Is the Southern Québec Humber Zone a Silurian Metamorphic Core Complex?

Field trip led by

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ABSTRACT

In the Notre-Dame anticlinorium of southern Québec, the internal Humber zone consist of greenschist- to lower amphibolite-facies metamorphic rocks that are characterized by polyphased deformation fabrics. To the NW, the internal Humber zone is limited by NW-dipping ductile shear zones (i.e. the Bennet fault) that represent backthrust or detachment faulting structures, whereas its southeastern boundary is marked by a major SE-dipping, brittle-ductile normal fault of the area, i.e. the St-Joseph fault. These faults correspond to significant breaks in the metamorphic and structural characteristics of rocks lying on both sides. This one-day field trip will focuses on structural features of the hangingwall and footwall rocks of both the Bennett and St-Joseph faults along the Chaudière River transect, and on their implications regarding the tectonic history of the Laurentian margin in that segment of the Appalachian orogen.

INTRODUCTION

The Appalachian orogen was formed by three sequential tectonic phases that occurred in Paleozoic time (Williams and Hatcher, 1983). The effects of the Carboniferous-Permian Alleghanian orogeny were mainly restricted to the Southern Appalachians, and the Northern Appalachians can thus be regarded as the product of two main orogenic events: the Middle/Late Ordovician Taconian orogeny and the Late Silurian/Middle Devonian Acadian orogeny (Osberg, 1978; Williams and Hatcher, 1983). Recently, the existence of a Silurian continental collision (referred to as the Salinian orogeny; Dunning et al., 1990; Cawood et al., 1994; 1995) has been proposed to account for widespread metamorphism and plutonism of Silurian age in western Newfoundland, but there are still uncertainties concerning the significance of isotopic ages and structures attributed to that Silurian event (Hibbard et al., 1995; Castonguay et al., 1997; Tremblay et al., 1997). In southern Québec, the Appalachian belt is composed of Cambrian to Lower Devonian rocks (Fig. 1) that record Taconian and/or Acadian deformation and metamorphism.

This one-day field trip is focused on metamorphic and structural features of Cambrian-Ordovician rocks deposited on the Laurentian continental margin (the Humber Zone) which, in southern Québec, consist of greenschist- to lower amphibolite-facies metamorphic rocks that are characterized by polyphased deformation fabrics. We will examine different structural features in the hangingwall and footwall of major faults along the Chaudière River transect, and discuss their implications regarding the tectonic and metamorphic history of the Laurentian margin in that segment of the Appalachian orogen. The field trip aims to be a forum for discussion of current interpretations of the Appalachian orogen and how they fit with metamorphic age constraints and structural styles of the Laurentian margin along the strike of the Northern Appalachians.

TECTONIC AND STRATIGRAPHIC SETTING

The southern Québec Appalachians are made up of Cambrian-Ordovician rocks of the Humber and Dunnage zones (Williams, 1979), which recorded the development and subsequent destruction of a passive continental margin (Humber Zone) and adjacent oceanic domain (Dunnage Zone). The Humber and Dunnage zones are in tectonic contact along the Baie Verte-Brompton Line (BBL; Williams and St-Julien, 1982). The Dunnage Zone lies tectonically over the Humber Zone and is disconformably overlain by, and in tectonic contact with Late Silurian and Devonian rocks of the Gaspé Belt (Bourque et al., 1995).

From west to east (Fig. 1), the southern Québec Appalachians consist of: (1) the autochthonous platformal and flysch deposits of the St.Lawrence Lowlands, (2) the slope and rise deposits of the Humber Zone, (3) the oceanic, magmatic and sedimentary rocks of the Dunnage Zone, and (4) the successor basin deposits of the Connecticut Valley-Gaspé trough (Gaspé Belt).

Along the Québec-Maine border (Figs. 1and 2), the Chain Lakes massif has been interpreted either as high-grade metamorphic rocks exotic to North America (Boone and Boudette, 1989), or recycled Grenvillian rocks (Trzcienski et al., 1992; Pinet and Tremblay, 1995).

STRUCTURE AND METAMORPHISM

From a structural point of view, the Baie Verte-Brompton ligne (BBL) grossly represents the limit between two major structuro-metamorphic domains: a Taconian-dominated domain to the NW and an Acadian-dominated domain to the SE (Tremblay and Pinet, 1994).

