Joint Meeting

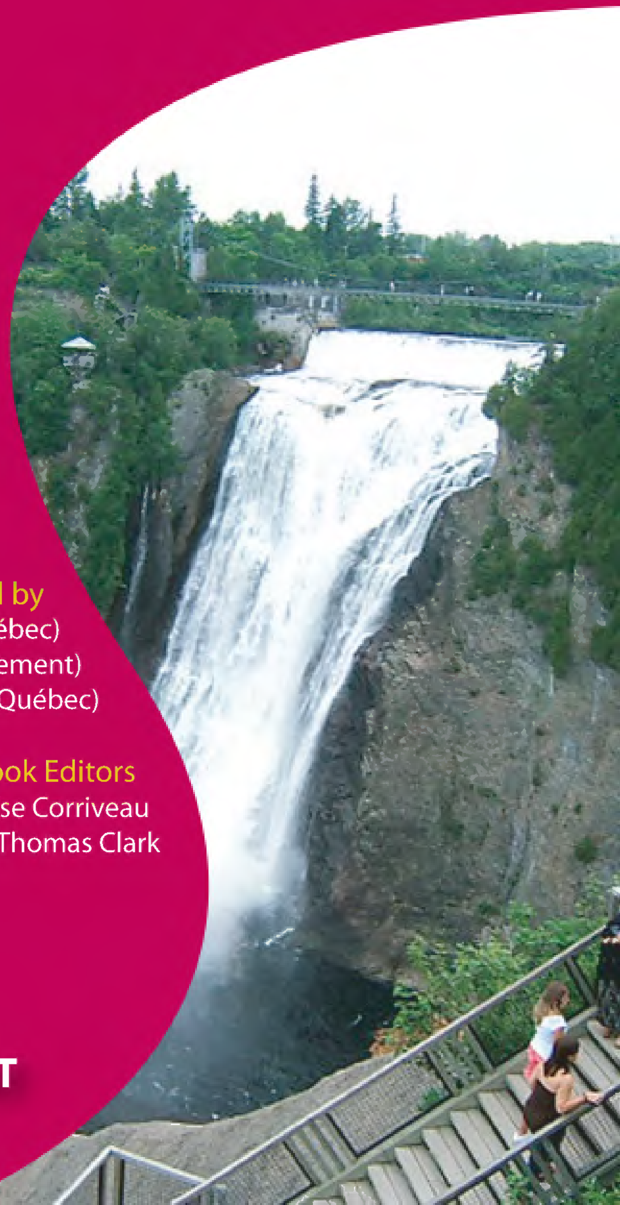
New England Intercollegiate Geological Conference

Friends of the Grenville

Association québécoise des Sciences de la Terre

October 5-7, 2007

Guidebook for Field Trips
in Southern Quebec

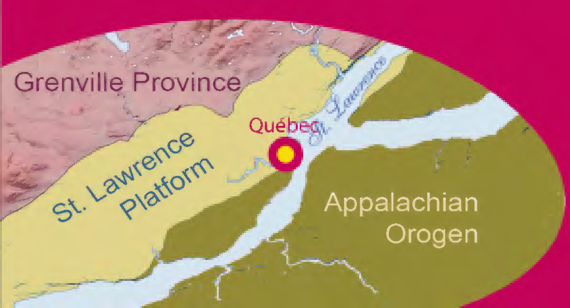


Hosted by

Geological Survey of Canada, Natural Resources Canada (GSC-Québec)
Institut national de la Recherche scientifique (Eau-Terre-Environnement)
Ministère des Ressources naturelles et de la Faune (Géologie Québec)

Guidebook Editors

Louise Corriveau
Thomas Clark



NEIGC FOG AQUEST

http://gac.esd.mun.ca/AQUEST/index.htm
www.neigc.org/NEIGC/

Joint Meeting
Quebec City, Quebec, Canada

New England Intercollegiate Geological Conference
(99th Annual Meeting)
Friends of the Grenville
Association québécoise des Sciences de la Terre

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(Géologie Québec)

Organized by

Louise Corriveau (Geological Survey of Canada)
Michel Malo (Institut national de la recherche scientifique)
Thomas Clark (Ministère des Ressources naturelles et de la Faune)

Guidebook Editors

Louise Corriveau
Thomas Clark

Participating Organizations

The **New England Intercollegiate Geological Conference (NEIGC)** began in 1901 with a field trip led by William Morris Davis to terraces of the Westfield River in south-central Massachusetts. The conference has since met annually, with exceptions during World Wars I and II, and a two-year gap during 1913 and 1914. The NEIGC may be the oldest geological "nonorganization" in North America. The largest number of meetings has been hosted in Massachusetts, followed by Maine, Connecticut, New Hampshire, Vermont, and Rhode Island. The conference has met outside of New England, in New York, Quebec, and New Brunswick. Nonorganizational rules have been unofficially established and include no dues, evening papers, talks, or lectures. The sole purpose of the NEIGC is, as it has always been, to organize and present field trips in areas of recent geologic mapping or topical studies, as well as to classic localities of interest.

The **Friends of the Grenville (FOG)** is a loose-knit fraternity that formally came into existence in 1972 but whose roots really go back to a monumental, 3000-km-long, 12-day fieldtrip in 1967 led by Hugh R. Wynne-Edwards. 2007 is thus FOG's 40th anniversary. Since 1970, there has been an unbroken chain of annual, September-October, two-day excursions that alternate between Ontario, Quebec, and New York. Like NEIGC, it is a "nonorganization" with no dues and no formal membership. A Friday-night gathering welcomes participants with an overview of the fieldtrip and a Saturday-night banquet salutes fieldtrip leaders and the participant having travelled the farthest to join the "Friends." It is the mixture of friendships developed over the years, the rocks and their beautiful enigmas, and the frank and broad discussions on their potential solutions that keep drawing FOG members back, year after year, rain or shine.

The **Association québécoise des Sciences de la Terre (AQUEST)** was founded in 2004 to promote Geosciences in Quebec and, one month later, officially became the Quebec Section of the Geological Association of Canada. AQUEST convenes and sponsors a variety of activities and awards certificates of excellence at geosciences venues to foster the quality of geoscientific education and research in Quebec. Publication of an electronic newsletter maintains contact with formal members. The parent Geological Association of Canada (GAC) aims at facilitating the scientific well-being and professional development of its members, the learned discussion of geosciences in Canada, and the advancement, dissemination, and wise use of the geosciences in public, professional, and academic life. It is supportive of the entire scope of the geosciences in Canada.

Acknowledgements

The organizers thank the following for their contributions to the meeting:

- the Institut national de la recherche scientifique for hosting and subsidizing the Friday welcoming reception
- the Ministère des Ressources naturelles et de la Faune du Québec for printing the guidebook, providing it at the lowest cost possible, and archiving it
- Laval University for providing a vehicle for the Lac Piché Anorthosite field trip
- the Forêt expérimentale Montmorency for logistical support
- their respective employers for allowing them to devote considerable time to this endeavor, as well as several of their colleagues for help and encouragement

This guidebook may be obtained at the addresses below:

Ministère des Ressources naturelles et de la Faune du Québec
880, chemin Ste-Foy, Québec, QC G1S 4X4, Canada
Website: www.mrnf.gouv.qc.ca/english/products-services/mines.jsp
This report is archived at the MRNF as GM 63037; a page charge will be applied for paper copies.

Maine Geological Survey
State House Station 22
Augusta, Maine 04333, U.S.A.

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(continued overleaf)

[1] The descriptions of field trips A1 and B2 are combined in one field guide.

[2] This field trip was conducted in French (trip A5) and in English (trip C5). Only the English version of the field trip is provided in this guidebook. The French version of the guide is available from the authors.

Dedication to Dabney W. Caldwell

Dee Caldwell at the Manicouagan impact crater, 2005 (photo by Alice Sheppard)

Although he was born in Virginia, Dee Caldwell was from Maine. He grew up in Mount Vernon, swam in "his" pond there, Parker Pond, attended Kents Hill Academy, became an athlete outstanding in baseball and skiing, and graduated from Bowdoin College in 1949. He had decided to become a geologist prior to this when he earned a geology merit badge as a Boy Scout. He completed graduate studies with an M.A. from Brown University and a Ph.D. from Harvard University, taught geology at Wellesley College for a few years, and eventually at Boston University.

It was at Boston University that Dee spent most of his career, and it was through that position as a mentor that he helped along many students in their careers. I met him at the BU Field Camp after my junior year in 1974, the summer of Watergate. With student field assistants, Dee was mapping the surficial geology of the wildlands of northwestern Maine for the Maine Geological Survey. The ski lodge in Rangeley was base camp for the field course and Dee led several field trips that made an impression on me, and certainly got me thinking about geology as a career. We visited the till sections at New Sharon, later to become my thesis as Dee's last Ph.D. candidate. We waded the South Branch Ponds Brook examining the Devonian Trout Valley Formation and hiked Katahdin on another trip to Baxter State Park, his Ph.D. thesis field area. But it wasn't just his love of geology that turned me to become a field geologist; it also was his approach to life. Each evening at the lodge upon returning from the field, Dee and his colleagues would sit out on the roof deck to watch the sunset over gin and tonic before dinner. Even at a rude campground Dee could make it a special place, with stories and well prepared camp food. There was elegance in his style.

His career working in Maine covered more than fifty-three years of geologic mapping, overseeing student theses, writing articles, professional papers, bulletins, and guidebooks, and especially leading field trips for professional geologists as well as the general public. He was an area compiler for the 1985 Surficial Geologic Map of Maine, and authored the popular *Roadside Geology of Maine*. Many people know Dee as the Secretary of the New England Intercollegiate Geological Conference, a position he relished and which he held for twenty-six years from 1969 to 1995. Since Dee first attended the NEIGC in 1949, he led many field trips, edited three guidebooks, and organized as many meetings. He was honored by the NEIGC in 2001 upon his retirement from Boston University and for his years of service to the Conference.

While most of his teaching time was in Massachusetts, Maine was as deep in him as wood smoke from a campfire. Dee spent much of his later years at the Chesuncook Lake Boom House with his wife Marvin, in Township 3 Range 12, just west of Ripogenus Dam. Of course, it is where the Boston University Summer Field Camp was based for many years, which holds many cherished memories of former students and professional colleagues who would often stop by to visit. The meals Marvin and Dee prepared there for guests were sumptuous; home cooking, as good as it gets. No one left the Boom House wanting, and never was there a lack of solid companionship.

With his passing on December 11, 2006, the geologic community of New England lost a dear mentor and friend, and a great contributor to our science. And although he probably would not want too much honoring and memorial, it is with admiration that we fondly dedicate this guidebook to him.

In closing, the words found below are written by a poet friend about a special characteristic, one that fits Dee, found in his eyes, his laugh, his heart, and in his whole being. Dee, we will miss you, yet you stay with us; you still are that special person, the one with shine.

In this life you are privileged to meet people of shine; you ought to be because it happens so rarely. It is not the temporary glow that some individuals have for many of us now, in a culture caught up on the fingers of a new type of hero; it is not burnish or silver plate or gold plate. It is not some electrolytic deposit of a rare metal veneer atop usual and common surfaces. It is a bone-deep and authentic shine coming from the inside out. It is the signal from the soul, part glow, part semaphore, that says, more honest than the day is long, "It's way in here where this shine starts."

Cirque basins and basin pond moraines; Ktaadn, Baxter State Park, Maine (photo by D.E. Johnson)

Tom Weddle
Secretary, NEIGC

THE LOWER PALEOZOIC SUCCESSIONS IN THE QUEBEC CITY AREA:

TECTONO-STRATIGRAPHY AND SEDIMENTOLOGY

FRIDAY FIELD TRIP

TECTONO-STRATIGRAPHY OF THE APPALACHIAN NAPPES AND STRUCTURAL FRONT, QUEBEC CITY AREA: EARLY PALEOZOIC EVOLUTION OF LAURENTIA AS RECORDED IN TACONIAN-DEFORMED DEEP MARINE SEDIMENTS

by

Donna Kirkwood and Denis Lavoie
Geological Survey of Canada
GSC-Québec
490, rue de la Couronne, Québec, QC G1K 9A9, Canada

SATURDAY FIELD TRIP

ORDOVICIAN FORELAND SHALLOW MARINE FACIES, QUEBEC CITY AREA: HARBINGERS OF THE LATE ORDOVICIAN GLACIATION AND SIGNIFICANCE FOR HYDROCARBON EXPLORATION

by

Denis Lavoie and Donna Kirkwood
Geological Survey of Canada
GSC-Québec
490, rue de la Couronne, QC G1K 9A9, Canada

GEOLOGICAL CONTEXT OF THE NORTHERN QUÉBEC APPALACHIANS

Regional Setting

The regional overviews of the Appalachian basins in Canada ("Geology of the Appalachian-Caledonian Orogen in Canada and Greenland"; Williams, 1995) and of the adjacent Lower Paleozoic cratonic platform ("Sedimentary cover of the craton in Canada"; Stott and Aitken, 1993) synthesized our knowledge of these belts in the mid to late 80's period. These volumes are still a source of invaluable information as they present the most complete and detailed account of the entire Paleozoic succession in eastern Canada (Fig. 1).

Since publication of these, even with cyclic downsizing of geological activities, critical new research results became available and refined our understanding of these domains. In eastern Canada for example, hydrocarbon exploration in the mid/late 90's in the lower and middle Paleozoic successions (Cooper et al., 2001; Lavoie and Bourque, 2001), major deep seismic project (Lithoprobe East, Quinlan, 1998), NATMAP (Canada NATional geoscience MAPping program) regional mapping and thematic studies (Maritimes Basin; 1993-1998, Forelands and Platform; 1999-2004) and Targeted Geoscience Initiative (Red Indian Line; 2000-2003; Appalachian Energy; 2003-2005) prompted some new research activities and resulted in improved understanding of the Canadian Appalachians (Lynch, 2001; Lavoie et al., 2003a; 2004; van Staal, 2005).

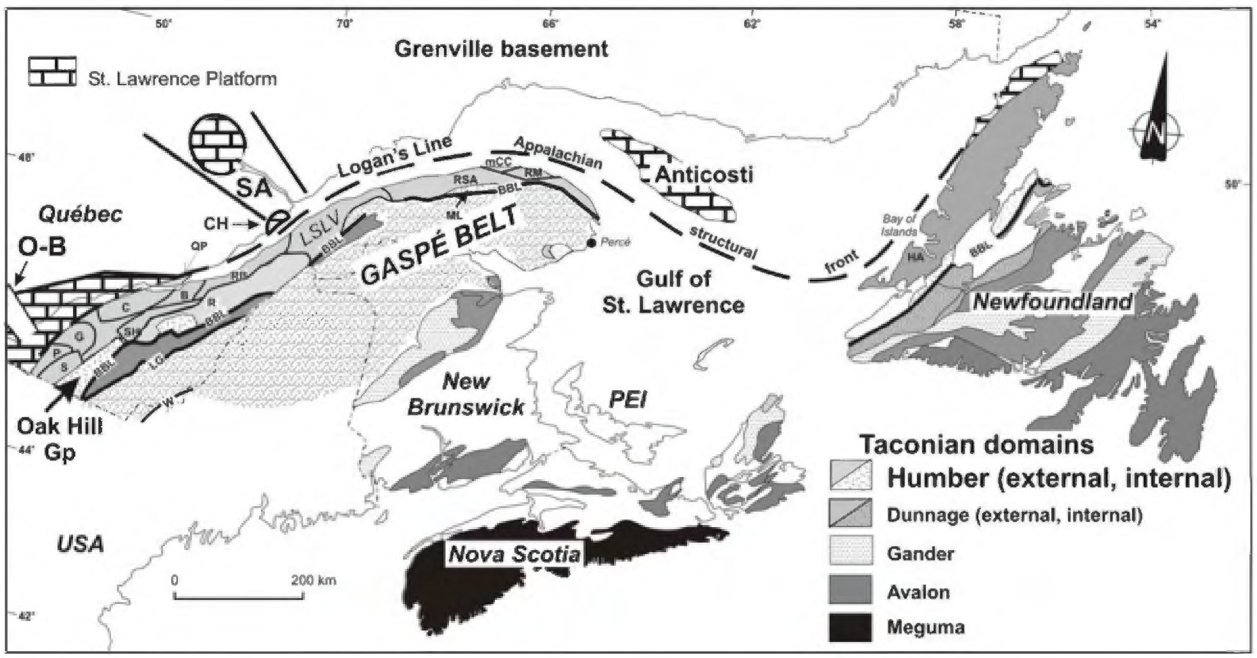

Figure 1. Taconian tectonostratigraphic domains and the Silurian-Devonian basin (Gaspé Belt) of the Canadian Appalachians. The Taconian belts are bordered to the northwest by the St. Lawrence Platform and the Grenville orogen of the Laurentia craton and are locally overlain by successor basin deposits. Note the position of the Early Cambrian shallow marine sediments of the Oak Hill Group in southern Québec. BBL: Baie Verte Brompton Line, CH: Charlevoix area, LG: La Guadeloupe fault, LSVL: lower St. Lawrence Valley, O-B: Ottawa-Bonnechère Graben, SA: Saguenay Graben, W: Woburn fault. Tectonostratigraphic nappes of the Taconian Humber Zone are: B: Bacchus, C: Chaudière, G: Granby, HA: Humber Arm, HB: Hare Bay, mCC: Cap Chat mélange, ML: Mont Logan, P: Philipsburg, QP: Promontoire de Québec, R: Richardson, RB: Rivière Boyer, RM: Rivière Marsoui, RSA: Rivière Sainte-Anne, S: Stanbridge, SH: Sainte-Hénédine. Modified from Williams (1995).

Rocks ranging from the Neoproterozoic to the end-Mesozoic are found in eastern North America. Six significant orogenic/deformation events are documented in the Appalachians and are related to the accretion of volcanic arcs, oceanic crust, microcontinents and continents to the progressively more and more composite margin of Laurentia (van Staal et al., 1998; van Staal, 2005). These events are 1) the late Cambrian Penobscot Phase (Cambrian oceanic units-Gander) and the coeval Lushs Bight Oceanic Tract-Dashwoods accretion, 2) the end-Middle Ordovician

Taconian Orogeny (volcanic arcs-Laurentia), 3) the Silurian Salinic Orogeny (Ganderia-Laurentia), 4) the Early - Middle Devonian Acadian Orogeny (Avalonia-Laurentia), 5) the end-Middle to Late Devonian Neoacadian Orogeny (Meguma-Laurentia), and 6) the end-Carboniferous - Permian Alleghanian Orogeny (Gondwana-Laurentia).

