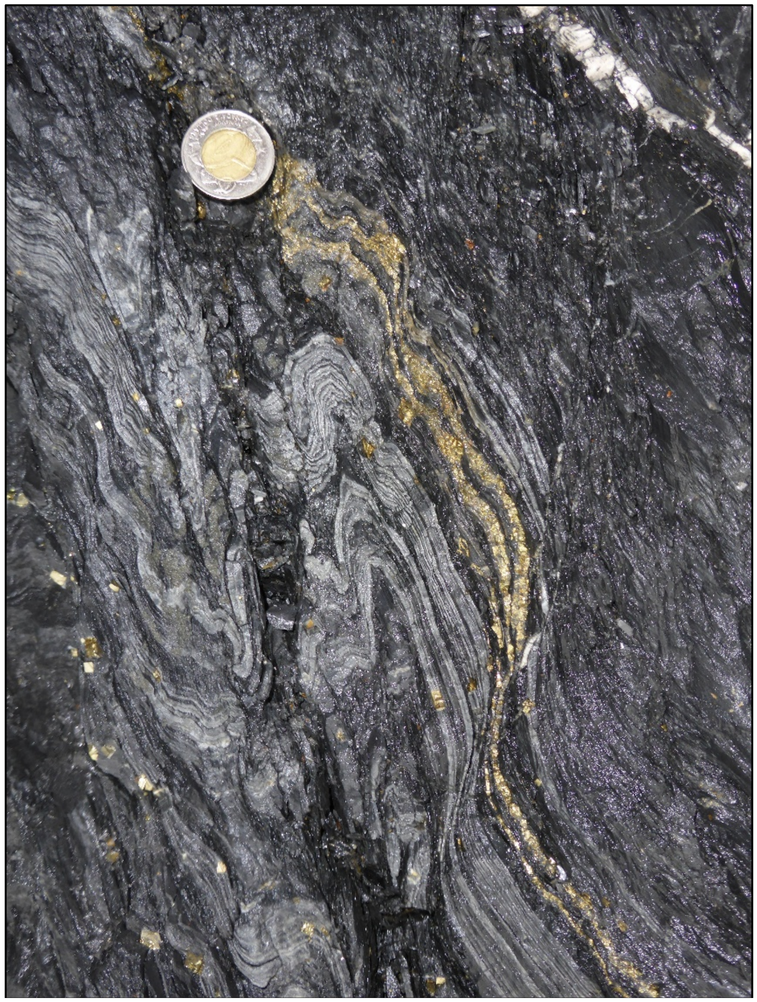

Figure 17. Field photograph of the phyllites, showing S_1 (parallel to bedding), S_2 and S_3.

STOP 1.10: Quartz-sericite schist of the Eustis domain.

Location: Continue on Road 143 for approximately 5 km and turn right onto Road 108 (Capelton Road). After ca. 1.5 km, turn right on Du Boisé Street. Drive ca. 100 metres and park.

Field description: The felsic pyroclastic rocks of the Eustis domain are lithologically and chemically similar to those of the Sherbrooke domain, suggesting that both domains are possible lateral equivalents. D_2 deformation is however stronger in the Eustis domain than elsewhere. S_2 is there a mylonitic foliation, axial-planar to F_2 folds which are crosscut by anastamosing ductile genetically related to the La Guadeloupe fault (Tremblay and St-Julien, 1990). This outcrops is structurally located a few tens of metres in the footwall of the La Guadeloupe fault and exposes a typical example of quartz-sericite schist of the Eustis domain. Note the intensity of structural fabric development and the down-dip plunges of the mineral lineation.

End of field trip.

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