The Humber Zone forms a classical, foreland-hinterland succession of parautochthonous and allochthonous, carbonate and siliciclastic rock units that were deformed and metamorphosed during the Taconian orogeny (St-Julien and Hubert, 1975). The metamorphism increases gradually toward the SE and culminates in upper greenschist grade in the core of dome structures adjacent to the BBL (Figs. 1 and 2a; Sutton-Notre-Dame Mountains anticlinorium). The Taconian structural history of the Humber Zone involved a ductile stage of NW(foreland)-directed thrust stacking (D_{1-2}), and the subsequent SE(hinterland)-directed backthrusting and folding of the orogenic wedge (D_3) (Tremblay and Pinet, 1994; Pinet et al., 1996a). The internal Humber zone is bounded to the SE by the St-Joseph fault (Pinet et al. 1996a), a major east-dipping normal fault that extends for at least 200 km and marks a boundary with less metamorphosed rocks in its hangingwall. Single-grain laser $^{40}Ar/^{39}Ar$ amphibole and muscovite plateau ages from metamorphic rocks occurring both in the footwall and hangingwall of the St-Joseph fault have yielded Silurian-to-Early Devonian and Middle Ordovician ages, respectively (Castonguay et al., 1997; 2000). The final geometry of dome structures such as the Sutton-Notre-Dame Mountains anticlinorium has been attributed to superposed folding (D_4) of Acadian age (Tremblay and Pinet, 1994; Fig. 2).

Regional structural features and greenschist-grade metamorphism within the Dunnage Zone and the overlying Gaspé Belt (Fig. 1) are mainly of Acadian age (Tremblay, 1992; Tremblay et al., 1999). The regional Acadian folds are upright to steeply inclined with tightness consistently increasing towards the SE. Major Acadian faults, such as the La Guadeloupe and the Rivière Victoria faults, are NW-directed reverse faults (Fig. 2a). Polyphase deformation of

Acadian age occurs along these major faults, as well as in the Québec-Maine border area (Tremblay et al., 1999).

Tremblay and Pinet (1994) subdivide the Taconian and Acadian orogens of southern Québec into external and internal zones (Fig. 2b) on the basis of their structural and metamorphic features, the internal zones being characterized by strongly-developed polyphase deformation and higher metamorphic grade. This tectonic subdivision shows that the two orogens have a significant geographic overlap and that structural windows of the Taconian orogen are found within both the external and internal zones of the Acadian orogen (Fig. 3).

TECTONIC EVOLUTION OF THE HUMBER ZONE

In the Northern Appalachians, the Taconian orogeny was historically interpreted as the result of a collision between the Laurentian continental margin and an island arc terrane that was formed over an east-facing subduction zone (e.g. Osberg, 1978; Stanley and Ratcliffe, 1985). The Acadian orogeny is considered to be 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 a Taconian subduction zone (van Staal et al., 1990).

The structural and metamorphic characteristics of the Humber zone in Québec and New England, as well as the current disposition of Ordovician ophiolites, mélanges, arc volcanics and flysch deposits (i.e. the Dunnage zone) within the Taconian orogen, indicate that Ordovician plate convergence was mainly accommodated by a subduction zone dipping away from Laurentia (Stanley and Ratcliffe 1985, Pinet and Tremblay 1995, Robinson et al. 1998), despite possible arc rifting or subduction reversals as locally invoked in New Brunswick (van Staal and de Roo 1995) and New England (Karabinos et al. 1998). Taconian metamorphism of the Humber zone and arc volcanism preserved in the Dunnage zone are geochronologically constrained to be no younger than uppermost Ordovician in Québec and New England (e.g. Sutter et al. 1985, Stanley and Ratcliffe 1985, Laird 1988, Castonguay et al. 1997, Ratcliffe et al. 1998).

Two main groups of $^{40}Ar/^{39}Ar$ geochronological results have been obtained: Middle Ordovician data in structural windows lying in the hangingwall of the St-Joseph fault and Silurian/Early Devonian data in and around the Notre-Dame Mountains (NDM) anticlinorium, i.e. the footwall of the St-Joseph fault. Amphiboles and micas $^{40}Ar/^{39}Ar$ ages from the NDM anticlinorium vary between 431 and 411 Ma, with high-temperature steps of Ordovician age (462-460 Ma) yielded by amphiboles. This suggests that Taconian metamorphism is only locally preserved and, more important, that there is no protracted cooling from Ordovician to Silurian times and that both periods correspond to geochronologically (and kinematically) unlinked thermal events (Castonguay et al. 2000). A statistical analysis of Silurian/Early Devonian muscovite age spectra reveals an irregular, but constant decrease in weighted apparent age maxima across the internal Humber zone.