In this guidebook, we only consider the Iapetan rift to the syn-Taconian Appalachian sedimentary basins, therefore covering a time interval ranging from the end of the Neoproterozoic to the Upper Ordovician (Fig. 1). This field trip guidebook presents an overview of the lower to middle Paleozoic stratigraphic architecture, paleogeographic scenarios and relative sea level history for the evolving sedimentary basins for the Québec part of the Canadian Appalachians. The field trip will provide an opportunity to examine the rift, passive margin and syn-Taconian sequences and foreland platform of the Early Paleozoic margin of Eastern Laurentia. Visits are planned to key outcrops located in the Québec City area to look at the stratigraphic architecture, primary facies distribution and diagenetic overprint, as well as the structural imbrication of the Laurentia's continental margin, during the Taconian Orogeny (Fig. 2).

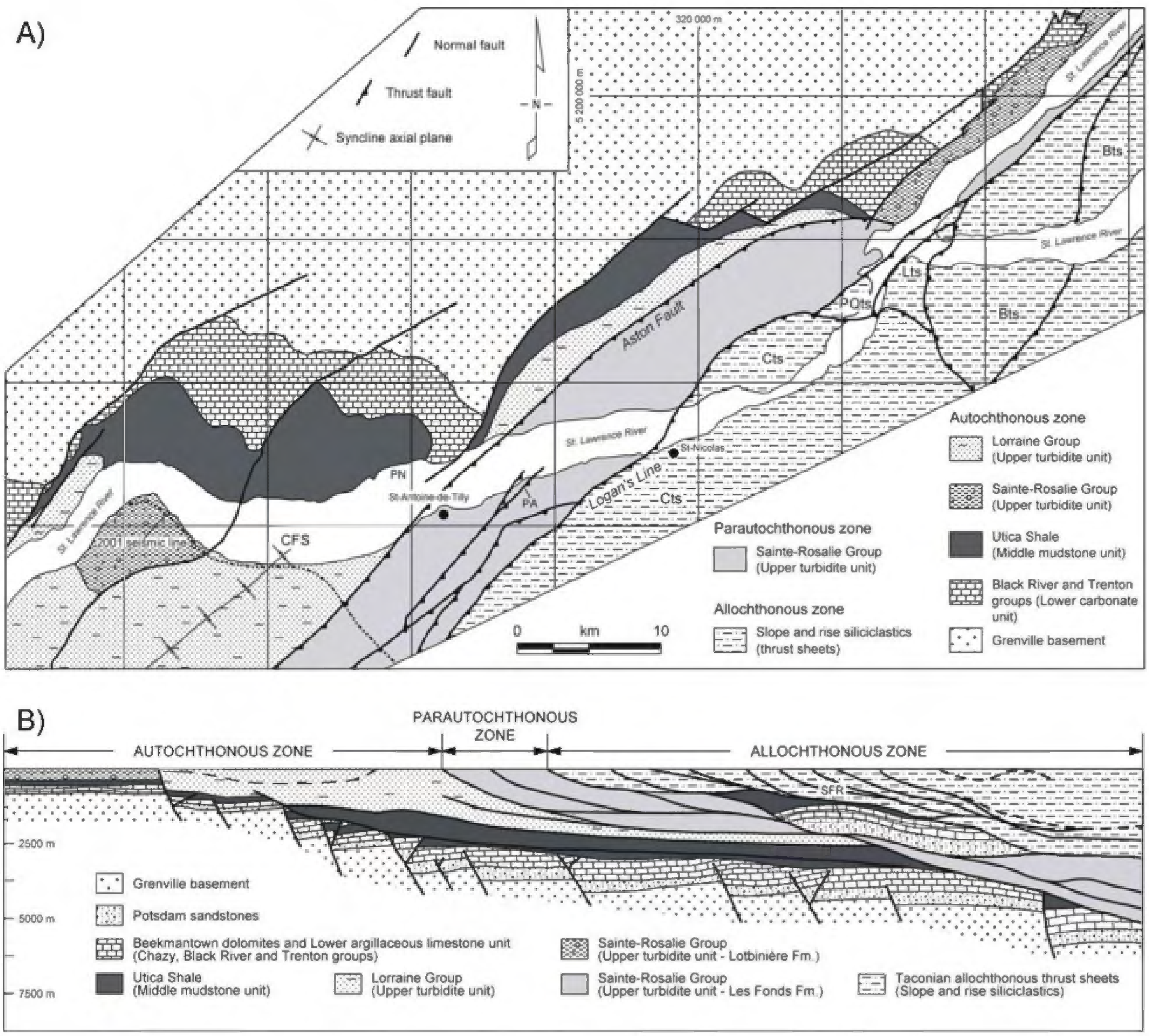

Figure 2. (A) Geology of the Appalachian front in the Québec City area modified from Globensky (1987) and adapted from Castonguay et al. (2006). (B) Cross section along 2001 seismic line adapted from St-Julien et al. (1983) and Castonguay et al. (2006). Location of the 2001 seismic line on figures 2a and 4. Abbreviations: Bts, Bacchus thrust sheet; CFS, Chambly-Fortierville Syncline; Cts, Chaudière thrust sheet; Lts, Lévis thrust sheet; PA, Pointe Aubin; PN, Plage Neuville; PQts, Promontoire de Québec thrust sheet; SFR, St-Flavien reservoir.

The shallow marine continental platform

In southern Quebec, the St Lawrence Platform corresponds to a siliciclastic and carbonate platform having a maximum thickness of 1200 metres, overlain by approximately 1800 metres of foreland deposits (Figs. 3 and 4) (Sanford, 1993; Lavoie, 1994).

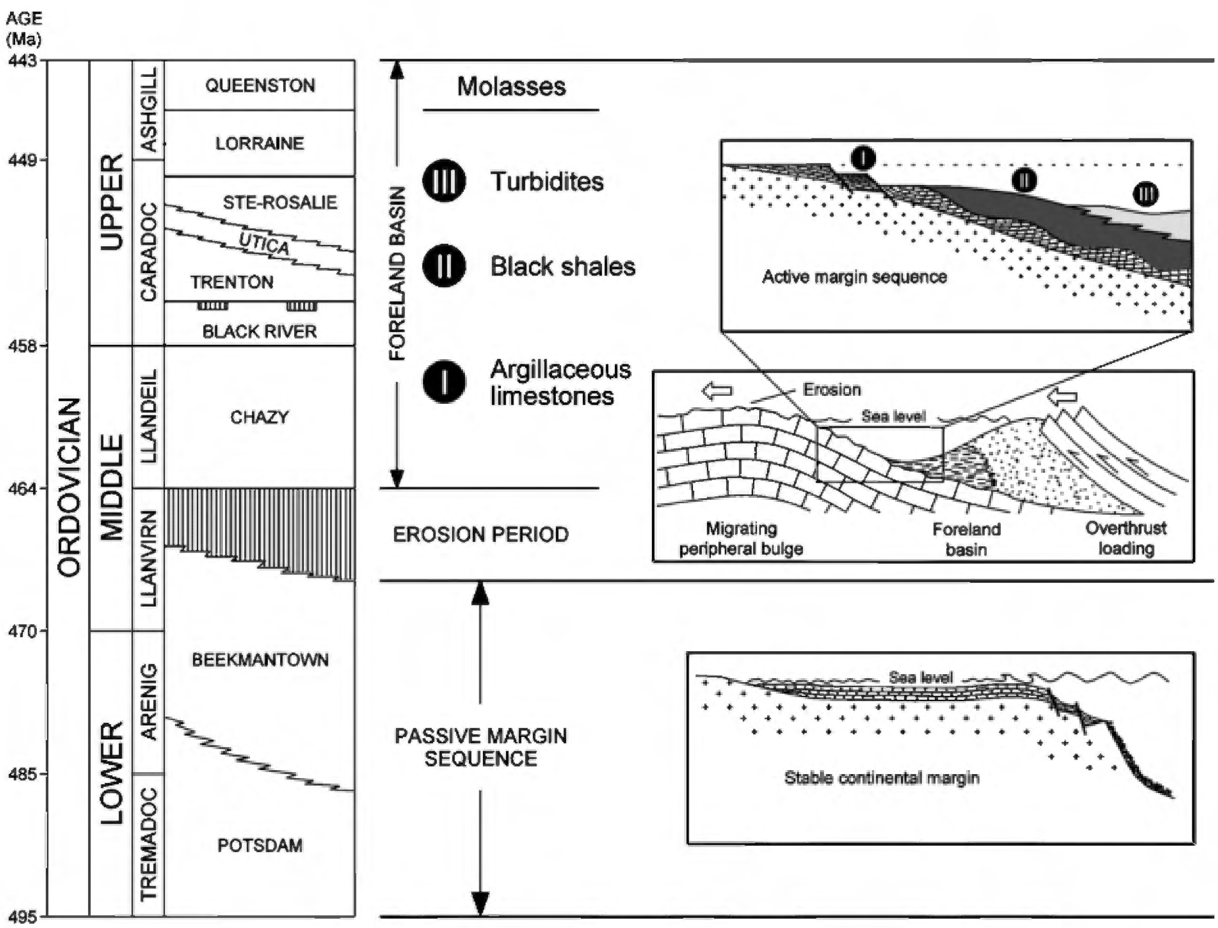

Figure 3. Stratigraphic framework for the Ordovician succession of the St. Lawrence Lowlands (modified from Lavoie, 1994). Vertical line pattern indicates non-deposition and erosion period.

The base of the platform sequence consists of the Cambrian Potsdam Group with fluvial to shallow-marine, conglomeratic arkose and subarkose in its lower part (Covey Hill Fm) that unconformably overlie the Precambrian basement. The Covey Hill is overlain by a shallow-marine, light grey to white quartz arenite (Cairnside Fm.) (Clark, 1972; Globensky, 1987; Salad Hersi and Lavoie, 2000a, 2000b; Salad Hersi et al., 2002a). The Potsdam Group is overlain by the Beekmantown Group, a Lower Ordovician carbonate platform that marks the final phase of passive margin sedimentation, and consisting of three stratigraphic units, the Theresa, Beauharnois, and Carillon formations (Bernstein, 1992; Salad Hersi et al., 2003). The top of the Beekmantown Group marks the regional Sauk - Tippecanoe Unconformity (Sloss, 1963) which resulted from a regional uplifting due to the westward-sweeping peripheral bulge that heralded the convergent phase of the Iapetus Ocean (Jacobi, 1981; Knight et al., 1991; Bernstein, 1992; Dix and Molgat, 1998).

The Beekmantown unconformity is correlative with the Knox and the St. George unconformities and widely recognized in many parts of North America, truncating Early to Middle Ordovician strata (Sloss, 1963; Mussman and Read, 1986; Knight et al., 1991). The nature of the unconformity surface in the Laurentian Margin of eastern Canada is manifested in different morphologic expressions that include karstic, erosional, planar (paraconformable) boundary and angular unconformity (Desrochers, 1988; Knight et al., 1991; Dix and Molgat, 1998).

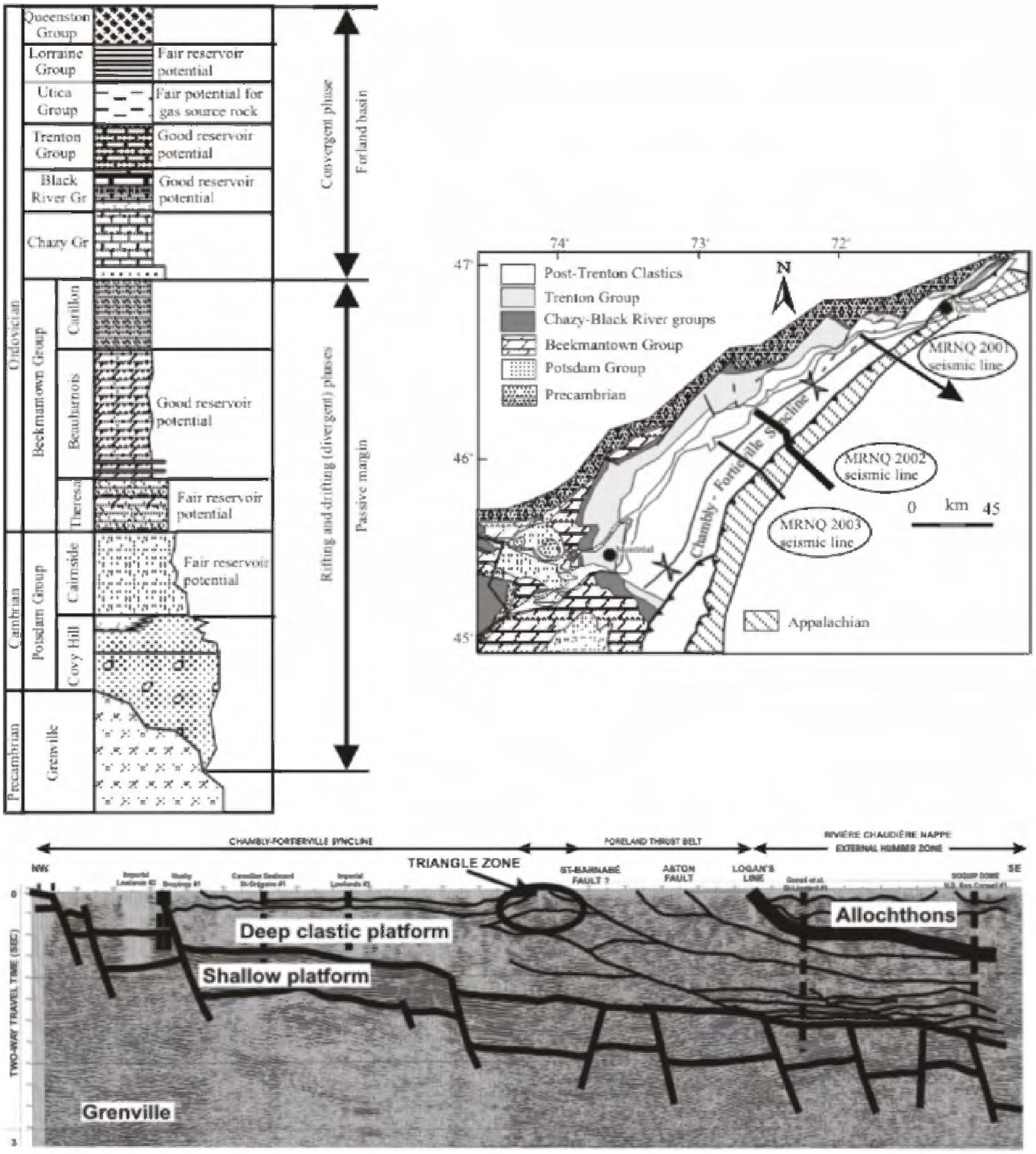

Figure 4. Simplified geological map of the St. Lawrence Platform in southern Quebec at the group level. Modified from Globensky (1987). The stratigraphic column presents the current framework for the Platform. Comments on reservoir and source rock potential are discussed in section 6. The seismic line MRNQ-2002 is located on the geological map. The reprocessed and reinterpreted data indicate significant deformation (including triangle zone) well within the previously assumed non-tectonized St. Lawrence Platform. From Castonguay et al. (2006).

The overlying Taconian foreland basin of Quebec can be viewed as a classical, under filled peripheral foreland basin and, following Sinclair's (1997) nomenclature, can be divided into three diachronous lithostratigraphic units: I-a lower argillaceous limestone-dominated unit, II-a middle mudstone-dominated unit and III-an upper turbidite dominated unit (Fig. 3). The overlying sequence of foreland basin carbonates comprises the Chazy, Black River and Trenton groups (Fig. 4). Salad Hersi and Dix (1997) and Lavoie (1994, 1995) recognize eustatic marine regressions between the Chazy and the Black River groups and between the Black River and the Trenton groups and the development of local unconformities atop tectonic paleotopographic highs in the Taconian foreland basin. Regional facies distribution and thickness variations within the Trenton Group have been attributed to syn-sedimentary normal block faulting (Lavoie, 1994, 1995). The top of the Trenton Group consists of muddy limestone beds with abundant interbeds of shales. The increasing proportion of shale heralds the overlying regressive flysch to molasse sequence that is made up of the Utica, Sainte-Rosalie, Lorraine and Queenston groups (Fig. 4), commonly seen as marking the erosion of Appalachian nappes adjacent to the St Lawrence Lowlands.

The middle mudstone unit (II of Fig. 3) consists of up to 1300 m of deep water siliciclastic sediments and hemipelagic mud of the Utica Shale. They were deposited over the carbonate units due to rapid subsidence of the foreland basin (Globensky, 1987). Black shale is characteristic of early flysch-phase fill along the distal flank of the Middle to Late Ordovician Taconian peripheral foreland basin (Bradley and Kidd, 1991). The Utica Shale is a diachronous unit which is older when located closest to the Appalachian front, as in the Québec City vicinity (Corynoides americanus-Orthogratus ruedemanni to the Climacograptus spiniferus zones) and younger to the southwest on the Laurentian platform, as in the Montreal region (Climacograptus pygmaeus Zone). Diachronous east to west progression of subsidence was coincident with the progressive westward change from carbonate-dominated to siliciclastic sedimentation within the foreland basin, also documented elsewhere in the Appalachian orogen (Ettensohn, 1991; Lehmann et al., 1995). In the Québec City area, the Utica Shale is only 30 m thick and yields graptolites spanning the O. ruedemanni to the C. spiniferus zones (Globensky, 1987). This unit is distinguished from younger facies that contain more abundant clastic beds suggesting that it was laid down prior to overthrusting of the thrust sheets onto the continental margin.

The upper turbidite unit (III of Fig. 3) consists of synorogenic sediments accumulated during the Caradocian to early Asghillian stages of the Late Ordovician during and after the overthrusting of the external thrust sheets. It is dominated by thick successions of alternating sandstone and mudstone of the Sainte-Rosalie and Lorraine groups. The siliciclastic source was located to the south-east and debris were derived from the thrust sheets (Globensky, 1987), representing a major reversal in the direction of sediment supply from the Laurentian shelf to more outboard elements of the tectonic wedge (Hiscott, 1995). The sandstones that accumulate at the toe of, and on top of the thrust wedge are highly immature and rich in lithic fragments with rarer volcanic detritus derived from erosion of the thrust wedge (Beaulieu et al., 1980; Schwab, 1986). Thrust-faulted highs generated during deposition of the middle unit lead to ponding of turbidite flows of the upper unit, generating thick sandstone beds overlain by thick mudstone drapes (Pickering and Hiscott, 1985).