Figure 4. Schematic diagram for the internal Humber zone of Québec Appalachians showing alternatives tectonic models for the Silurian. B1: backthrusting coeval with or followed by normal faulting; B2: crustal extension. 1- Taconian deformation; 2- Acadian deformation; 3- Grenville; 4- Silurian-Devonian sedimentary basin. BF-Bennett fault; SJF-St-Joseph fault. From Castonguay and others (1997).

Figure 4. Diagramme schematique illustrant différents modèles tectoniques pour le Silurien des la zone de Humber interne des Appalaches du Québec. B1: rétrochevauchement contemporain, ou suivi de failles normales; B2: extension crustale. 1-déformation taconienne; 2-déformation acadienne; 3-Grenville; 4-basin sédimentaire siluro-dévonien. BF-faille de Bennett; SJF-faille de St-Joseph. Tiré de Castonguay and others (1997).

This age-decreasing trend is interpreted to result from the temporal (ca. 431-411 Ma) and possibly spatial (from NW to SE) migration of deformation, recrystallization and fluid circulation during backthrusting and extensional deformation. In the hangingwall of the St-Joseph fault, metamorphic rocks of the Humber zone are locally exposed through Acadian structural outliers and yielded Middle Ordovician $^{40}Ar/^{39}Ar$ muscovite ages (464-461 Ma; Whitehead et al. 1996, Castonguay et al. 2000), which show no evidence for younger thermal overprint and are consistent with high-temperature step ages of amphiboles from the footwall of the St-Joseph fault.

Middle Ordovician ages are attributed to Taconian metamorphism related to crustal thickening and are consistent with the inferred age of deformation in the Appalachian foreland and external zone in Québec and New England (e.g. St-Julien and Hubert 1975, Stanley and Ratcliffe 1985). For Silurian-Early Devonian ages and the associated hinterland-directed deformation, Castonguay et al. (1997) have proposed two alternative models (Fig. 4), (i) a backthrusting model in which metamorphic ages are related to the tectonic wedging of basement rocks at depth that induced the formation of Silurian backthrusts, such as the Bennett fault, followed by the collapse and the exhumation of the internal zone due to normal faults, and (ii) an extension model in which the Bennett - St-Joseph faults depict a low-angle normal faults system that has been rotated and folded in response to isostatic rebound during Silurian crustal extension. Both models imply significant upper crustal extension and provide structural mechanisms and timing contraints that are compatible with the deposition of Silurian and Early Devonian deposits (i.e. the Gaspé Belt) currently fringing the Humber zone. During the Acadian orogeny, the collision between Laurentian with an Avalonian continental terrane contributed to superimposed metamorphism and deformation.

FIELD TRIP ROAD LOG

The field trip is a section between Quebec City and St-Joseph-de-Beauce with two complementary stops in the Thetford-Mines area (Fig. 1). It focuses on the structural characteristics of the external and internal Humber Zone. Stops 1 and 9 are located on figure 1, stops 2 to 6 are on figure 5, and stops 7-8 are on Figure 14. Figure 6 shows a simplified structural profile of the transect.

STOP 1: THE EXTERNAL HUMBER ZONE: thrust faults and folds of the Chaudière nappe.

Location: From Quebec city, take Highway #73 South. After ca 7 km, take the exit to Saint-Etienne-de-Lauzon. At the intersection with road 171, turn left and drive for ~6 km. There is a rest area on the left side of the road. Park your vehicle. The outcrop is along the Chaudière River just in front of the rest area.

Stratigraphy and structural setting: In Cambrian and Ordovician time, the passive margin sedimentation in the Québec reentrant is recorded by carbonate and siliclastic slope and rise deposits preserved in the Appalachian allochtons (Fig. 1). Sedimentary facies consist of four principal successions; 1- Lower - Middle Cambrian red and green shales, green sandstones and some carbonates; 2- Upper Cambrian black mudslates, white quartzites and conglomerates with carbonate clasts; 3- Lower to Middle Ordovician slope deposits; 4- Upper Middle Ordovician flysch deposits.

The external Humber Zone is bounded by the Logan's line to the NW, and by the Richardson fault to the SE (Fig. 1; St-Julien and Hubert, 1975). South of the Chaudière River, the Richardson fault is not precisely located, and the external-internal boundary corresponds to a major backthrust fault of the southern Québec Appalachians, the Bennett fault (Pinet et al., 1996a). Within the external zone, the regional deformation is mostly characterized by west-directed thrust faults and folds, and by a regionally-developed schistosity (S_1).

Field description: The lithologies exposed at this outcrop consist of a sequence of green sandstones, locally up to 2-3 metres thick, interbedded with red mudslates and minor, thinlybedded limestones. The outcrop exposes a major zone of thrust faulting and related folding within the Chaudière nappe. Thrust faults are sub-horizontal or slightly inclined east or southeast, and marked by cm- to metre-thick zones of cataclastic brecciation and brittle/ductile deformation. The shear-related foliation is well-developed and is hosting down-dip striations and slickenlines. Locally well-developed C/S fabrics clearly indicate west- to NW-verging faulting. Asymmetrical tight to isoclinal folds are nicely exposed in the hangingwall of thust faults (Fig. 7).

Regional implications: The Chaudière nappe is limited by a major thrust fault and forms a klippen that represents the highest structural element of the Québec Allochtons (St-Julien, 1995). The external Humber Zone consists of sub- greenschist, fine to coarse-grained, mainly siliciclastic and calcareous rocks of Late Cambrian to Middle Ordovician age. The thrust-imbricated nappes form east-dipping duplex sequences and depict a typical foreland succession that was deformed in Late Ordovician time. Age constraints from correlative rocks of New England suggest that the tectonic emplacement of the Taconian allochthons and their subsequent metamorphism have occurred between 455 and 440 Ma (Hames et al., 1991; Armstrong et al., 1992).

STOP 2: THE EXTERNAL HUMBER ZONE: superposed folding in the hangingwall of the Bennett fault.

Location: Follow road 171 East up to Saint-Lambert-de-Lévis. Turn left at the intersection with road 218 and follow the direction to Highway 73. Follow the highway 73 South for ~25 km and take the exit to Sainte-Marie-de-Beauce. Turn left and drive back on Highway 73 North. The outcrop is a roadcut, on the right side of the road, at 800 m from the Sainte-Marie-de-Beauce highway entrance.

Structural setting: Along the Chaudière River transect (Figs. 5 and 6), the Chaudière nappe structurally overlies different rock units belonging to various nappes. This outcrop is located within the St-Maxime nappe (St-Julien, 1995) that is essentially made up of red-and-green slates and mudslates interbedded with sandstones, conglomerates and limestone conglomerates. The Richardson fault belongs to a northwest-directed D_{1-2} thrust fault system (Tremblay and Pinet, 1994). Fifteen kilometres north of the Chaudière River, the Richardson fault is folded by a NE-plunging, SE-verging anticline (Fig. 1, Vallieres, 1971) which we attribute to a D_3 deformational event related to backthrusting. Rock units of the eastern limb of the anticline are in inverted position and exhibit a NW-dipping S_3 cleavage which overprints the dominant schistosity. **Field description:** From NW to SE, exposed lithologies are 1) red and green siltstones, 2) conglomerates with quartz pebbles and limestone clasts. Quartz fragments are well-rounded with a maximum size of 2-4 cm, whereas limestone fragments are angular, grey to black in color, and up to 1 metre in diameter. Graded-bedding clearly indicate an inverted polarity. 3) Black siltstones and shales with grey quartzitic beds; the transition with unit 2 is gradual and several conglomeratic horizons are present at the base of unit 3 (Fig. 8).

The dominant fabric is a NE-trending schistosity that is overprinted by a NW-dipping crenulation cleavage (regional S_3). Folds associated with both fabrics can be found. S_3 is regionally-developed and associated with SE-verging folds. Structural relations between the various fabrics and the inverted polarity of the sequence indicate that this site is located on the eastern flank of an overturned anticline on the hangingwall of the Bennett fault.

Regional implications: Fabrics formed during the westward emplacement of Taconian nappes were overprinted by SE-verging folds and faults of inferred Silurian age (Castonguay et al., 1997; 2000). The Richardson fault, which marked the external-internal boundary of the Taconian orogen in southern Québec, is folded by similar backfolds (Fig. 6).