Tectonostratigraphic zones of the Appalachians

The tectonostratigraphic domains of the evolving orogenic belt are used to divide the Appalachians into workable packages for geological considerations. The lower Paleozoic tectonostratigraphic domains (Williams, 1979) include the Humber (Laurentia continental domain), Dunnage (peri-Laurentia and peri-Gondwana oceanic domains), Gander and Avalon (peri-Gondwana oceanic and continental domains, respectively), and Meguma (a late-accreted peri-Gondwana continental terrane) zones (Fig. 1). These belts record the complex evolution of the Cambrian and Ordovician orogenies (Penobscot and Taconian; van Staal, 2005) and were affected by post-Taconian events that shaped up the Appalachians. Salinic, Acadian, Neoacadian and Alleghenian deformation, magmatism and metamorphic events affected the Taconian belts. This contribution focuses on Laurentia Humber Zone and its adjacent cratonic cover sequence preserved in the St. Lawrence Platform. The post-Taconian (*sensu stricto*) to syn-Acadian basins developed over the various Taconian tectonostratigraphic domains (Fig. 1); the best known of these basins is the Gaspé Belt that is preserved in various tectonostratigraphic assemblages: the Connecticut Valley – Gaspé synclinorium, the Aroostook-Percé anticlinorium, and the Chaleurs Bay – Tobique and the Kearsarge – central Maine synclinoria (the latter being also known as the Merrimack Through). The Middle Devonian Acadian Orogeny is the main phase that shaped up these elements (Malo and Bourque, 1993; Williams, 1995). The expression of the Silurian Salinic Orogeny (Dunning et al., 1990; van Staal, 2005) varies along strike in the Appalachians (Waldron et al., 1998; Malo, 2001; Tremblay and Castonguay, 2002). Alleghenian deformation recorded in pre-Acadian units is restricted to some extensional faulting (Bourque et al., 1995).

Conventional and event stratigraphy

An irregular-shaped continental margin, with recesses and salients, characterized the southern edge of Laurentia following the craton break-up in Neoproterozoic time (Fig. 5; Thomas, 1977, 1991). The shape of the margin played a significant role in the evolution of the cratonic St. Lawrence foreland platform (Stenzel et al., 1990; Lavoie 1994; Sharma et al., 2003).

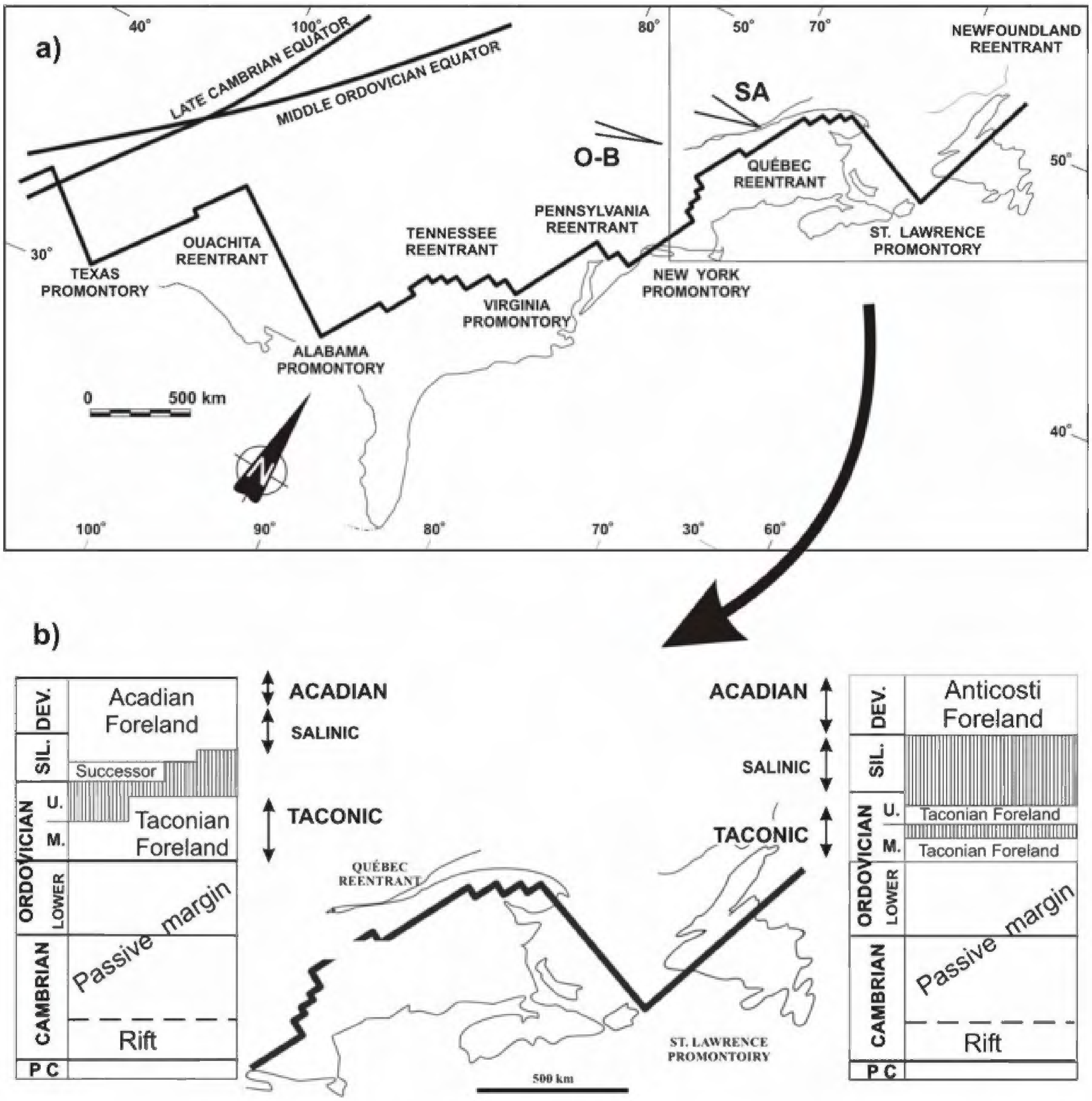

Figure 5. (a) The Lower Paleozoic continental margin of Laurentia with the distribution of reentrants and promontories. O-B: Ottawa-Bonnechère Graben, SA: Saguenay Graben. Modified from Thomas (1977). (b) General tectonostratigraphic event zonation of the Québec Reentrant and St. Lawrence Promontory together with the most significant tectonic events.

Detailed information on the rift, passive margin and foreland basin evolution of the shallow marine lower Paleozoic continental margin platform is available for western Newfoundland (James et al., 1989) and the coeval slope succession is well-studied (James and Stevens, 1986; James et al., 1989; Waldron and Palmer, 2000; Palmer et al., 2001; Burden et al., 2001; Waldron et al., 2003).

The term Humber Zone (Williams, 1976) was given for the north-westernmost tectonostratigraphic domain of the Taconian orogenic belt (Fig. 1). First defined in western Newfoundland, this belt was later recognized and extended on the Canadian mainland down to the northern US segment of the Appalachians (Williams, 1978). In the Humber Zone, stacks of tectonic slices of Neoproterozoic basement and Lower Cambrian to Upper Ordovician rocks of Laurentia continental affinity (St. Lawrence Platform and coeval slope and rise sediments) are deformed and thrusted over the St. Lawrence cratonic platform in a thin- to thick-skinned tectonic scenario (St-Julien and Hubert, 1975; Williams, 1978; Stockmal et al., 1998; van Staal et al., 1998; Waldron et al., 1998, 2003; Glasmacher et al., 2003; Pincivy et al., 2003; Stockmal et al., 2004). The Humber zone is bordered to the west by the St. Lawrence Platform (Sanford, 1993); the map limit is the westernmost transported tectonic slices (Globensky, 1987; Waldron et al., 1998). This limit in southern Québec is commonly referred to as the Logan's line or as the Champlain Thrust in northern Vermont. Reprocessing and reinterpretation of seismic data indicate that the St. Lawrence Platform records significant Taconian (?) compressive deformation in southern Québec such as triangle zone and blind thrusts in the central segment of the St. Lawrence Platform (Fig. 4; Castonguay et al., 2003; 2006). Therefore in Québec, the Appalachian structural front does not coincide with Logan's line. To the east, the Humber Zone is bordered by the Dunnage Zone, which consists of various Cambrian (?)-Ordovician oceanic rocks; the limit consists of major faults that form the Baie Verte – Brompton Line (Fig. 1; Tremblay et al., 1995; van Staal, 2005). Differences in the degree of deformation and metamorphism led St-Julien and Hubert (1975) to divide the Taconian-deformed Laurentia continental rocks of the Québec Reentrant into two domains (Fig. 1): a western external domain with low deformation and low-grade metamorphosed rock units that passes eastward to an internal domain with higher-grade metamorphic grades as well as polyphase tectonic deformation (Pinet et al., 1996; Waldron et al., 1998; Castonguay et al., 2001; Tremblay and Castonguay, 2002).

In the Québec Reentrant, platform rocks were marginally involved in tectonic stacking, slices of the St. Lawrence Platform units form a spatially restricted frontal Taconian deformation zone known as the "parautochthonous" or imbricated fault domain (St-Julien and Hubert, 1975; Comeau et al., 2004). This Taconian-deformed domain is not part of the Humber Zone as it is rooted in the St. Lawrence Platform (St-Julien and Hubert, 1975; St-Julien et al., 1983; Castonguay et al., 2006). The relative timing of obduction of oceanic seafloor units on the continental margin in the Québec Reentrant has been traditionally indirectly constrained by the biostratigraphic age of the successions that under- and overlie the accreted units of the Dunnage Zone (St-Julien and Hubert, 1975). Recent $^{40}Ar/^{39}Ar$ and K/Ar metamorphic ages confirm the "classic" Middle to Late Ordovician Taconian age (Castonguay et al., 1997; Glasmacher et al., 2003; Pincivy et al., 2003) for the ophiolite obduction on the continental slope margin successions.

At the St. Lawrence Promontory in western Newfoundland, the obduction of the Bay of Island ophiolite and the associated Humber Arm Allochthon on the continental margin of Laurentia was long considered to be Middle Ordovician (Williams, 1975). This "classic" Taconian age is supported by the biostratigraphic ages of the Taconian flysch and of the overlying assumed post-Taconian units. In contrast, detailed geochronology, structural studies and industry seismic data indicate that the emplacement of oceanic domain units over the shallow segment of the continental margin started in Silurian (Dunning et al., 1990) and ended prior to the Viséan (Carboniferous), likely in Middle Devonian (Cawood, 1993; Stockmal et al., 1998, 2004; Waldron et al., 1998). The "Taconian" event near the St. Lawrence Promontory resulted from the emplacement of the oceanic seafloor and composite terranes on distal deep marine continental slope succession (van Staal et al., 1998; Waldron and van Staal, 2001). It has been proposed that subduction near the continental margin of Laurentia started in the latest Cambrian with the obduction of the Lushs Bight Oceanic Tract (Swinden et al., 1997) over the Dashwoods microcontinent (van Staal et al., 2004), the latter being a continental fragment lately detached from Laurentia (Waldron and van Staal, 2001). The accretion of the new composite terrane along the continental margin at the St. Lawrence Promontory marks the onset of the Taconian Orogeny there (van Staal, 2005).

In the following sections, we will only consider the Quebec succession; interested readers on the correlation with Newfoundland are referred to the literature cited above.

THE QUEBEC REENTRANT

In Québec, the Lower Paleozoic continental margin of Laurentia formed within the Québec Reentrant (Fig. 5) (Thomas, 1977, 1991).

Rift-early drift

Within the Grenville Province component of the re-entrant, dike swarm tholeiites yielded a 590 Ma age (Kamo et al., 1995). Rift-related, greenschist facies alkaline basalts and comendites of the Tibbit Hill Formation yielded a 554 Ma age (Kumarapeli et al., 1989). Similar rift basalts are found in the Caldwell and Shickshock groups and the Montagne de Saint-Anselme Formation in southern Québec, Gaspé and eastern Québec, respectively. U-Pb dating of the volcanic rocks at the Montagne Saint-Anselme yields an age of 561 +/- 7 Ma, whereas similar basalts of the Shickshock Group at the Lac Matapédia (Gaspé) yield ages of 565 +/- 6 Ma and 556 +/- 5 Ma (Hodych and Cox, 2007). A felsic phase within the Caldwell lavas have a radiometric age of 562 +/- 2 Ma.

The shallow marine platform. The shallow marine record of the rift episode is meagre in southern Québec. In the St. Lawrence Platform, the Potsdam Group unconformably overlies the Precambrian basement; the lower formation (Covey Hill Formation) has been equivocally assigned an Early Cambrian age (Sanford, 1993) without supporting faunal element. At the eastern end of the Humber external domain (Fig. 1), tectonic stacks of the shallow marine Oak Hill Group (Charbonneau, 1980) overlie rift volcanics of the Tibbit Hill Formation (Kumarapeli et al., 1989). In the Oak Hill Group, the Cheshire (quartz arenite) and Dunham (dolostone/limestone) formations have yielded Early Cambrian faunal elements (Clark, 1936; Clark and McGerrigle, 1944) (Fig. 6).

The undated Potsdam Group is dominated by fluvial to shallow marine interbeds of locally conglomeratic arkose, with some subarkose in its lower part (Covey Hill Formation, Fig. 6). A thin (~ 5 m), fossiliferous, dolomitic sandstone unit locally lies at the top of the Covey Hill Formation in SW Québec (Rivière Aux Outardes Member, Salad Hersi and Lavoie, 2000a). The upper part of the group is represented by shallow marine strata of the Cairnside Formation. The latter consists of a lower unit of light gray to creamy white quartz arenite, and an upper unit of quartz arenite similar to that of the lower unit but with subordinate dolomitic sandstone interbeds (Clark, 1972; Globensky, 1987; Salad Hersi and Lavoie, 2000b). Where the dolomitic sandstone interbeds are missing, the upper unit is not distinguishable from the lower unit

The slope and rise. The Humber succession in the Québec Reentrant occurs in number of stacked structural nappes (Fig. 1), most of which carry their distinct stratigraphic nomenclature (St-Julien and Hubert, 1975; Lavoie, 1997, 1998, 2002; Lebel and Kirkwood, 1998) that was only recently synthesized (Lavoie et al., 2003b) (Figs. 2 and 6).

At the base of the succession, a thick interval of variegated mudstone with subordinate sandstone overlies rift volcanics. Decimetre- to metre-thick beds of conglomerate with calcisiltite and phosphate fragments and resedimented oolitic grainstone beds are locally abundant (Lavoie, 1997). These lowermost units are known as the Sainte-Foy Formation and as the basal beds of the Saint-Roch Group. This lowermost succession is devoid of macro and microfauna.

A distinctive unit of massive, pebbly green sandstone and red and green mudstone overlies the lower mudstone-sandstone succession (Fig. 6). This predominantly coarse-grained succession forms the Saint-Nicolas Formation, the informal "green sandstone" unit, the Armagh Formation and the upper beds of the Caldwell Group (Lavoie, 2002; Lavoie et al., 2003b). The age of that unit is constrained by the presence of the inarticulate brachiopod *Botsfordia pretiosa* and the trace fossil *Oldhamia curvata*, both diagnostic of middle to late Early Cambrian (Sweet and Narbonne, 1993). Palynological study documented a late Early to early Middle Cambrian acritarch assemblage (Burden, 2003: Lavoie et al., 2003b). The very distinctive and time-constrained (late Early Cambrian) massive sandstone unit is a regional correlation unit. It has been proposed that this coarse grained unit represents the deep marine expression of the late Early Cambrian sea level lowstand that coincides with the end of the rift phase (Lavoie et al., 2003b).

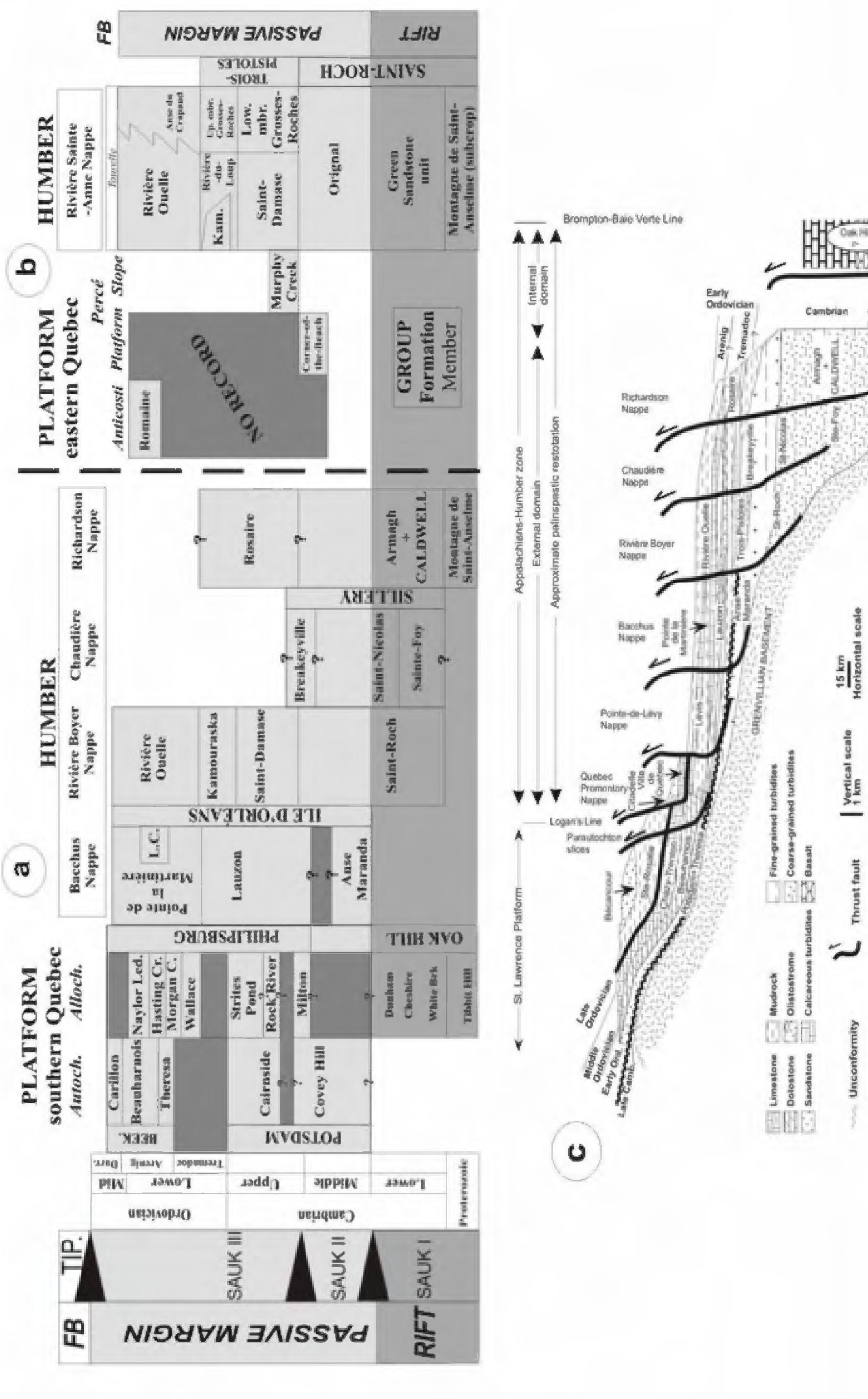

Figure 6: Rift (dark shaded) and passive margin (pale shaded) stratigraphic correlations of slope and platform rocks in the Québec Reentrant in (a) southern Québec and (b) eastern Québec - Gaspé. The interpretation for the Oak Hill Group is preliminary. See figure 6 for unit status. Autoch.: Autochthonous units of the St. Lawrence Platform, Alloch. Allochthonous platform thrusts in the Humber Zone. BEEKMAN.: Beekmantown Group, Hasting Cr.: Hasting Creek Formation, Naylor Led.: Naylor Ledge Formation, Kam: Kamouraska Formation, L.C.: Lévis Formation conglomerate. Very dark shaded areas are for hiatus. c) Schematic composite diagram of the St. Lawrence Platform and Humber Zone illustrating the assumed palinspastically restored lateral relationships of some tectonostratigraphic nappes. Note that the Richardson Nappe at the eastern limit of the external domain contains the thickest sedimentary pile. The Early Cambrian carbonate platform units of the Oak Hill Group are part of a distinct tectonic nappe. Vertical exaggeration 15x. Modified from Lebel and Kirkwood (1998).