STOP 3: THE INTERNAL HUMBER ZONE: metamorphic rocks in the footwall of the Bennett fault.

Location: Continue northward, take the next exit and drive back to Highway 73 South (Fig. 5). On your way, note when you cross the Chassé River near Sainte-Marie-de-Beauce. The outcrop is a roadcut on the left side of the road, at 4.3 km south of the bridge over the Chassé River.

Stratigraphic and structural setting: In the internal Humber Zone, the Caldwell Group is mostly made up of quartzo-feldspathic sandstones interbedded with red and green slates and with lava flows (St-Julien 1987, Cousineau 1990), and is conformably overlain by quartzites and black shales of the Rosaire Group. Following Vallieres (1984), we correlate the Caldwell and

Rosaire groups respectively with the St-Roch (Early Cambrian) and the Trois-Pistoles groups (Late Cambrian to Early Ordovician) which belong to the external Humber Zone.

The internal Humber Zone encompasses the Sutton Mountains and Notre-Dame Mountains anticlinoria. Regional structures (D_{1-2}) of the internal Humber Zone are overprinted by a penetrative crenulation cleavage (D_3), axial-planar to SE-verging folds, and closely associated to SE-directed backthrusts mainly represented by the Bennett fault (Fig. 6; Pinet et al., 1996b).

Field description: The outcrop exposes metamorphic lithologies that are divided into two principal assemblages: Rosaire-type, black-and-rusty phyllites and quartzites in the eastern half, and Caldwell-type green-and-red phyllites and metasandstones in the western half. The dominant fabric is the backthrust-related, penetrative foliation associated to SE-verging isoclinal folds and shear planes (Fig. 9). Refolded folds (sheath folds?) can be locally seen (Fig. 9). Asymmetrical structures, such C/S fabrics, shear bands and quartz porphyroclasts attest for hinterland-directed movement. Less penetrative, NW-dipping shear zones are present. Note the strong contrast in intensity of deformation and metamorphism compared to the previous outcrop.

Regional implications: D_3 fabrics of the Chaudière River area are regionally developed and correspond to backthrust structures as described by Colpron (1990) and Tremblay and Pinet (1994). Along the western limb of the Sutton-Notre-Dame mountains anticlinorium, these structures root within the Bennett fault (Fig. 6) and the correlative Brome thrust (Colpron, 1990). Shear-sense indicators and the overall vergence of F_3 folds indicate southeast-directed motion.

STOP 4: THE INTERNAL HUMBER ZONE: the core of the Notre-Dame anticlinorium.

Location: Continue on Highway #73 South. The next stop is a roadcut located 2.4 km south of the exit to Vallée-Jonction (see Fig. 15).

Structural setting: Within the Sutton-Notre-Dame Mountains anticlinorium (SNMA), there is evidence for four generations of structures. The regional schistosity is a NW-SE striking S_{1-2} composite foliation, axial-planar to F_2 isoclinal folds associated with NW-SE trending stretching lineations. D_{1-2} fabrics and structures were refolded by tight to isoclinal recumbent F_3 folds that are associated with a flat-lying foliation (S_3). F_3 folds vary in orientation from slightly plunging toward the northeast or the southwest. They are frequently coaxial with older folds and lineations (NW- or SE-plunging), although they clearly refolded D_2-related planar and linear fabrics. All structures were then refolded by NE-SW trending, upright open folds (F_4) associated with the development of the SNMA. A syn-D_4 planar fabric is observed across the anticlinorium. From NE to SW, it varies from a fracture cleavage (Notre-Dame Mountains anticline) to a penetrative crenulation cleavage (Sutton Mountains anticline).

Field description: The outcrop exposes lithologies included in the Rosaire Group. It consists of dark grey, massive quartzite beds and black and rusty pelitic schists. Quartz veins are abundant both in the quartzites and the pelitic schist. The dominant schistosity is subhorizontal and axial-planar to recumbent folds (Fig. 10). A discrete but well-developed series of SE-dipping normal-sense shear planes are visible and crosscutt the dominant schistosity.

Regional implications: Foreland- and hinterland-verging structures are refolded by NE-SW trending upright open folds (F_4) which have been attributed to the Acadian development of the Sutton-Notre-Dame mountains anticlinorium (Tremblay and Pinet, 1994a). The SNMA is the most prominent, large-scale structural feature of the internal Humber zone of southern Québec. It is defined by doubly-plunging anticlinoria that are bounded in the Thetford-Mines and Chaudière River areas by the St-Joseph fault to the east, and in the core of which are found the highest grade metamorphic rocks of the Taconian orogen. The Chaudière River area is, however, located at a periclinal termination of the SNMA, and exposes a higher structural level of the Taconian orogenic wedge than those cropping out within the anticlinorium.

STOP 5: THE INTERNAL HUMBER ZONE: extensional structures in the footwall of the St-Joseph fault.

Location: Continue to follow Highway #73 South. The next stop is a roadcut located 3 km south of the previous outcrop (see Fig. 5).

Structural setting: In the Chaudière River area, the St-Joseph fault (Pinet et al., 1996b) is interpreted as a major normal fault within the internal Humber Zone. The fault strikes NE-SW and separates similar rock units that have recorded different structural and metamorphic histories. Metamorphic rocks of the footwall are characterized by well-developped polydeformed fabrics and structures. Rock units of the hanging wall are less deformed and are found in normal or inverted position. The most striking evidence for SE-directed normal motion comes from several quarries located in the Thetford Mines area, along the NW-SE trending branch of the Pennington ultramafic sheet (Kirkwood and Tremblay, 1994). We will observe well-developped extensional fabrics that are found up to 4 km to the northwest of the St-Joseph fault. (Fig. 6).

Field description: In this outcrop, two rock packages are recognized, 1) to the NW, light grey to greenish siltstones and sandstones that are attributed to the Caldwell Group, and 2) to the SE, black shales and quartzites that belong to the Rosaire Group. Near the contact between 1) and 2), a 1,5 metre-thick high strain zone is marked by numerous quartz veins. Well-developed extensional fabrics are exposed SE of the contact, and consist of asymmetrically boudinaged quartz veins and metre- to decimetre-spaced, SE-dipping (30-70°) brittle-ductile shear zones (Fig. 11). Quartzite beds are clearly affected by SE-verging folds that are associated with an axial-planar schistosity.

The relationship between SE-dipping shears and folds is not clear, and the latter can be interpreted either as overprinted backfolds, or as structures genetically related to normal faulting. Crosscutting relationships shown by the dominant foliation with both the extensional and sheared quartz veins (Fig. 12), however, suggest that all these structures have been generated during a SE-verging deformational event.

Regional implications: The recognition of normal faults of inferred Silurian/Early Devonian age (Castonguay et al., 1997; 2000) in the internal zone of the Taconian orogen provides a mechanism for the deposition of thick sequences of Silurian and Devonian rocks preserved in large sedimentary basins such as the Connecticut Valley-Gaspé trough (see Fig. 7).

STOP 6: THE INTERNAL HUMBER ZONE: the hangingwall of the St-Joseph fault.

Location: Follow Highway #73 South and take the exit to St-Joseph-de-Beauce. Turn left on road 276 North (toward Lac-Etchemin) and take the entrance back on 73 North. The outcrop is a roadcut that is accessible via a construction road that is the southward continuation of Highway 73.

Structural setting: In the hangingwall of the St-Joseph fault (Fig. 5), rocks that belong to the Caldwell and Rosaire groups are less deformed than in the footwall. Primary textures and structures such as graded-bedding and massive or pillowed lava flows are well-preserved, in marked contrast with rock units present in the footwall of the St-Joseph fault.

Field description: The outcrop exposes typical sandstones and red-and-green shales of the Caldwell Group. Note the lithological similarity with the sedimentary sequence of the Chaudière nappe as seen at stops 1 and 2. Well-developed antiformal upright folds can be seen (Fig. 13), and are associated to a NE-SW trending, axial-planar cleavage.

Gradded-bedding and cross-laminations in sandstone beds indicate that the sequence is up-side-down. This regional feature implies the presence of pre-existing, recumbent folds in the Caldwell/Rosaire sequence, east of the St-Joseph fault. Regional constraints suggest that the superposed upright folding is Acadian-related, and that pre-existing recumbent folding should be pre-Acadian. Such folds probably belong to the SE-verging folding phase (D_3) recognized in the footwall of the St-Joseph fault.

Regional implications: Even tough the existence of normal-sense metamorphic break does not necessarily imply crustal extension (e.g. Wheeler and Butler, 1994), it is important to note that the St-Joseph fault also coincides with a strong metamorphic and structural contrast (compare this stop with stops 3 to 5).