Sea level record. The sea level history recorded by these successions can be tied with the well-studied shallow marine rocks of western Newfoundland, which span the Sauk I sub-sequence of the Early Cambrian (James et al., 1989). Following the initiation (late Neoproterozoic) of spreading and eruption of basalts with associated coarse-grained sedimentation (Saint-Anselme Formation, Caldwell and Shickshock groups), the ensuing relative sea level rise led to shallow marine carbonate-siliciclastic sedimentation on local horst structures (i.e., Dunham Formation), whereas in more deeper graben settings, fine- and coarse-grained sediments were deposited as proximal and distal submarine fans (Sainte-Foy and Armagh formations, lower beds of Saint-Roch Group, upper beds of the Caldwell Group) (Figs. 6 and 7a). The major sea level lowstand that coincides with the end of the rift episode (late Early Cambrian) is recorded in prograding shallow marine sandstone units such as the Hawke Bay (Newfoundland; Knight and Boyce, 1987) and Monkton (Vermont; Landing et al., 2002) formations. This event is expressed in the sandstone and conglomerate found in the Saint-Nicolas Formation and in the "green sandstone" unit of the Saint-Roch Group (Figs. 6 and 7b).

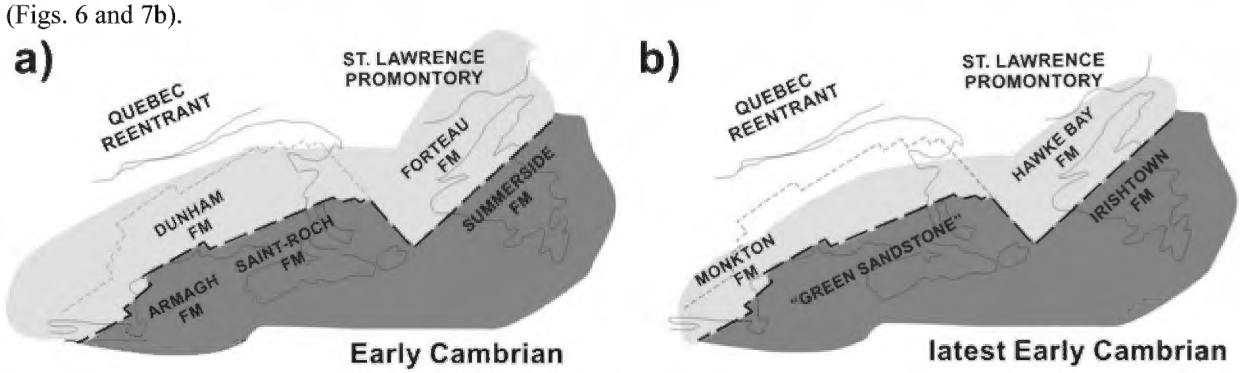

Figure 7. (a) Interpreted paleogeographic reconstruction of Laurentia continental margin in Early Cambrian. Geographically restricted carbonate platforms (Forteau / Dunham) are located on rift-related horsts, whereas intervening deep grabens are filled by coarse- to fine-grained slope sediments (Armagh / Saint-Roch / Summerside). The thick dashed line represents the assumed position of the continental shelf edge. (b) Paleogeographic reconstruction in late Early Cambrian at the time of the "Hawke Bay event" (first major sea level lowstand) that marks the end of the rift-early drift episode. Shallow marine quartzite (Monkton / Hawke Bay) prograded towards the shelf break while deeper slope were fed by coarse-grained sediments ("green sandstone" / Irishtown) from the prograding clastic wedge. Modified from Lavoie et al. (2003b).

The passive margin

The shallow marine platform. In the Québec Reentrant, the oldest known passive margin shallow marine platform unit is the upper Middle Cambrian Corner-of-the-Beach Formation in the Percé area (Figs. 2 and 6; Kindle, 1942; Lavoie, 2001). In southern Québec, the shallow marine carbonate platform of the Strites Pond Formation (Salad Hersi and Lavoie, 2001a; Salad Hersi et al., 2002a; Salad Hersi et al, in press) in the Philipsburg Nappe of the Humber Zone yielded Upper Cambrian (lower Skullrockian) conodont fauna (Fig. 6). For both formations, facies are indicative of a platform margin (Lavoie, 2001; Salad Hersi and Lavoie, 2001a; Salad Hersi et al., 2002a). The shallow marine record of the Sauk II and III sub-sequences is best expressed in the Lower Ordovician extensive carbonates of the Beekmantown and Philipsburg groups of southern Québec (Globensky, 1987; Bernstein, 1992; Salad Hersi et al., 2002a, 2003) as well as of the Romaine Formation on Mingan Islands (Desrochers, 1988) and in the sub-surface of Anticosti Island (Brennan-Alpert, 2001) (Fig. 6). All these Lower Ordovician units are truncated by the unconformity resulting from the migration of the peripheral bulge (Knight et al., 1991; Lavoie, 1994).

Detailed lithostratigraphy of the Beekmantown Group of southwestern Quebec has refined the field application of the previously proposed tripartite division of the group (i.e., Theresa, Beauharnois and Carillon formations). The group is a peritidal-dominated succession that accumulated on the Laurentian passive margin from Early to early Middle Ordovician (Salad Hersi et al., 2003); the Beekmantown is partially time-correlative with the Wallace Creek to Naylor Ledge strata of the Philipsburg Group, southern Quebec (Salad Hersi et al., 2002b, 2003). The platform evolved as a distally steepened ramp during deposition of the Theresa Formation and the lower member (Ogdensburg) of the Beauharnois Formation (early to middle Ibexian). By late Ibexian, the platform developed a pronounced margin where thrombolites flourished under high-energy conditions and consequently, a broad lagoon formed on the lee side of the platform margin, where low energy conditions prevailed and accumulation of burrow-mottled dolostones of the Huntingdon Member, upper Beauharnois Formation took place. The lagoon became more restricted during the latest stages of the basin fill (Whiterockian), and high intertidal to supratidal sediments of the Carillon Formation were deposited.

The slope and rise. The first passive margin sediments that overlie the rift-ending massive green sandstone unit consist of a thick succession of red, green and minor black mudstone with siliceous, feldspathic and locally glauconitic sandstone with a thin interval of quartizitic sandstone, limestone conglomerate, slope dolosiltite and ribbon limestone at the base. This succession occurs in the Saint-Nicolas, Saint-Roch, Anse Maranda, Orignal and Armagh formations (Longuépée and Cousineau, 2001; Cousineau and Longuépée, 2003; Lavoie et al., 2003b; Longuépée and Cousineau, 2005) (Fig. 6). Palynological analyses of these units yielded late Early Cambrian to early Middle Cambrian fauna (Lavoie et al., 2003b). The upper meters of that Middle Cambrian interval consist of an informal olistromal unit formed through slumping of slope sediments (Lebel and Hubert, 1995; Lebel and Kirkwood, 1998).

A distinctive coarse-grained unit overlies the Middle Cambrian fine-grained dominated interval (Fig. 6). This unit is known as the Lauzon, Breakeyville, Saint-Damase, Grosses-Roches and Murphy Creek formations (Lavoie et al., 2003). This unit consists of thick, channel-fill carbonate conglomerate, feldspathic and siliceous sandstone and minor mudstone. Beds are commonly meter-thick and arranged in decametre-thick thinning- and fining-upward cycles (Lavoie, 1998). Fragments in the conglomerate consist of nearshore to platform margin limestone facies that indicate a high-energy platform with an oolite shoals and thrombolites rimmed-margin. Metre-sized sandstone, basalt fragments and basement-derived gneiss and orthoquartzite (Lavoie, 1997, 1998) are noted. Fauna in limestone fragments indicate erosion of Lower to early Upper Cambrian shallow marine facies (Rasetti, 1945, 1946, 1948; Nowlan, 2003). Palynological study of interbedded mudstone documented a faunal assemblage of Late Cambrian age (Lavoie et al., 2003b).

The Upper Cambrian coarse-grained interval is overlain by a fine-grained succession of grey and black mudstone and subordinate sandstone (Fig. 6). The succession forms the Lauzon and Rivière-du-Loup formations and the upper member of the Grosses Roches Formation (Lavoie et al., 2003b). Palynological analyses of that unit suggest a latest Cambrian age from acritarchs (Lavoie et al., 2003b) and scolecodonts (Lavoie et al., 1998). This fine-grained unit is locally intercalated with a succession of highly discontinuous and massive quartz arenite beds (Fig. 6). These quartz arenites are medium grained with local limestone conglomerate and form the Kamouraska and Rosaire formations (Lavoie et al., 2003b). Interbedded mudstone yielded a latest Cambrian to earliest Ordovician fauna of scolecodonts, chitinozoans and acritarchs (Lavoie et al., 1998; Burden, 2003).

The youngest passive margin unit consists of red, green and black mudstone with subordinate sandstone, ribbon limestone, calcarenite and limestone conglomerate. This unit comprises the Pointe de la Martinière, Lévis, Rivière-Ouelle and Cap-des-Rosiers formations (Fig. 6). Based on graptolites and chitinozoans, this unit is Arenigian-Darriwilian in age (Landing and Benus, 1985; Landing et al., 1986; Bernstein et al., 1992; Maletz, 1992, 2001; Asselin and Achab, 2004).

Sea level record

The passive margin history consists of two major transgressive-regressive (T-R) cycles identified as the Sauk II and III sub-sequences (Fig. 6). The shallow marine record of the initial Sauk II transgressive and early highstand sea level (Middle Cambrian) is poorly expressed in Québec (Corner-the-Beach Formation), whereas the slope record consists only of mudstone and sandstone (e.g., Orignal Formation and equivalent units). A sea level lowstand is recognized near the base of the Late Cambrian (Steptoan) succession and correlates with the end of Grand Cycle A (Chow and James, 1987; Cowan and James, 1993; Lavoie et al., 2003), the shallow marine record of that lower Upper Cambrian event is unknown in Quebec although the nature of the fragments in the widespread lower Upper Cambrian (Steptoan) slope limestone conglomerate unit (Breakeyville, Lauzon, Saint-Damase, Grosses-Roches and Murphy Creek formations) indicates the presence of this platform. These thick conglomerates correlate with the end of the Sauk II sub-sequence.

The presence of pre-Upper Cambrian fragments in the conglomerate suggests that simple late highstand to lowstand shedding of platform margin clasts cannot be invoked. The thick olistromal unit that underlies the conglomerate, indicates that in late Middle-earliest Late Cambrian time, the area located around the Saguenay Graben (Aulacogene of Kumarapeli and Saull, 1966; Figs. 2 and 8a) suffered from tectonic instability, which resulted in submarine slides. These submarine slides scoured the slope, creating new and enhancing old submarine canyons that retrograded and cut into the adjacent platform. This tectonically triggered erosion of the continental margin ended in basement rocks with erosion of the entire carbonate, clastic and volcanic succession deposited during and after the rift episode. The local tectonic instability was coeval with the significant sea level lowstand that marks the end of the Sauk II sub-sequence.

The exact cause for the reactivation of the Saguenay Graben is still unclear, however, the first accretionary events recorded in circum Iapetus terranes occurred in Late Cambrian. This is relatively well documented by the Penobscotian Phase in the units of the peri-Gondwana Gander terrane (Neuman, 1967) and possibly in the obduction of the peri-Laurentia Bushs Bight Oceanic Tract over the Dashwoods microcontinent (van Staal et al., 2004). The latter accretion occurred in the neighbourhood of Laurentia and could be the trigger for the late Cambrian tectonic activity in the Quebec Reentrant.

At the onset of the Sauk III sub-sequence (Fig. 6), a sea level highstand is recorded in the Grand Cycle C and is dated late Steptoan. No shallow marine carbonate platform of that age is known in the Québec Reentrant, with only a fine-grained siliciclastic slope record (Rivière-du-Loup Formation and equivalents units). This highstand was followed by another sea level lowstand in latest Cambrian (early Skullrockian); in southern Québec, the platform carbonates of the Strites Pond Formation are dated latest Cambrian (Skullrockian); this unit is capped by an erosive subaerial unconformity, which separates it from the outer shelf facies of the upper Tremadocian Wallace Creek Formation (Salad Hersi and Lavoie, 2001a; Salad Hersi et al., 2002a). The coeval slope recorded that event in the local shedding of clean quartz sands and subordinate limestone conglomerates o the Kamouraska Formation.

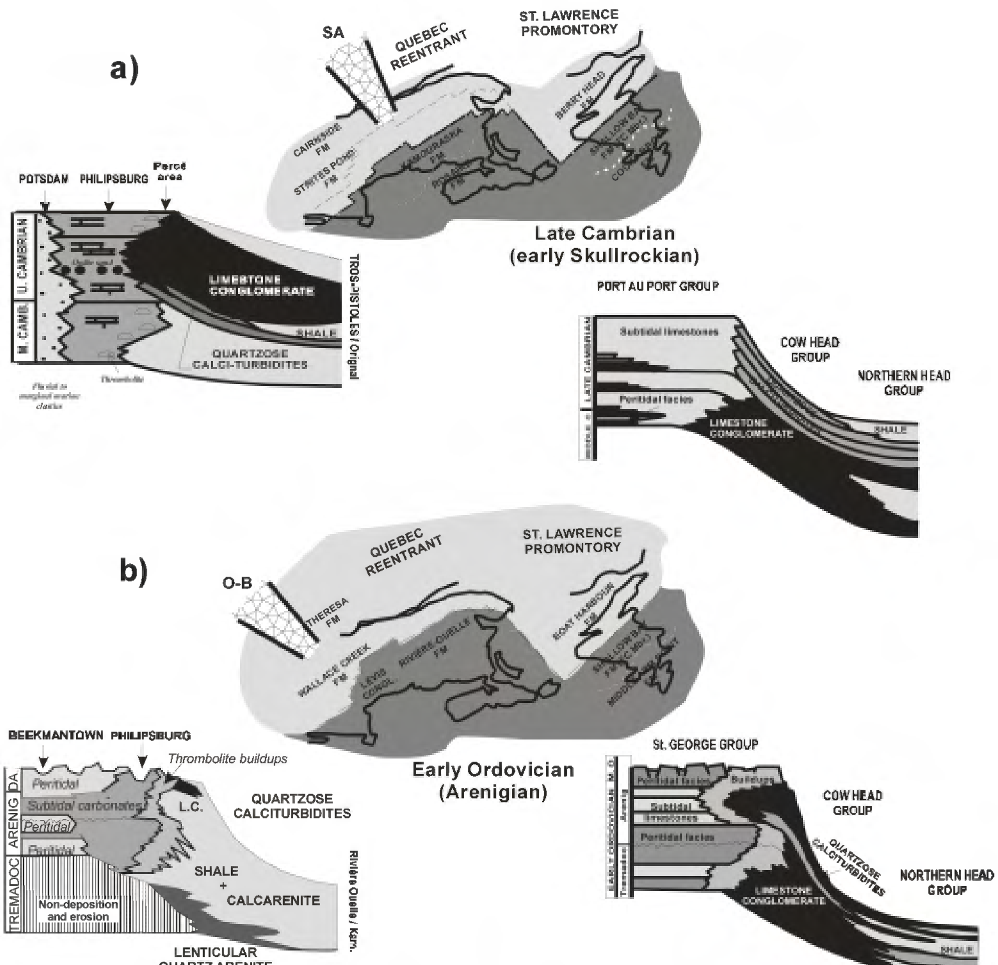

Figure 8. (a) Interpreted paleogeographic reconstruction of Laurentia continental margin in mid Late Cambrian (Skullrockian). Lateral relationship between the Cairnside and Strites Pond formations is discussed in Salad Hersi et al. (2002a, 2002b). The thickest succession of the Upper Cambrian conglomerates (Saint-Damase and correlative units) with older basement and platform rocks are found in the Lower St. Lawrence Valley, near the Saguenay Graben (SA), see text for details. The two cartoons illustrate the depositional settings and lateral platform slope relationships in Middle-Late Cambrian. Port au Port / Cow Head / Northern Head groups in Western Newfoundland (modified from James et al., 1989) and Potsdam-Philipsburg / Trois-Pistoles groups in southern Québec. Not to scale. (b) Interpreted paleogeographic reconstruction of Laurentia continental margin in Early Ordovician (Arenigian). The lateral relationship between the Theresa and Wallace Creek formations are discussed in Salad Hersi et al. (2002a, 2003).

The Early Ordovician was marked by craton-wide transgression leading to the deposition of the Romaine Formation on Mingan and Anticosti islands (Desrochers, 1988; Brennan-Alpert, 2001) and the Beekmantown Group in southern Québec and eastern Ontario (Bernstein, 1992; Salad Hersi et al., 2002b, 2003) (Fig. 6 and 8b). Two T-R depositional cycles are recognized and separated by the mid-Arenigian Theresa – Beauharnois formations contact (Salad Hersi et al., 2003; Dix and Salad Hersi, 2004). The first cycle is upper Tremadocian to mid-Arenigian whereas the second one is mid-Arenigian to Darriwilian in age (Dix and Salad Hersi, 2004). Tectonic instability associated with the Ottawa – Bonnechère Graben has been proposed to explain the diachronism with the Newfoundland succession (James et al., 1989) in the sea level fluctuations, conversely imprecise biostratigraphic data could also be envisaged to explain the discrepancies (Dix and Salad Hersi, 2004). In the Québec Reentrant, the slope record consists of the fine-grained facies of the Rivière Ouelle Formation (and equivalent units) and indicates transgressive to highstand sedimentation (Lavoie et al., 2003b).

A regional sea-level scenario for the Lower Paleozoic rift and passive margin

The proposed Newfoundland-Quebec correlation allows the recognition of four distinctive major sea level lowstands (Fig. 9):

1) A late Early Cambrian event ("Hawke Bay event") expressed by massive sandstones and conglomerates. This event coincides with the end of the rift stage and marks the upper limit of the Sauk I subsequence,

2) An early-mid Upper Cambrian event (Steptoan-Sunwaptan) expressed in limestone conglomerates on the slope. Coeval tectonic instability is indirectly documented along the Saguenay Graben in the Québec Reentrant. This event marks the end of the Sauk II subsequence,

3) A latest Cambrian event (early Skullrockian) represented by local limestone conglomerates and coarse-grained clastics. This event occurs within the Sauk III subsequence but marks the end of the Cambrian Grand Cycle C,

4) a) In western Newfoundland, a sea level lowstand at the Tremadocian – Arenigian boundary represented by more limestone conglomerates, and b) in southern Québec – eastern Ontario, a slightly younger sea level lowstand in mid-Arenigian expressed in the major limestone conglomerate of the Levis Formation. Diachronism is related to tectonic instability of the Ottawa – Bonnechère Graben (Dix and Salad Hersi, 2004).

The stratigraphic record indicates that tectonism was sporadically active in the Quebec Reentrant from Late Cambrian to Early Ordovician (Lavoie et al., 2001, 2003b; Dix and Salad Hersi, 2004). Evidence for such instability is invariably associated with the two failed aulacogenes in the Quebec Reentrant, the Ottawa – Bonnechère and the Saguenay grabens. It is possible that the Late Cambrian obduction of the Lushs Bight Oceanic Tract over the Dashwoods microcontinent (van Staal et al., 2004) triggered this tectonic instability in the Quebec Reentrant.

The Taconian foreland basin

The building of the marine passive margin successions along the eastern seaboard of Laurentia was stopped by emergence and sub-aerial exposure of the platform in earliest Middle Ordovician. The resulting unconformity is known as the St. George (Newfoundland; Knight et al., 1991), the Romaine (Anticosti; Desrochers, 1988), the Beekmantown (southern Québec; Dykstra and Longman, 1995; Salad Hersi et al., 2003), the intra-Philipsburg (southern Québec – Vermont; Knight et al., 1991), and the Knox (east U.S.A.; Read, 1989) groups. This unconformity coincides with the limit between Sloss' (1963) Sauk and Tippecanoe sequences and marks the inception of the foreland basin at Laurentia continental margin (Fig. 2). The evolution of the foreland basin became strongly diachronic along the continental margin, this suggests that the reentrant-promontory morphology played a key role in the evolution of the continental margin of Laurentia at that time (Lavoie, 1994).

Platform succession. The inception of the foreland basin and increased tectonic subsidence in the Québec Reentrant was marked by a significant change in the St. Lawrence platform (Sanford, 1993). Siliciclastic units covered the unconformity (Globensky, 1987; Desrochers, 1988; Salad Hersi and Dix, 1997). The depositional environment later became favourable to carbonate production (Mingan Formation and Ottawa, Chazy, Black River and Trenton groups; Desrochers, 1988; Sanford, 1993; Lavoie, 1994; Sharma et al., 2003). These carbonates were deposited on a ramp affected by synsedimentary extensional faults (Lavoie, 1994; Lemieux et al., 2003), with the successions recording progressive deepening upward conditions (Fig. 10).

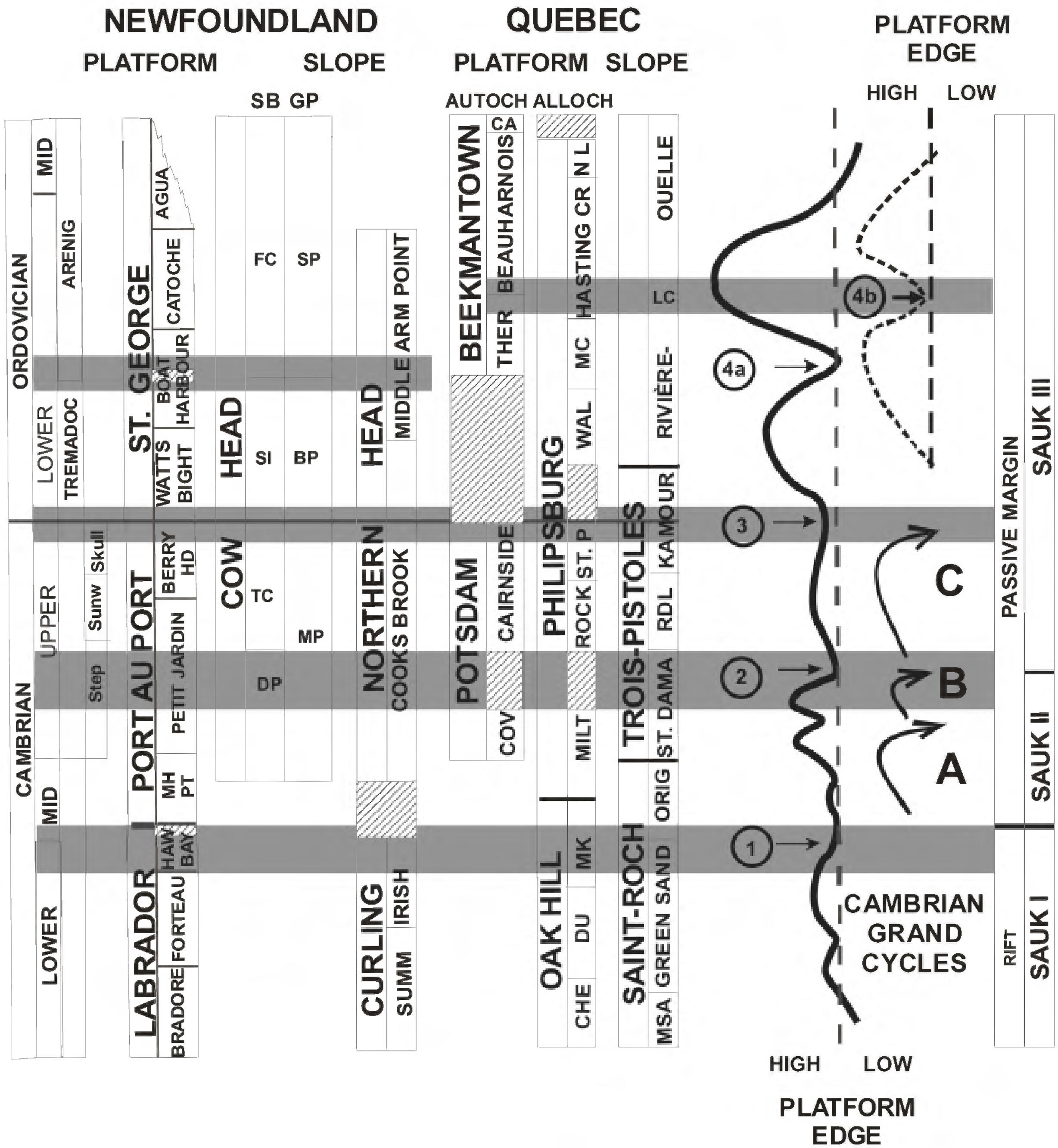

Figure 9. Chronostratigraphic correlation for selected units of the rift passive margin successions along the entire Canadian segment of Laurentia. The four major sea level lowstands discussed in text (dark shaded bands) are identified (1 to 3) and the slightly diachronous 4a and 4b. The sea level curve is from James et al. (1989); the curve applies well to the Québec succession prior to the Early Ordovician. The dashed line displays the Quebec Reentrant departure from the James et al. (1989) curve. Correlation with Cambrian Grand Cycles is shown. MH PT : March Point Fm., Berry HD: Berry Head Fm., Agua: Aguathuna Fm., SB: Shallow Bay Fm., GP: Green Point Fm., DP: Downes Point Mbr., TC: Tuckers Cove Fm., SI: Stearing Island Mbr., FC: Factory Cove Mbr., MP: Martin Point Mbr., BP: Broom Point Mbr., SP: St. Pauls Mbr., Summ: Summerside Fm., Irish: Irishtown Fm., Covey H: Covey Hill Fm., CHE: Cheshire Fm., DU: Dunham Fm., Strites P: Strites Pond Fm., Wal Cr: Wallace Creek Fm., MC: Morgan's Corner Fm., Hast Cr: Hasting Creek Fm., Naylor L: Naylor Ledge Fm., MSA: Montagne de Saint-Anselme Fm., Orig: Orignal Fm., St.Dama: Saint-Damase Fm., RDL: Rivière-du-Loup Fm., Kamour: Kamouraska Fm, L.C.: Lévis Formation conglomerate. Modified from Lavoie et al. (2003b).

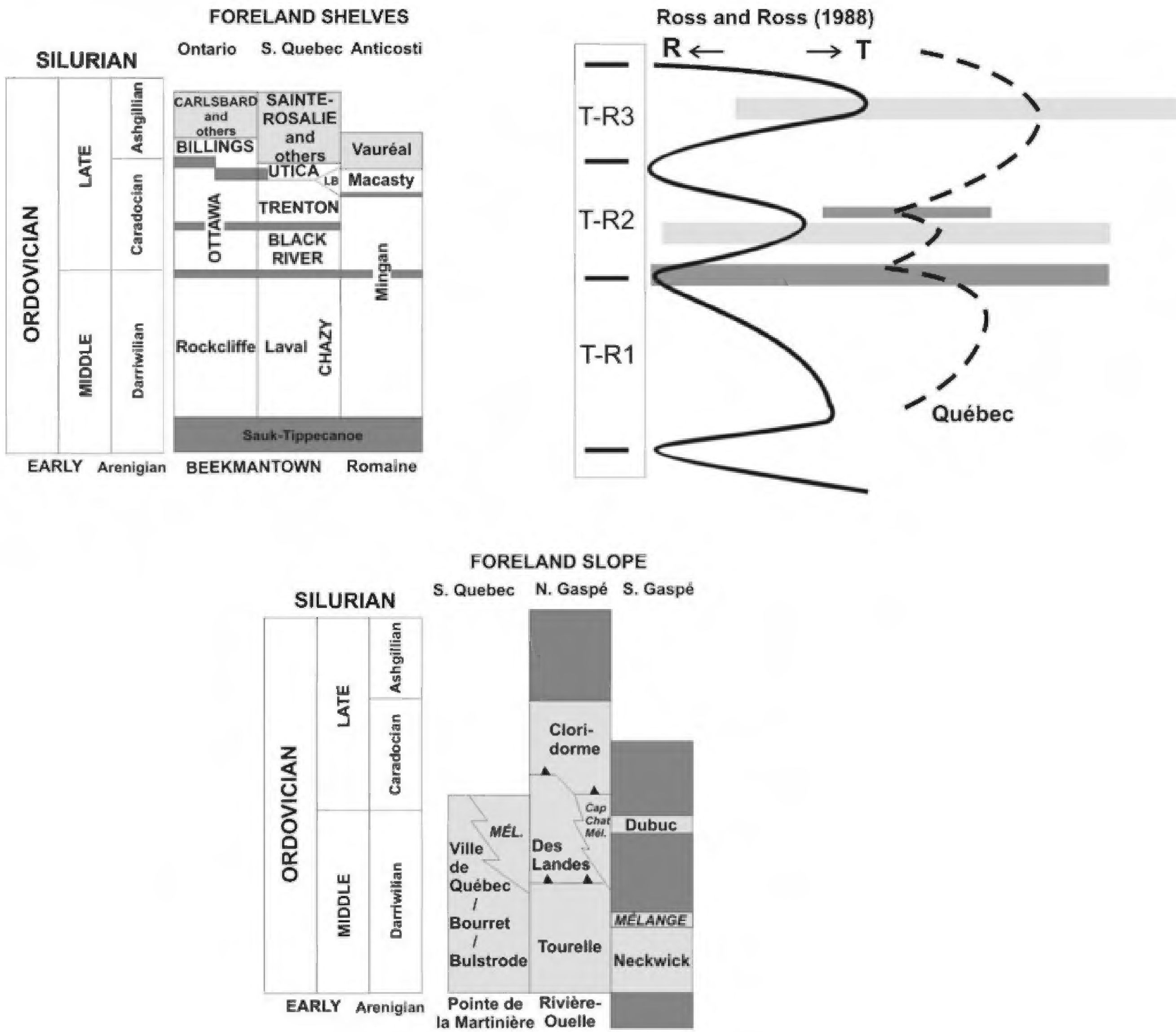

Figure 10. Middle to Late Ordovician foreland shelf-to-slope stratigraphic framework and in the Quebec Reentrant, a westward progressive foundering (Macasty / Utica / Billings) of shallow marine settings occurred in Late Ordovician time (Caradocian / Ashgillian). Taconian flysch sedimentation on the slope was initiated in early Darriwilian time. Shallow marine framework derived from Sanford (1993), Lavoie (1994) and Sharma et al. (2003). Not to scale. The eustatic sea level curve of Ross and Ross (1988) indicates that in the Québec Reentrant successions locally record some eustatic events (latest Darriwilian lowstand, early Caradocian highstand, early Ashgillian highstand) in a tectonically active basin. F: relative sea level fall, R: relative sea level rise. T-R cycles are discussed in text.

The Middle Ordovician Chazy and Black River groups in southern Quebec are relatively thin units that are dominated by muddy carbonates carrying a foramol-like faunal assemblage dominated by corals, stromatoporoids and green algae (Guilbeault and Mamet, 1976; Lavoie, 1995; Salad Hersi, 1997; Salad Hersi and Lavoie, 2001b). The overlying upper Middle to lower Upper Ordovician Trenton Group is primarily a deep marine fine-grained unit, however, the base of the group (the Deschambault Formation) is a coarse-grained calcarenite unit that is phosphate-rich and characteristically displays a bryomol-like fauna dominated by bryozoans, crinoids and a total lack of green algae (Guilbeault and Mamet, 1976; Lavoie, 1995; Lavoie and Asselin, 1998). Similar transition from warm-water like to cool-water like in the early Late Ordovician is recorded along the entire segment of the eastern Laurentia margin that was located south of the 10-15°S of paleolatitude (Pope and Read, 1997; Pope and Harris, 2004; Cherns and Wheeley, 2007).

The carbonate sedimentation was shut down diachronically in a westerly direction, with the sedimentation of deep marine shales and overlying Taconian flysch and final molasses (Sanford, 1993; Lavoie, 1994; Sharma et al., 2003) (Fig. 10). In the Québec Reentrant, the carbonate sedimentation lasted from Darriwilian to late Caradocian.

Slope and rise succession. In eastern Québec, the units that overlie the last passive margin slope deposits consists of green flysch sandstone with subordinate mudstone, calcarenite, lithic conglomerate and chert of the uppermost Arenigian to lowermost Caradocian Tourelle, Neckwick, Des Landes and Dubuc formations (Biron, 1974; Hiscott, 1978; Slivitzky et al., 1991; Bloechl, 1996; Prave et al., 2000) (Fig. 10). In southern Québec (Fig. 10), Darriwilian sediments are predominantly fine-grained calcareous sediments with subordinate flysch sandstone and limestone conglomerate. These units are known as the Ville de Québec (Slivitzky and St-Julien, 1987) or Citadelle (Globendsky, 1985; Gayot, 2002), the Bourret (Clark and Globensky, 1973) and Bulstrode (St-Julien and Hubert, 1975) formations.

Peculiar mélanges are widely distributed and are interpreted to be roughly coeval with these Middle Ordovician units (Fig. 10). The best exposed of these mélanges is the Cap Chat Mélange in the Gaspé Peninsula (Cousineau, 1998). This mélange consists of broken units of the adjacent formations, in particular, centimetre to kilometre-sized blocks of the Rivière Ouelle, Tourelle and Des Landes formations (Arenigian to Darriwilian) in a muddy to sandy matrix (Cousineau, 1998), although current research suggests a more significant tectonic imprint than previously recognized (N. Pinet, pers. comm., 2007). In southern Québec (Fig. 10), chaotic units described as polymictic conglomerate (Citadelle Formation; Osborne, 1956), olistostrome (Drummondville Olistostrome; Slivitzky and St-Julien, 1987) and the tectonosedimentary Rivière Etchemin and Pointe-Aubin mélanges (Lebel and Kirkwood, 1998; Comeau et al., 2004, respectively) are exposed. These chaotic units in southern Québec differ from the Cap Chat Mélange; they are composed of small to large-sized blocks of the various lithologies found in the shallow and deep marine passive margin and foreland basin succession (Early to Middle Ordovician). The age of the matrix is locally known to be Middle Ordovician (Globensky, 1978).

Syn-orogenic sedimentation lasted until the latest Caradocian in the Gaspé Peninsula. Upper Ordovician coarse and fine-grained flysch is known as the Cloridorme Formation (Enos, 1969; Prave et al., 2000) (Fig. 10). The Cloridorme Formation is coeval with the flysch of the Lorraine and Sainte-Rosalie formations on the St. Lawrence Platform (Globensky, 1987) (Fig. 10). The upper member of the Cloridorme Formation is time correlative (*C. spiniferus*) with the Garin Formation (Malo, 1988) of southern Gaspé and with the Long Point Group (Williams, 1979; Barnes et al, 1981) in western Newfoundland. The Garin and Long Point overlie a depositional hiatus at the top of the allochthons and supports the westward diachronism of Taconian events (Fig. 11).

The evolution of the rift and passive margin episodes was primarily controlled by eustacy with tectonism only recognized at proximity of failed rift grabens (Ottawa – Bonnechère and Saguenay grabens). Differences are recorded at the onset of closure of the Humber Seaway (Waldron and van Staal, 2001), a sea arm of the Iapetus Ocean that separates the Dashwoods microcontinent from Laurentia. This is first noted by the slightly diachronic migration of the peripheral bulge on the continental margin (Knight et al., 1991). These differences are clearly expressed in the timing of various tectono-sedimentary events (Fig. 10). This diachronic evolution suggests that the overriding control on development and evolution of depositional successions was tectonic. The Middle to Late Ordovician eustatic sea level curve of Ross and Ross (1988) suggests three transgressive – regressive (T-R) events in that period (Darriwilian to end-Ashgillian) corresponding to Sloss's (1963) Tippecanoe I Sub-sequence (Fig. 10). These T-R cycles are: 1) Darriwilian, 2) Caradocian and 3) Ashgillian (Fig. 10). Glacio-eustatic processes controlled the last one of these cycles (Brenchley et al., 1994; Gibbs et al., 1997; Lavoie and Asselin, 1998).