STOP 7: THE ST-JOSEPH FAULT

Location: Take the bridge over the Chaudière river in St-Joseph-de-Beauce, turn right. Turn left on the next road and follow it until the intersection with road 112 (~6 km). Turn left on road 112 West, and drive for ~15 km. At the intersection with road 271 South, turn right on rang IX. The outcrop is a quarry that is located on your left at 1 km from road 112. Contact Carey Canada Inc. for the permission to access the site.

Structural setting: The St-Joseph fault is clearly recognized over a distance of approximately 200 km from Thetford-Mines to the Québec-Maine border in the northeast (Fig. 1). Existing geological maps of the Chaudière River area show the St-Joseph fault as a thrust fault (St-Julien, 1987; Cousineau, 1990). In the Thetford-Mines area (Fig. 14), the fault is commonly marked by slivers of sheared serpentinites and follows the NE-SW trending branch of the Pennington ultramafic sheet (St-Julien, 1987). The St-Joseph fault dips approximatively 70°

toward the southeast.

Field description: The St-Joseph fault is exposed in the quarry and is marked by serpentinite slivers (Fig. 15). The footwall consist of dark-colored, finely laminated "gneissic" rocks and chlorite schists showing multiple generations of fabrics and complex fold interferences. The hangingwall rocks are dark quartzites interbedded with pelitic and quartz-sericite schists with abundant quartz veins and veinlets parallel to the mylonitic foliation. Abundant shear bands and SE-verging folds in the footwall clearly attest for normal-sense motion. Serpentinite in the fault zones is most commonly scaly. In this quarry, the St-Joseph fault corresponds to a series of interfering low-angle and high-angle, ductile/brittle normal faults (Fig. 15). We interpret the former structures as low-angle synthetic shear zones formed during progressive deformation. Extensional faulting has been localized by the serpentinite layers which probably flowed up- and down-dip along fault planes.

Regional implications: Structures related to the St-Joseph fault are superposed on Silurian SE-verging folds (F_3) of the footwall (Castonguay et al., 1997), thus indicating that normal faulting post-dates backthrusting, and excluding the possibility that this normal fault is a rotated backthrust or a reimbricated D_{1-2}-related thrust. In southern Québec, the recognition of extensional structures related to the St-Joseph fault is important and indicates that an extensive system of normal faults developed prior to the Acadian orogeny. Southward, the St-Joseph fault merges with the BBL on both side of which similar metamorphic and structural contrasts occur. $^{40}Ar/^{39}Ar$ dating of metamorphic rocks from the footwall of the BBL bordering the Sutton Mountains anticlinorium also yielded Silurian ages (Castonguay, unp. data) and field data also indicate the predominance of southeast-dipping normal sense faulting. Northward, the St-Joseph fault merges into an unamed normal faults system mapped at the boundary between the CVG trough and pre-Silurian rocks in northwestern Maine (e.g. Osberg et al. 1985). This suggests that, from southern Québec to northwestern Maine, the St-Joseph fault is part of an extensively developped, normal fault system of probably Late Silurian to Early Devonian age that extends for more than 400 km. We suggest that evidence for extensional deformation has been locally preserved within the Québec reentrant because this segment of the Taconian orogen has suffered less intense Acadian deformation and metamorphism than elsewhere in the Appalachian belt.

STOP 8: ULTRAMAFIC ROCKS OF THE INTERNAL HUMBER ZONE: the Pennington Sheet.

Location: Drive back to road 112 West. At the intersection with Rang X, turn right toward St-Pierre-de-Broughton. Follow this road for 4 km and park your vehicule. The outcrop is located in the field on the south side of the road. Ask for permission to the owner of the land.

Structural setting: The Pennington Sheet is a fault zone (D_2?) within the Bennett Schist (Kirkwood and Tremblay, 1994) (Fig. 14). The NW-SE trending branch of the Pennington Sheet is characterized by mylonitized and brecciated serpentinite that is deformed by the regional D_3 and D_4 structures, whereas the SE portion of the ultramafic sheet is truncated by the St-Joseph fault. Mapping in correlative rocks of southernmost Québec (Colpron, 1990; Rose, 1993), New England (Stanley and Ratcliffe, 1985) and Newfoundland (Hibbard, 1983) has shown the existence of fault zones similar to the Pennington Sheet.