The Darriwilian record in the Québec Reentrant suggests the presence of an overall transgressive-regressive cycle, which starts at the Sauk-Tippecanoe unconformity and ends in an unconformity that separates the Chazy and Black River groups (Salad Hersi and Lavoie, 2001b; Dix, 2003) (Fig. 10). This suggests that the Darriwilian succession in the Québec-Ontario shallow foreland recorded a sea level eustatic signal. The Caradocian and Ashgillian T-R eustatic cycles are imperfectly recorded in the Québec succession; the transition from carbonate ramp (Trenton Group) to deep marine sediments (Utica) and flysch (Sainte-Rosalie) records tectonically-driven deeper marine conditions (Lavoie, 1994; Lavoie and Asselin, 1998) (Fig. 10). Dix (2003) documented that the eustatic signal can still be detected.

Detailed sedimentologic analyses are unavailable for the deeper marine successions preserved in the Taconian Allochthons. The lateral variation in time and nature of Middle-Upper Ordovician Mélanges in the Québec Reentrant and St. Lawrence Promontory reflects foreland-propagating compression and local exhumation and erosion of different segments of the foreland and passive margin facies. The propagation of compressive deformation and stacking can form epidermal depositional basins fed by the exposed succession at the top of the structural stack (Stockmal et al., 2003). The mid-Darriwilian Cape Cormorant in western Newfoundland represents one of these proximal tectonic epidermal basin (Stenzel et al., 1990; Waldron et al., 1993). In the Quebec Reentrant, the Darriwilian Cap Chat Mélange formed far away from the shelf break as it only consists of cannibalized coeval to slightly older deep marine units. The Darriwilian chaotic units in southern Québec formed closer to the shelf break as suggested by the nature of the fragments (Comeau et al., 2004). These epidermal basins reached the shelf in Caradocian; this resulted in the Lacolle Breccia, for which a facies correlation with the Darriwilian Cape Cormorant Conglomerate has been proposed (Lavoie, 1994).

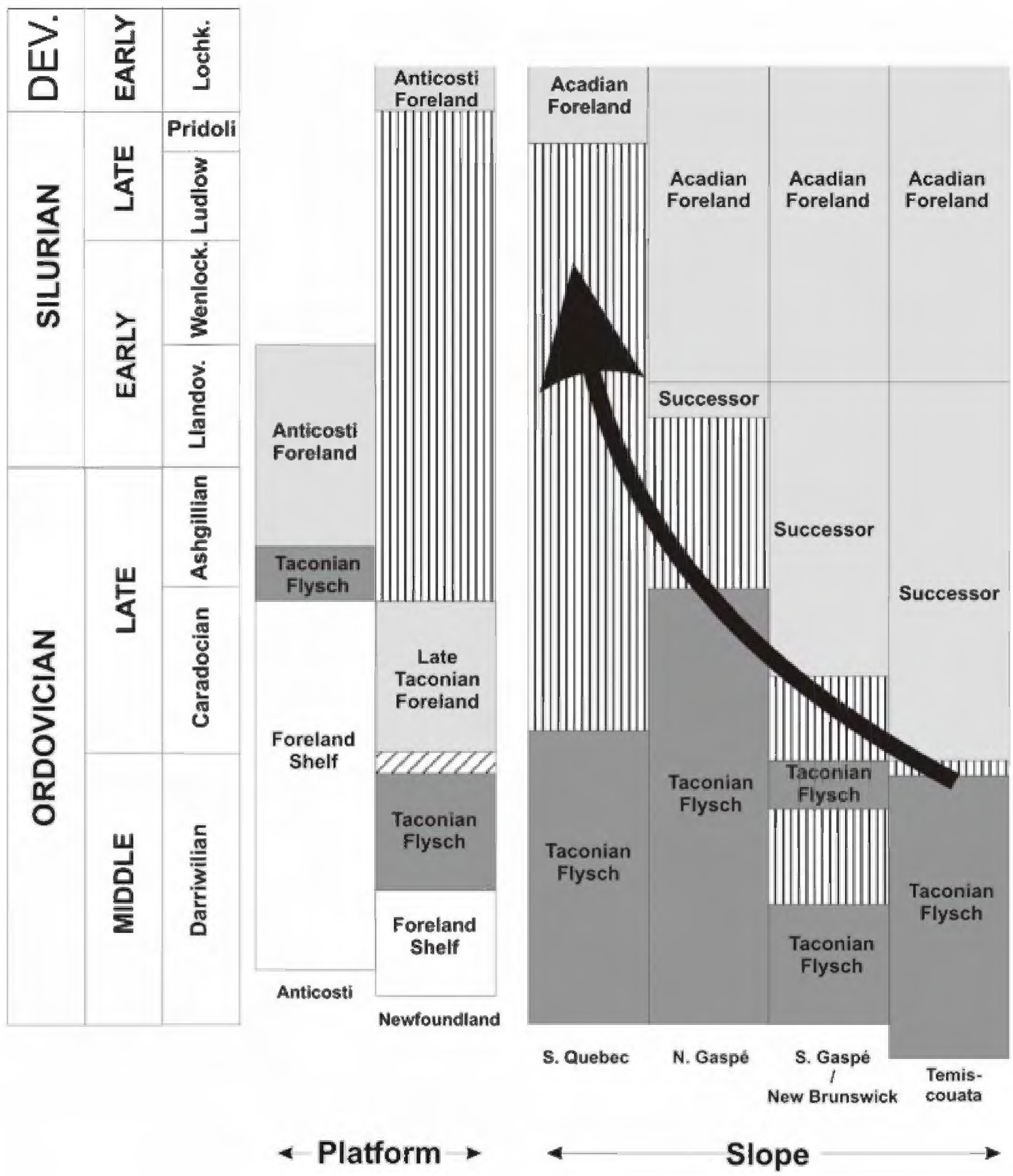

Figure 11. Stratigraphic relationships between Taconian foreland shelf and flysch and the succeeding post-Taconian basins. Note that the time hiatus (vertical hatched areas) increases northwesterly from the St. Lawrence Promontory and adjacent outboards settings of the Québec Reentrant (Témiscouata, southern Gaspé, northern New Brunswick) towards the more inner part of the Québec Reentrant (northern Gaspé, southern Québec).

PETROLEUM GEOLOGY

St. Lawrence Platform

The Lower Paleozoic St. Lawrence carbonate platform was initially tested for hydrocarbons in the late 50's-70's. Gas shows were reported in most of the wells in both passive margin (Beekmantown Group) and foreland basin (Trenton Group) carbonates. However, these first exploration efforts failed to encounter economic accumulations. Extensive organic matter studies resulted in detailed maturity map of the St. Lawrence Platform and in the recognition of source rock potential of the Utica Shale (Bertrand, 1991). In the 1990's, a new round of exploration targeted the deep autochthon below the Taconian Nappes again without significant success. All these previous exploration campaigns tested faulted structural highs and unconformity-bounded Lower Ordovician units. Current exploration activities focus on hydrothermal dolostones (Lower and Middle Ordovician) (Lavoie et al., 2005). In the early 2000's, various gas discoveries have been reported, although without volume and potential production values; these discoveries are reported in the Beekmantown and Trenton groups. The first significant exploration success occurred in early 2007, when Talisman Energy reported from their second exploration well, significant natural gas flows up to 4.5 mmcf/d from hydrothermally-dolomitized intervals of the Trenton-Black River. Moreover, the shale gas potential of the Utica Shale is currently under aggressive technical evaluation.

Source Rocks. Over the years, little oil has been recovered. A 46.9°API oil has been reported in a hole north of Montréal. Detailed organic matter petrography and Rock Eval analysis have shown that the Upper Ordovician Utica Shales has a potential for gas (Bertrand, 1991). The formation contains Type II kerogen and a small amount of Type I. The best Total Organic Carbon (TOC) values range from 1.0 to 3.0wt% and Hydrogen Index (HI) up to 150. The Utica Shale is a facies equivalent of the Middle Ordovician Black Cove Formation in Newfoundland, the Upper Ordovician Macasty Formation on Anticosti Island and the Upper Ordovician Pointe Bleue Formation (TOC: up to 15.5% and HI up to 633) in the Lac Saint-Jean outlier. Other potential source rocks with poor potential include the upper Trenton Group and shales of the Lorraine Group.

Maturation and generation. Maturation increases southerly in the St. Lawrence Platform and three maturation domains are proposed. The Quebec City area is the least mature sector (Bertrand, 1991). A significant maturation jump is noted at the Appalachian structural front. Studies of wells show that maturation positively correlates with depth. The Utica Shale is in the upper part of the condensate zone in the northernmost sector of the St. Lawrence Platform. Elsewhere, the Utica Shale is within the condensate to dry gas zones. Maturation of the source rock resulted from burial of the succession and preceded the formation of the Chambly-Fortierville syncline. Hydrocarbon generation occurred before the emplacement of the Taconian allochthons over the platform. Geochemical data indicate that Utica Shale has generated its entire hydrocarbon.

Migration and accumulation. From geochemical and maturation data, most of the hydrocarbons derived from the Utica Shale were generated just before the Late Ordovician Taconian Orogeny (Bertrand et al., 2003). The presence of thermogenic gas in the Pointe-du-Lac Quaternary reservoir indicates that the Utica Shale still has locally some potential to generate gas (St. Antoine and Héroux, 1993). Recent gas shows in the St. Lawrence Platform (Dundee, Bécancour, Batiscan, Gentilly) argue for an up-dip (southeast to northwest) and vertical (along some of the extensional faults) migration of hydrocarbons of the Upper Ordovician Utica Shale towards Lower and Middle Ordovician carbonate reservoirs. Detailed petrographic study of the Beekmantown dolostones indicates a liquid hydrocarbon migration event after chemical compaction and a later phase of gas migration. There is no absolute age data on hydrocarbon migrations.

Reservoir facies. A first target consists of shallow water, intertidal to shallow subtidal facies of the Lower Ordovician (upper Tremadocian-Arenigian) Beekmantown Group (Chi et al., 2000; Bertrand et al., 2003a; Lavoie et al., 2005). Depositional facies include peritidal dolostones and marine limestones. Facies are arranged in m-thick shallowing-upward cycles. The upper beds are locally karsted as result of sub-aerial exposure at the Sauk-Tippecanoe sequence boundary. Porous potential reservoir units only formed where dissolution and secondary dolomitization / brecciation occurred. The late secondary dolomitization is of hydrothermal origin. Pore coating bitumen and methane inclusions in late quartz cement indicates 2 pulses of hydrocarbon migration.

A second target is the Upper Ordovician (lower Caradocian) Trenton and Black River groups. The favourable facies are shallow subtidal clean bioclastic and oolitic limestones (e.g., Deschambault Formation). Potential reservoir development is associated with hydrothermal dissolution and dolomitization. Proximity to extensional faults is a prerequisite for development of secondary porosity. A major gas discovery in the Trenton-Black River groups has recently been publicized.

Secondary targets consist of the Cambrian and Middle Ordovician basal sandstone units that overly the Precambrian and Sauk-Tippecanoe unconformities, respectively. These nearshore sands are locally porous and gas shows are reported. Finally, most of the wells that intercepted the Upper Ordovician flysch sandstones on the southern flank of the Chambly-Fortierville syncline have generated various amounts of gas.

Porosity and Permeability. Dolostones of the Beekmantown Group contain vuggy, moldic, intercrystalline and fracture porosities. Multiple events of dolomitization are known (early, late burial and hydrothermal; Chi et al., 2000). Measured porosities in the Beekmantown is highly variable and can even reach 17% in the deeply, allochthon buried successions. The limestones of the Trenton Group are locally fractured, although current interest lies in the potential presence of hydrothermal dolostones in that unit. No porosity/permeability values for the Trenton and basal sandstones are available. Recent tests report gas flows up to 4.5 MMcf/d.

Traps and seals. The St. Lawrence Platform strata form a broad monocline with no fold closure. In the target zone (Lower to Middle Ordovician succession), extensional faults are the most likely traps for reservoirs. The top of the Beekmantown Group is marked by the Sauk-Tippecanoe sequences boundary that, if not breached by faults, could have acted as a seal. The Utica Shale could have not only provided hydrocarbons but also likely sealed off the underlying Trenton Group. Diagenetic seals produced by lateral transition from porous hydrothermal dolostones to tight carbonates are expected in the Beekmantown and Trenton groups. Finally, compressional structural elements such as triangle zone and duplexes are locally documented along the SE limb of the Chambly-Fortierville syncline (Castonguay et al., 2006).

Exploration plays. The actual play concept for exploration in the St. Lawrence platform is derived from the model of fault-controlled hydrothermal dolomitization that has proven highly successful in coeval rocks in eastern USA (e.g., Albion-Scipio in Michigan Basin; Fingers Lake area in Appalachian Basin of New York) (Smith 2006). Detailed petrographic and geochemical studies in the Beekmantown Group have revealed the presence of late saddle dolomite in both field and well samples. Reprocessed seismic profiles have documented the presence of still untested fault-bounded platform sags. Movement along these faults is assumed to have taken place during the early Taconian foreland basin development (e.g., Chazy to Trenton) as suggested by thickness increases on the downthrown block. The recent significant discovery that has been announced in March 2007 indicates that the Upper Ordovician hydrothermal dolomite play extends from New York and Ontario into southern Quebec.

As in many places in North America, the potential of shale gas to produce economic volume of natural gas is currently a major field of investigation in southern Quebec. A large number of companies are technically evaluating the potential of the Upper Ordovician Utica Shales in southern Quebec.

Secondary types of conventional play consist of the Cambrian to Middle Ordovician porous sandstone units that are structurally put in favourable contact with the Upper Ordovician Utica Shale. Finally, compressive structural plays involving deep marine impure Upper Ordovician flysch sands at the Appalachian structural front are considered.

Appalachian Humber Zone

The Saint-Flavien gas field was drilled in 1972 by Shell Canada on the seismic identification of a foothill-style major anticline (Béland and Morin, 2000; Bertrand et al., 2003a). Over its production life, the field produced 5.7 Bcf of gas. The Humber Zone of the Appalachians is the least explored domain in Quebec. Presence of natural gas and viable reservoirs is documented in other exploration wells (Parke) and in shallow water wells; surface oil seeps are locally reported. Following the 1995 oil discovery in the Humber Zone of Newfoundland (Cooper et al., 1995), some exploration efforts were carried in this belt. Current exploration targets consist of imbricated shallow marine platform slabs (the Saint-Flavien model; Bertrand et al., 2003a) and coarse-grained thick channel-fill successions in submarine fans.

Exploration history/Discoveries to date. The oldest report of surface seeping oil in the Humber Zone of Quebec goes back to 1958 with notice of soaking oil in a gravel pit in the Montmagny area. Most of the early hydrocarbon exploration in Quebec focussed on the St. Lawrence Platform and on the Gaspé Belt. The Lower Paleozoic Appalachians did not receive significant attention until a late 1960's exploration seismic survey by Shell Canada on a foothill-style concept. This led to the successful drilling of the Saint-Flavien gas field. Few other exploration wells have been drilled in the Humber Zone of Quebec, most of which did encounter gas shows. Of interest are three holes drilled in the Rivière du Loup area (Parke wells), which documented a significant porous reservoir unit (water-filled). This reservoir unit is currently evaluated for underground gas storage. Finally, some shallow water wells in the eastern Quebec stroked natural gas in fractured deep marine clastic unit.

Source Rocks. Liquid hydrocarbon fluid inclusions have been reported in fracture-filling quartz cements in Cambrian - Lower Ordovician coarse-grained submarine fan deposits, methane inclusions are more common (Chi et al., 2000). Source for these hydrocarbons is uncertain. A detailed isotopic analysis of the gas in the Saint-Flavien gas field points to a thermogenic origin with emplacement following the maximum burial (St. Antoine and Héroux, 1993). At the Appalachian structural front, the best-known source rock is the Upper Ordovician Utica Shale with TOC values reaching 3wt% and HI up to 154 (Bertrand, 1991). The organic matter is of Type I/II algal origin. The more or less coeval black shales of the Ruisseau Isabelle Mélange in Gaspé have TOC values up to 3.6wt% (Roy, 2004). Recent study of Lower Ordovician Rivière Ouelle Formation indicates that relatively thick shale intervals have a fair source rock potential (TOC up to 1.6wt%; Bertrand et al., 2003b). These potential source rocks are too mature to generate extracts for geochemical analysis; they are assumed to have had a fair gas potential. However, facies correlative Lower Ordovician shales in western Newfoundland have sourced the oil reservoirs there (Fowler et al., 1995).

Maturation and generation. Surface maturity data indicate a northeasterly decrease from the US border (sterile; reflectance (Ro) of kergonens > 3%) towards Quebec City (oil window – condensate; Ro = 1.3%) (Bertrand, 1991). Conversely, a general north-easterly increase is noted from the Quebec City area towards the Gaspé Peninsula (dry gas to sterile; Ro > 2%) (Chi et al., 2000). In the few wells that were studied, a depth related maturation increase is observed. Evidence for transported burial maturation is indicated by significant maturity jumps from one tectonic slice to the other and at the transition between the St. Lawrence Platform and the Appalachian basin. The presence of units with lower maturity values in the lower nappes of the structural stack is a likely scenario. The available burial history scenarios indicate that the Utica Shale entered in the oil window during in Late Ordovician; these source rocks were significantly buried beneath syn-orogenic Taconian flysch, it is only in the Quebec City area that the shales are still in the dry gas zone.

Migration and accumulation. Migration of hydrocarbons in the Appalachian basin is documented. In the Saint-Flavien gas field, the gas accumulation formed after maximum burial and is assumed to be late Taconian in age (Bertrand et al., 2003a). Combined fluid inclusions and organic matter maturation studies show a strong correlation between type of hydrocarbon inclusions (oil, methane), homogenization temperature of aqueous inclusions and Ro of autochthonous organic matter (Chi et al., 2000). This suggests that in most cases, some migration occurred during or near maximum burial. Late fractures commonly host hydrocarbon fluid inclusions in diagenetic phases (silica, calcite), solid petroleum residue (impsonite) and gas shows; this supports a late tectonic scenario of migration through fractures.

Reservoir facies. The main target reservoir consists of fractured intervals in tectonic slices of shallow water, intertidal to shallow subtidal facies of the Beauharnois Formation (Beekmantown Group) (Bertrand et al., 2003a). Depositional facies include peritidal dolostones and various open marine limestones. Evidence for local episodic subaerial exposure and carbonate dissolution is minor. Reservoirs formed where burial and hydrothermal dolomitization formed thick intervals that were preferentially fractured during tectonic emplacement (Bertrand et al., 2003a). The calcite-cemented fractures were later (post or late emplacement) dissolved forming the reservoir. The lateral and vertical distribution of the reservoir is highly variable and compartmentalization occurred through faulting.

Secondary target reservoirs are found in the thick Cambrian-Lower Ordovician coarse-grained submarine fan deposits. The "green sandstone" unit of the Saint-Roch Group (Lower Cambrian) is typified by open secondary porosity (water-filled in the Parke wells) related to significant dissolution of feldspars. The Kamouraska Formation quartz arenite (Lower Ordovician) is characterized by bitumen that coats both primary pore space as well as open late fractures (gas shows in shallow water wells in eastern Québec and hydrocarbon inclusions in late silica cement).

Other potential targets are hydrothermal dolostones in tectonic slices of the Middle Ordovician carbonate platform facies (Black River and Trenton groups equivalents), thick sand sheets in passive margin (Upper Cambrian Saint-Damase Formation) and flysch (Middle Ordovician Tourelle Formation) submarine fans.

Porosity and Permeability. In the Saint-Flavien gas field (Béland and Morin, 2000), the Beauharnois reservoir has porosity (fracture and minor intercrystalline) ranging between of 2.8% to 15% (average of 6%). Permeability varies between of 0.1 mD to 70 mD (average of 4 mD) in a 3.5 m average pay zone at 1500m. DST in Parke wells suggest local high permeability in the Cambrian sandstone.

Traps and seals. The Saint-Flavien gas field is hosted in a large open anticline cut by secondary extensional and reverse faults that provide excellent closures (Bertrand et al., 2003; Castonguay et al., 2006). The presence of hydrothermal dolomites suggests that diagenetic seals are also likely in tectonic slices of platform facies (Bertrand et al., 2003). Late-Middle to Upper Ordovician shales of the flysch succession could likely form good stratigraphic seals above various carbonate reservoirs. Deep coarse-grained submarine fans are also involved in fold and thrust structural traps; deep marine shales (locally potential source rocks) likely provided impermeable caps.

Exploration plays. At the Appalachian structural front, current exploration play is focussed on the Saint-Flavien model: fault-imbricated tectonic slices of the shallow marine Ordovician dolomitized (hydrothermal?) platform (Beekmantown / Black River-Trenton groups). Recent seismic acquisition program by the MRNQ in Gaspé indicates the presence of such imbricated platform units with roll-over anticlines and duplexes at relatively shallow depth (1 sec). Either Lower (Rivière Ouelle Formation) or Upper Ordovician (Utica and Ruisseau Isabelle shales) source rocks fed the potential reservoirs. In Gaspé, surface maturation of the deep marine allochthons in the Humber Zone is high; no information on the maturity level of the intercalated platform slices is available. In the hypothesis of transported maturation, this type of play is still viable.

A secondary exploration play occurs in the passive margin submarine fans. Thick successions of very coarse-grained facies are known in the Lower St. Lawrence Valley. Significant secondary porosity through either dissolution of metastable aluminosilicates or fractures is documented. The succession is stratigraphically and structurally interstratified within potential source rocks that could also provide excellent seals. The fold and thrust belt tectonic scenario provides multiple tectonic traps that are imaged in recent seismic surveys.

FRIDAY FIELD TRIP

In the Québec City area, rocks of the Appalachian Humber Zone lie in tectonic contact with rocks of the undeformed St. Lawrence Platform (Fig. 12). The geology in this area has been subdivided into three tectonic zones, namely the autochthonous, parautochthonous and allochthonous domains (St-Julien, 1979). The autochthonous Cambrian to Ordovician siliciclastic and carbonate platform shelf sediments of the St Lawrence Platform are tectonically overlain by rocks of the parautochthonous domain which consists of moderately deformed and imbricated strata originally deposited on the shelf or outer shelf. To the southeast, the allochthonous domain, also known as the external part of the Humber Zone, comprises tectonically transported strata originally deposited on the continental shelf edge, slope or rise. The allochthonous domain is divided into five thrust sheets or nappes each displaying distinct sedimentary units, internal stratigraphy, and characteristic structural style (St-Julien, 1995). These are, from northwest to southeast, the Promontoire de Québec, Pointe-de-Levy, Bacchus, Rivière Boyer and Chaudière nappes. According to St-Julien (1995), the emplacement of the allochthonous thrust sheets occurred through progressive accretion and forward stacking over the Cambro-Ordovician sedimentary prism during the Upper Ordovician Taconian orogeny. Consequently, the uppermost Chaudière Nappe comprises the oldest and farthest-travelled rocks, whereas the lowest structural unit, the Promontoire de Québec Nappe, is made up of the most proximal and least-transported strata.

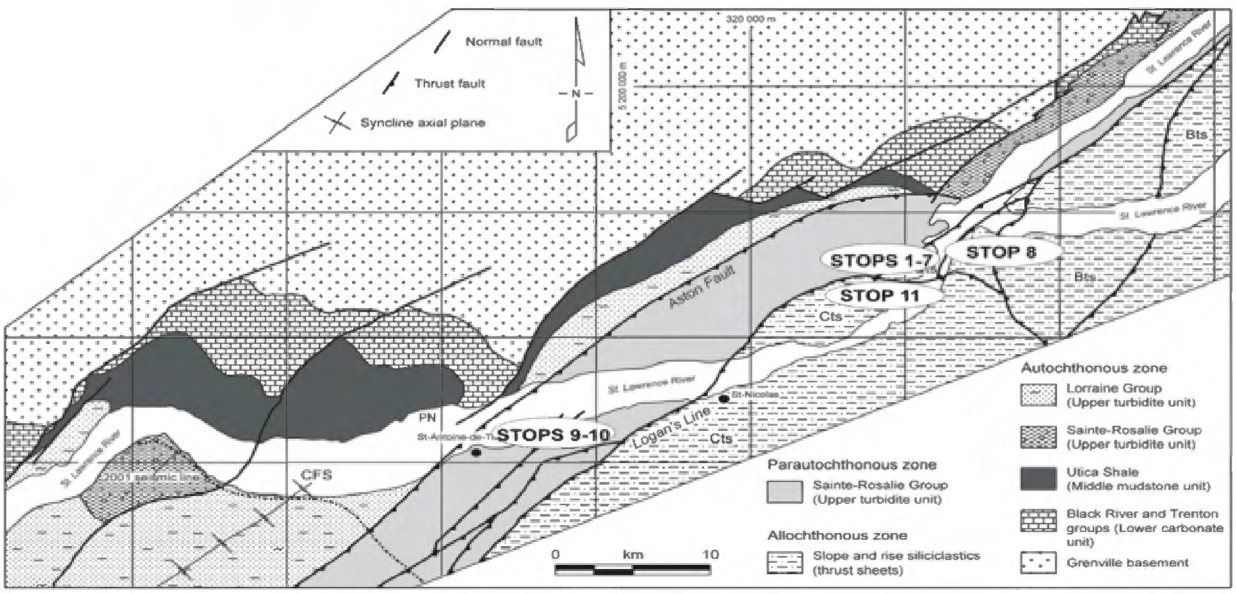

Figure 12: Location of stops, Appalachian trip near Québec City

OUTER SHELF AND SLOPE SEQUENCES

Geological Context

During the Friday field trip we will visit outcrops that expose different parts of the outer shelf of the passive margin sequence as well as the foreland basin flysch sequence. The first stops are located along the walls of Old Québec (Fig. 12). These outcrops expose different parts of the Promontoire de Québec thrust sheet, made up of rocks of the Upper Ordovician (Caradocian) Citadelle Formation, the outer shelf equivalent of the Black River Group.

The following stop is located within the Pointe de Levy slice and consists of exposure of the Lower Ordovician Lévis Formation conglomerates that are interpreted as proximal slope deposits (Lavoie et al., 2003b). The next two stops are located in the parautochthonous zone and expose the turbiditic rocks of the Late Ordovician foreland basin and finally the last stop will allow us to examine the base of the succession, lower Cambrian end-of-rift clastic sediment.

STOPS 1 to 7. The Promontoire de Québec thrust sheet

Rocks of the Promontoire de Québec thrust sheet were folded and thrust over the autochthonous platform during the Taconian orogeny (St-Julien, 1995) (Figs. 1 and 12). Structurally, the Promontoire de Québec thrust sheet represents the lowest thrust unit of the allochthonous zone. It is structurally overlain by the Pointe de Levy and Sainte-Pétronille slices as well as the Chaudière thrust sheet. To the south the Foulon fault separates the Promontoire de Québec thrust sheet from the Chaudière thrust sheet.

The Promontoire de Québec thrust sheet is made up entirely of rocks of the Citadelle Formation that has been divided into two units, a first unit consisting of alternating limestone and mudshale and a second unit that includes different levels of mélange type rocks and olistostromes. The first unit of the Citadelle Formation is made up of argillaceous limestone and mudshale, and more rarely sandstone and siltstone, dolomitic limestone and pyrite-bearing black shale. The argillaceous limestones are massive and frequently contain bitumen. The overall thickness of this unit is estimated at 900 meters along the section that runs parallel to Champlain boulevard (St-Julien, 1995). The second unit of the Citadelle Formation includes conglomerates, olistostromes, mélange type rocks and debris layers that can be found at different levels throughout the formation. Numerous discontinuous lenses of 30 cm to 5 m thick limestone conglomerates can be observed in the north-east part of the thrust sheet, along Saint-Vallier, Côte d'Abraham et Arago-ouest streets, as well as in the underground parking at Place d'Youville, suggesting that these conglomerates are indeed interlayered with the massive argillaceous limestones of the first unit. Variably sized (from 2 to 10 cm) subrounded to round calcarous limestone, bioclastic limestone calcarous sandstone and limestone clasts are cimented by a calcarous matrix. Some clasts are in fact larger fragments of massive argillaceous limestone up to 1.5 meters in size and typical of unit 1 of the Citadelle Formation. Olistostromal layers represent the main facies of the second unit of the Citadelle Formation. These layers are made up of different lithotypes of variable size, from a few cm to a few meters in length. This facies is recognized mostly along Côte de la Montagne and Côte Dinan, as well as along Sault au Matelot, Sous le Cap, Dambourgès and de la Canoterie streets. Outcrops from Côte de la Montagne to Côte-du-Colonel-Dambourgès consist of the same stratigraphic layer whereas those along De la Canoterie street and Côte Dinan are stratigraphically lower, suggesting indeed that there are at least two separate layers of olistostromes in the Citadelle Formation (Gayot, 2002). The olistostromal layers can be followed for more than a couple hundred meters and their thickness is estimated at approximately 15 meters. Contacts between unit 1 and unit 2 can be either conformable, unconformable or faulted. Numerous field evidence such as soft-sediment deformation features, syn-sedimentary faults and dragged bedding along fault planes suggests that rocks of the Citadelle Formation were deposited in an extensional basin on the outer shelf in the immediate foreland of advancing nappes. Thus, the outer shelf was dissected by extensional faults defining local topographic highs from which were shed debris flows into fault-bounded basins. Tectonic instability and subsidence of the outer shelf are attributed to flexural extension of the North-American margin during the Taconian orogeny (Kirkwood et al., 2000).

The Québec Promontory thrust sheet is characterized by regional NNE-SSW trending anticlines and synclines (Fig. 13). A well-developed, steeply-dipping first-phase cleavage (S1) and local folds (F1) are observed throughout the thrust sheet. Fold axes strike N185°, parallel to the regional NNE-trending folds and plunge 45° towards the SSW. Along the escarpment next to the Champlain boulevard, the stratification is oriented towards the SE near the Gare Maritime, becoming nearly vertical below the Citadel and plunging toward the NW in the Du Petit Champlain street sector. Many faults occur within the Promontoire de Québec thrust sheet. Major NNE trending thrust faults, such as the Logan's fault are mainly present to the north. Low-angle thrust faults cut through the steeply-dipping, overturned limbs of the regional anticlines and synclines and can be observed mainly along the southern part of the thrust sheet along Champlain boulevard. Numerous normal faults also occur within the thrust sheet. They consist of a set of regularly oriented and continuous NE-trending subvertical faults. Two other sets of small scale normal faults are also present throughout the thrust sheet. Although their orientation is quite variable along both limbs of the regional syncline, they consistently trend NW and SE when restored to their original orientation after unfolding of the strata. These faults are in fact high angle normal faults that developed early on during deposition of the Citadelle Formation in the foreland basin (Kirkwood et al., 2000).

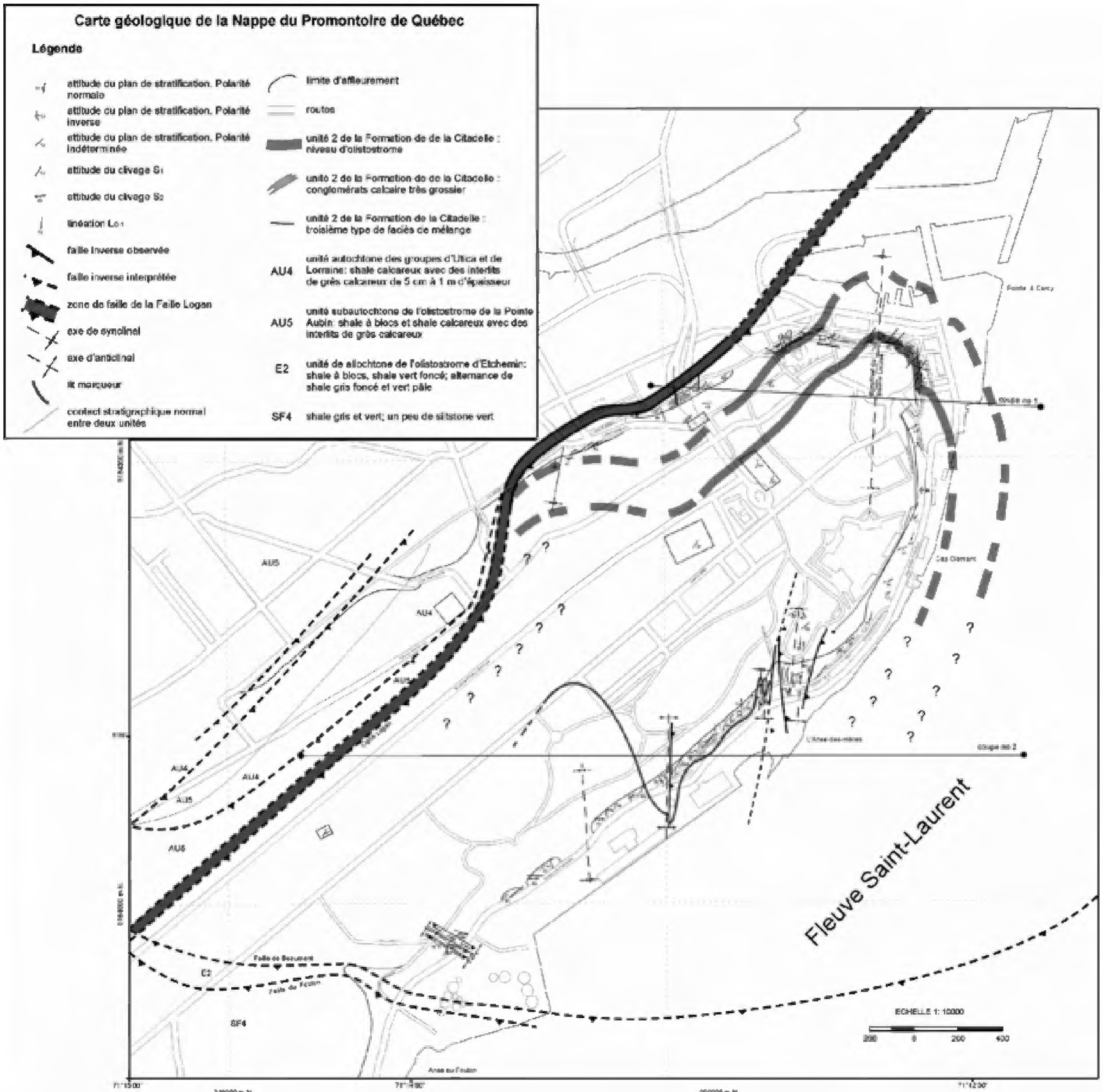

Figure 13. Geological map of the Promontoire de Québec Thrust Sheet (from Gayot, 2002).

Fracture sets and veins were studied within the Promontoire de Québec thrust sheet in order to characterize the nature of fluids and timing of internal migration (Fig. 14). Four distinct fracture sets were recognized. The first two sets are almost always completely filled with calcite and/or quartz. They are oriented either N-S, with shallow to moderate dips or E-W, with moderate to steep dips. Their geometry, orientation, and kinematics are compatible with syn-tectonic normal faulting within the basin. The last two sets are oriented either NE or NW and are compatible with Taconian folding and thrusting. The paragenetic sequence of vein and fracture fill consists of fibrous calcite (I), idiomorphic calcite (II), and/or quartz crystals and/or bitumen. Hydrocarbon fluid inclusions and precipitation of bitumen and impsonite (Levine et al., 1991) in open fractures attest to petroleum migration within rocks of the Promontoire de Québec thrust sheet. Structural relationship of fracture sets in the Promontoire de Québec thrust sheet combined with fluid-inclusion data and isotopic composition of vein infill help constrain the P-T history of the basin. Results suggest that a warm (60°C), low salinity fluid of meteoric origin migrated through fracture networks and normal faults in the Citadelle rocks during the extensional collapse of the outer shelf in the lowermost Caradocian (Kirkwood et al., 2002). This fluid was progressively mixed with a warmer (150-160°C) high salinity, basinal fluid associated with hydrocarbon gases and fluids. P-T modelling of inclusions (Fig. 2) related to the second pulse suggests a 3 to 4 km maximum burial depth for rocks of the Promontoire de Québec thrust sheet that we equate with thrusting of the rocks over the autochthonous margin and/or overthrusting by the Chaudière thrust sheet.

Departure from INRS-ETE, 490 de la Couronne Québec, at 8h30 (a few underground pay parking lots are available within a short distance)

STOP 1. St-Vallier St.