Rocks adjacent to the Pennington Sheet belong to the Rosaire and Caldwell groups and to their metamorphic equivalents in the Bennett Schist. These rocks consist of quartzite, pelitic schist, and quartz-albite-muscovite-chlorite+/-biotite schist.

Field description: At this locality, the contact between the Pennington Sheet and adjacent metamorphic rocks can be observed. Host rocks are graphitic schists, quartzites and micaschists which are characterized by isoclinal folds, coaxial with well-developed quartz rods and mineral lineations. The ultramafic sheet is a foliated ophiolitic mélange. Most fragments are serpentinized dunite and harzburgite. The outcrop locally shows nice examples of progressive tectonic brecciation. Two generations of structural fabrics can also be observed. $^{40}Ar/^{39}Ar$ muscovite dating from adjacent metamorphic rocks yielded a plateau age of 425+/-2Ma (Castonguay et al., 1997) which has been attributed to the backthrusting thermal imprint.

Regional implications: The geometry and tectonic significance of the Pennington Sheet are still not well understood. On map scale, these ultramafic rocks make complex fold patterns and it is not excluded that the sheet has been folded by D_2 structures as well. The link between the Pennington Sheet and the Thetford-Mines ophiolitic complex (Fig. 14) is not clearly established. According to the actual knowledge of the regional geology, we believe that structures such as the Pennington Sheet are most probably related to pre- to syn-D_2 ductile shearing within the Laurentian margin.

STOP 9: BACKTHRUST STRUCTURE AND METAMORPHISM: The Bernierville section.

Location: Drive back and follow road 112 West across Thetford-Mines and to Black Lake (~22 km). In Black Lake, turn right on road 265 North and drive for ca. 17 km. Take the entrance to Bernierville. The outcrop the roadcut adjacent to that entrance.

Stratigraphy and tectonic framework: In the external Humber zone, the Oak Hill Group forms a complete rift- and drift-related sequence of the Laurentian margin. It records the progressive development of a continental margin from Early Cambrian to early Middle Ordovician time (Charbonneau,1980; Colpron, 1990; Marquis, 1991). The Oak Hill Group consists of volcanic rocks, calcareous rocks, quartzites and slates. The age of the volcanics (Early Cambrian) is defined by U/Pb zircon ages from the Tibbit Hill Formation (554 Ma; Kumarapeli et al., 1989). The age of the upper part of the Oak Hill Group is believed to be late Arenigian to early Llanvirnian on the basis of conodonts (Marquis and Nowlan, 1991).

The Bennett Schist of the internal Humber Zone consist of metamorphosed rocks of the Oak Hill, Caldwell and Rosaire goups. Several generations of structures are recognized. The regional schistosity (S_{1-2}) is overprinted by a S_3 crenulation cleavage. Variations in the intensity of D_3 fabrics reflect the inhomogeneous strain pattern during this deformation. D_3 high strain zones correspond west-dipping shear zones, such as the Bennett fault (Pinet et al., 1996a), developed along flanks of large-scale SE verging antiforms.

Field description: Several deformational events are recognized in this outcrop. The oldest structural fabric (S_{1-2}) is defined by a compositional layering. Metamorphism associated to D_{1-2} structures is of upper greenschist facies as indicated by mineral assemblages which comprise biotite and muscovite. The presence of biotite has been attributed to the proximity of a D_{1-2} faulted contact between the lower Oak Hill Group (Tibbit Hill Formation) with its upper units (Fig. 16). D_{1-2} structures are overprinted by a mm-spaced S_3 crenulation cleavage which is marked by the recrystallisation of muscovite. Shear sense indicators related to D_3 and the vergence of associated folds suggest a hinterland-directed tectonic transport. Biotite and muscovite $^{40}Ar/^{39}Ar$ dating from this outcrop yielded Silurian ages (Castonguay et al. 2000).

Regional implications: In southern Québec, the internal Humber Zone records backthrusting structures of Silurian age that are poorly documented (or absent?) in correlative rocks of the New England Appalachians. On the basis of seismic reflection data from southern Québec (St Julien et al., 1983), the existence of basement duplexes is inferred at depth under the Sutton-Notre-Dame Mountains anticlinorium (Bardoux and Marquis, 1989). Backfolds and backthrusts of the internal zone has been consequently interpreted as resulting from the tectonic wedging of basement rocks (Pinet et al., 1996a).

This marks the end of the field trip. Beer and chatting time!!

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