- *Itinerary: walk along the walls of the Old Québec City starting at the outcrop located on St-Vallier street beneath the now-removed overpass of the Dufferin-Montmorency highway. The outcrop shows the following features:*
    - Stratigraphic sequence of the Citadelle Formation
    - Normal faults and fractures
    - Geochemistry of veins

STOP 2. Côte Dinan

- *Itinerary: From St-Vallier, continue east towards Côte Dinan just below the Hôtel Dieu hospital. The outcrop shows the following features:*
    - Stratigraphy of the Citadelle mélange unit
    - Soft sediment deformation
    - Fractures, cleavage, faults

STOPS 3 to 7. Côte-du-Colonel-Dambourgès, Sous-le-Cap, Sault-au-Matelot and De la Montagne street and Champlain boulevard

- *Itinerary: From Côte Dinan turn right (east) along Côte de la Canoterie and follow the walls of the Old City along Côte-du-Colonel-Dambourgès and Sous-le-Cap street. Continue south along Sault-au-Matelot street to De la Montagne street. Proceed along Notre-Dame street to the east cliff below the Château Frontenac on Champlain boulevard. The outcrops show the following features:*
    - Stratigraphy of the Citadelle Formation
    - Normal faults and fractures, Taconian thrust faults

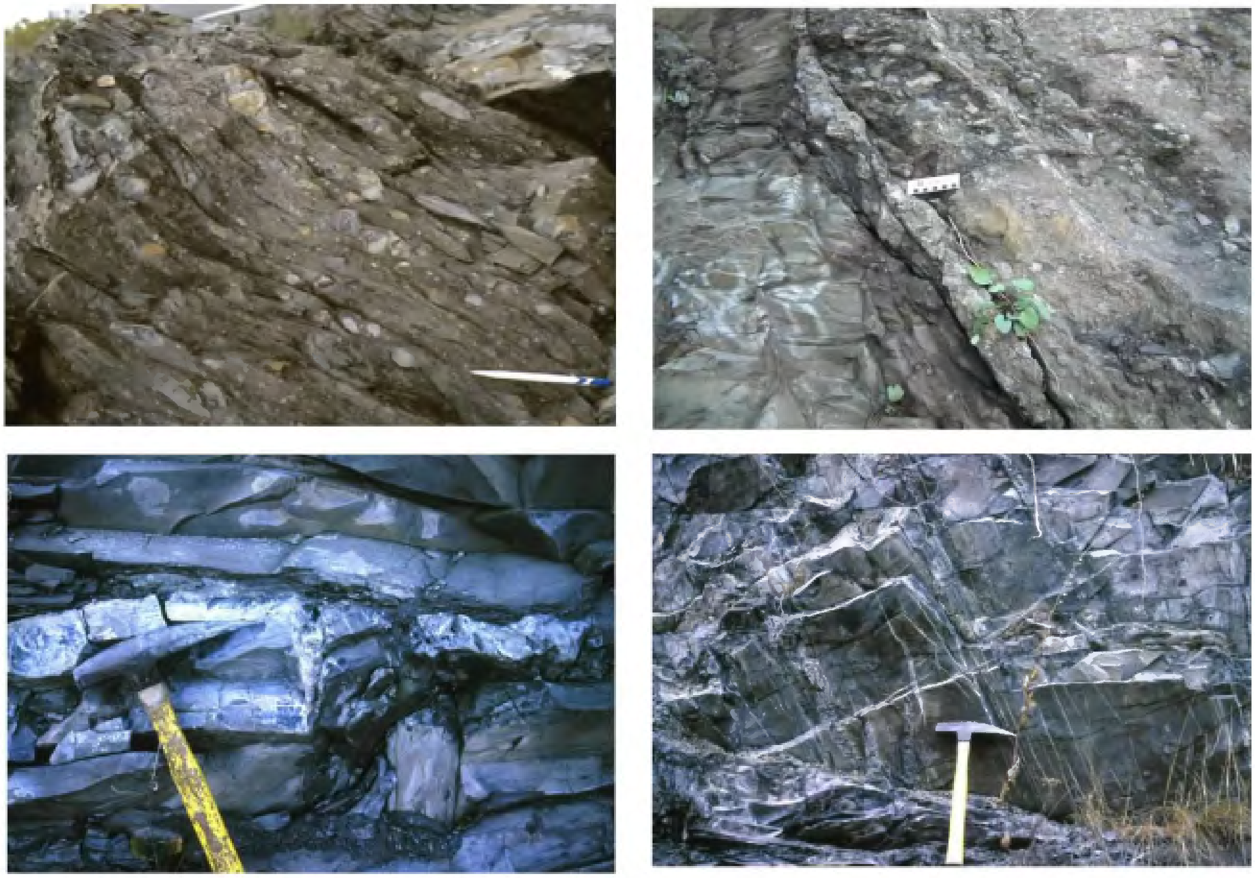

Figure 14. (a) Olistostrome mélange of the Citadelle Formation. Note the soft-sediment deformation in some of the clasts. (b) Normal fault in the Citadelle Formation. Limestone breccia in the hanging wall of the fault. (c) Fractures, veins and small-scale normal fault in the Citadelle argillaceous limestones. Veins contain calcite, quartz and bitumen. (d) Bedding perpendicular fractures and veins in the Citadelle Formation.

STOP 8. The Pointe de Lévy thrust sheet

Go back to pick up your vehicules and drive to the ferry wharf

0.0	*From the Quebec – Lévis ferry exit, take "Côte du Passage" road towards the west (towards the old Lévis)*
0.0 – 1.0 km	*Take left at traffic light, you are now on Saint-George street*
1.0 – 2.3 km	*Take right at indicated "Cimetière" entrance, Mont Marie street*
2.3 – 2.5 km	*Parking space*

The succession at this locality is known as the Lévis Formation or Conglomerate. The conglomerate is dated Arenigian on the basis of graptolites and chitinozoan fauna in the muddy matrix and interbeds. The Lévis Conglomerate is only known in the Lévis area, elsewhere in eastern Quebec, the time correlative unit are known as the Rivière-Ouelle and Pointe de la Martinière formations which are dominated by a fine-grained multicoloured mudstone and siltstone succession with secondary sandstone, calcilutite, calcarenite and limestone conglomerate. Lavoie et al. (2003) have interpreted the Levis Conglomerate – Rivière-Ouelle – Pointe de la Martinière formations as a laterally coeval proximal to distal slope succession. This conglomerate is interpreted as the result of the sub-aerial exposure and erosion of the Early Ordovician platform with various shallow marine limestone fragments deposited on the continental slope. The age of that event is constrained by the Arenig age of the matrix. Along the eastern margin of Laurentia, the initiation of Iapetus oceanic crust subduction and hence of the Taconian foreland basin is considered to occur at the Arenig (van Staal, 2005). The initiation of subduction and the resulting lithospheric rebound led to the migration of a tectonic peripheral bulge along the continental margin of Laurentia (Jacobi, 1981; Knight et al., 1991; Lavoie, 1994). Major subaerial exposure and erosion of the Early Ordovician shallow marine platform is recorded from southeastern USA (Knox and Beekmantown groups: Mussman and Read, 1986; Read, 1989) to southern Quebec (Beekmantown and Philipsburg groups: Lavoie, 1994; Salad Hersi et al., 2002; 2003) up to western Newfoundland (St. George Group: James et al., 1989; Knight et al, 1991). From that erosion, coeval major limestone conglomerates were deposited on the continental slope (James and Stevens, 1986; James et al., 1989; Lavoie, 1997; Lavoie et al., 2003; Salad Hersi et al., 2003).

These Arenig conglomerates mark the end of the passive margin and the inception of the Taconian foreland basin along the continental margin of Laurentia. It is noteworthy that this transition is coeval with the Sauk – Tippecanoe sequences boundary for the cratonic successions (Sloss, 1963).

Outcrops

We will examine two outcrops at this locality; the first one is immediately behind the main cemetery building (a small cliff) whereas the second one is adjacent to the easternmost apartment building that you see on the cliff to the north of the parking lot. In both cases, these are private properties and we ask you to act accordingly.

The first outcrop is a 6 meter-wide cliff face that exposes a limestone conglomerate. The conglomerate consists of crudely-bedded conglomerates with beds ranging from 50 cm up to 2 meters in thickness (Fig. 15a). Thinner conglomerate beds with interbedded fine-grained sandstone to siltstone/mudstone beds are seen near the stratigraphic top of the succession. The conglomerate is commonly clast-supported and the matrix is fine sand. The conglomerate consists of unsorted, small (mm) to large (up to 1.5 meter in diameter) limestone fragments. The large fragments are angular with irregular margins that testify for little traction transport and remobilization, whereas some of the small clasts are more sub-angular to sub-rounded. The clasts are dominated by micritic limestone with also abundant wackestone to packstone mollusc-rich calcarenite. Some dolomite clasts are present in subordinate number.

The second outcrop is adjacent to the apartment building on the cliff to the north of the cemetery. There, the outcrop is 15 meters long by 4 meters large and includes one major block of 10 x 4 meters (Fig. 15b). This large block consists of micritic limestone with irregular patches of intraclastic calcarenite and calcirudite. The micritic limestone is a thrombolite with a growth framework that consists of a framework of cryptomicrobial material in particular of *Renalcis* and *Epiphyton* commonly forming layers with thin isopachous crusts of fascicular-optic calcite cement crust of most likely marine origin. The irregular-shaped cavities in the thrombolite are interpreted as growth cavities in the organic framework that are filled by material derived from the bio-mechanical erosion of the organic framework. These cavities are commonly metric in visible size and are characterized by abundant biota in particular large-sized molluscs. Locally, parts of the block are irregularly dolomitized (work in progress). The large block is encased in limestone and siliciclastic conglomerate similar to the one of the outcrop at the entrance of the cemetery. In the conglomerate, there are alternating clast- and matrix-supported layers. Clasts are dominated by micritic limestone some of which are clearly thrombolitic in origin, other clasts in decreasing abundance are: bioclastic and intraclastic calcarenite, algal laminites (locally strongly dolomitized), monogenic limestone conglomerate, sandy limestone and sandstone/siltstone. The clastic clasts are autochthonous and represent eroded fragments of the background sediments.

Figure 15. (a) Unsorted limestone conglomerate, the larger clasts have highly irregular margins. (b) A 10 x 4 meters thrombolite clast in the Lévis conglomerate. The upper contact of the clast with the conglomerate facies is marked by the dashed line.

LUNCH

PARAUTOCHTHONOUS SEQUENCE AND IMBRICATE FAULT ZONE

The foreland basin sequence is well preserved within the autochthonous zone of the Quebec Appalachians (Lavoie, 1994). An important part of this basin can also be found within the outermost deformed zone of the Appalachian orogen in the Quebec parautochthonous zone. However, the presence of chaotic units within the parautochthonous sequence as well as the highly disrupted and imbricated nature of this zone at surface has complicated the stratigraphic correlations of these rocks with those of the autochthonous foreland basin. Within the parautochthonous zone, the observed facies differ slightly lithostratigraphically and chronostratigraphically from the autochthonous facies and reflect a more distal setting with respect to the autochthonous sequence.

In the Québec City area, the parautochthonous zone is completely exposed at low tide between St-Nicolas and St-Antoine-de-Tilly on the south shore of the St-Lawrence river along a 15 km section (Fig. 12). The southern contact between the parautochthonous and the allochthonous zones, i.e., Logan's Line, occurs a few kilometers west of St-Nicolas and consists of a major fault zone, where rocks of the Upper Ordovician Ste-Rosalie Group flyschoid sequence are overthrusted by red and green shales of the Cambrian Sillery Group outcropping within the allochthonous Chaudière thrust sheet. A few kilometers to the northwest, the limit between the autochthonous and the parautochthonous zones occurs along the Aston fault which juxtaposes rocks of the Les Fonds Formation (Sainte-Rosalie Group) to rocks of the Nicolet Formation (Lorraine Group) (Globensky, 1987).

Structurally, the parautochthonous zone consists of a series of steep, southeast-dipping thrust faults that display imbricate thrust fan geometries (Figs. 1 and 12) (St-Julien et al., 1983; Castonguay et al., 2001, 2006; Séjourné et al., 2003). Deformation within the zone features large-scale northeast-trending, slightly overturned folds. Smaller-scale mesoscopic folds are upright to slightly overturned, northwesterly-verging and plunge gently to the northeast or to the southwest. In cross-section, thrusts affect progressively older rocks as the main decollement surface cuts down to deeper stratigraphic levels (St-Julien et al., 1983). At the outcrop to be visited, the rocks of the parautochthonous zone consist essentially of typical Upper Ordovician flysch of the foreland basin.

STOP 9. St-Nicolas – Pointe-Aubin

0.0 km	*Depart from the cemetery parking lot, Mont Marie street*
0.0 – 0.2 km	*Take Saint-George street, straight ahead*
0.2 – 1,5 km	*At the traffic light, turn left on Alphonse-Desjardins street*
1.5 – 4.0 km	*Take Highway 20 west, towards Quebec City / Montréal*
4.0 – 23.4 km	*Take exit # 305, St. Nicolas*
23.4 – 27.3 km	*Take road # 171 North, up to the intersection with highway #132*
27.3 – 36.6 km	*Take Highway #132 west (left), up to intersection "Côte de Pointe Aubin"*
36.6 – 37.4 km	*St. Lawrence River shore outcrop*

Outcropping rocks of the parautochthonous zone in the Québec City area are included within the Les Fonds Formation. The stratigraphic succession of the Les Fonds Formation can best be described in the Pointe Aubin area where a variety of lithological assemblages crop out in the core of a southeast-dipping and southwest-plunging syncline (Fig. 16). Thrust faults occur along both limbs of the syncline. In the axial zone of the syncline the stratigraphic succession of the Les Fonds Formation is rather well exposed and consists mainly of mudstone and fine- to coarse-grained sandstone with less abundant fine-grained limestone, conglomerate and chaotic units.

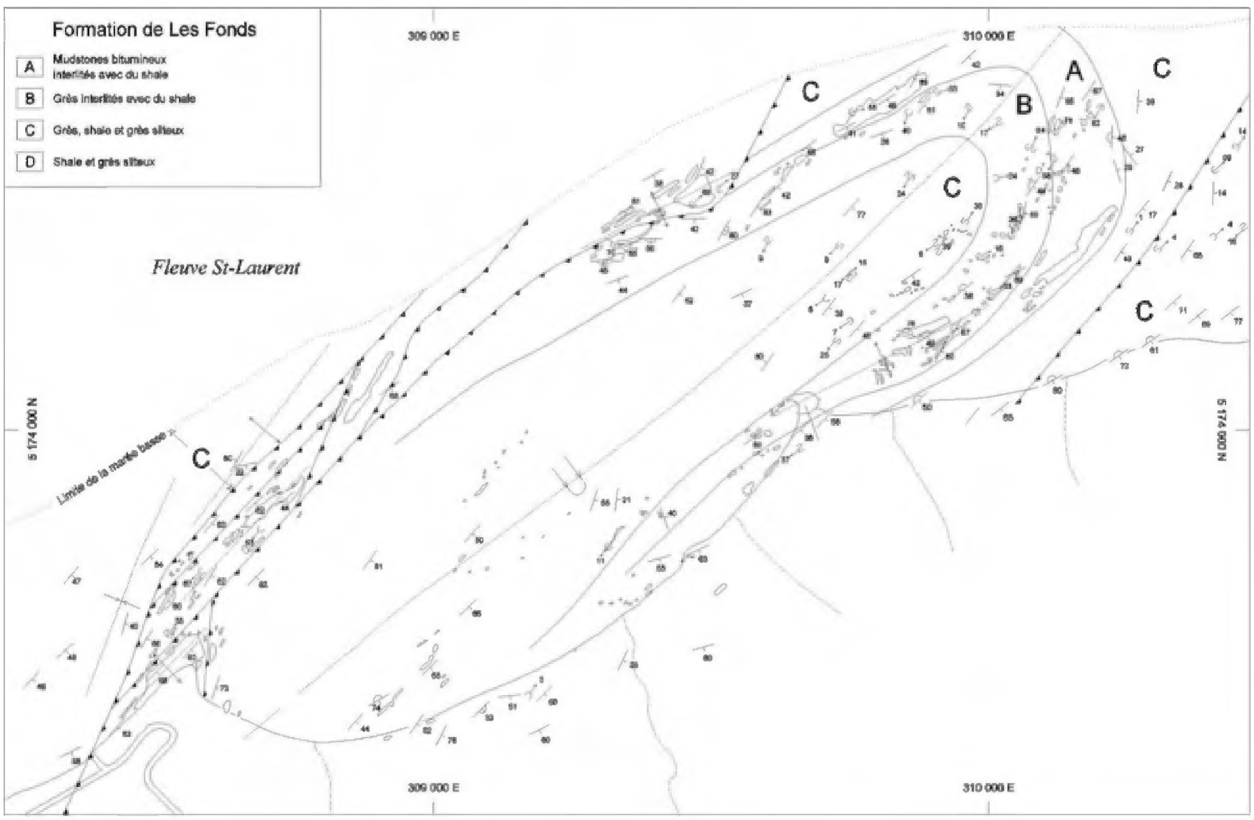

Figure 16. Geological map at Pointe-Aubin (from Comeau et al., 2004).

The main lithologic assemblage of the Les Fonds Formation cropping out at Pointe Aubin consists of mudstone and very fine grained sandstone interbedded with thin- to thick-bedded sandstones and more rare chaotic units. Lithologic assemblage A of figure 16 consists of a 50 meters thick chaotic zone of bituminous mudstone blocks set in a shale matrix. Bituminous mudstone blocks vary in size from 1 m to more than 100 m in length and from 1 m to about 10 m in thickness and are aligned on both limbs of the syncline. This interval of meter-scale blocks is in fact interbedded within the flyschic sequence and is folded around the syncline (Fig. 17a). The overlying lithologic assemblage B is composed of 75 meters of thick coarse sandstone beds (0.25 m to 1 m) alternating with shale (Fig.17). Lithologic assemblage B is overlain by the turbiditic facies of assemblage C that fines upward into a 700 m thick succession of lithic sandstone beds (2 to 40 cm thick), shale and silty sandstone. Within the Les Fonds

Formation, sandstone beds are more abundant in the lower half of the section (Beaulieu et al., 1980). Thickness of sandstone beds and size of the detrital fraction also diminishes towards the upper half of the section. This fining upward section suggests episodic tectonic activity in the basin at the time of deposition of the Les Fonds Formation.

Based on graptolite data (Riva, 1972; Walters et al., 1982), the age of the stratigraphic units within the Les Fonds Formation is Late Ordovician. Most of the graptolites collected from the mudstones (assemblage C) of the Les Fonds Formation along the section belong to the Caradocian C. spiniferus Zone (Riva, 1972; Walters, 1979; Walter et al., 1982). However, graptolites collected in the chaotic units and thrust slices belong to the N. gracilis, C. americanus, O. ruedemanni and C. spiniferus zones (St-Julien, 1968; Riva, 1972; Walters, 1979; Walters et al., 1982).

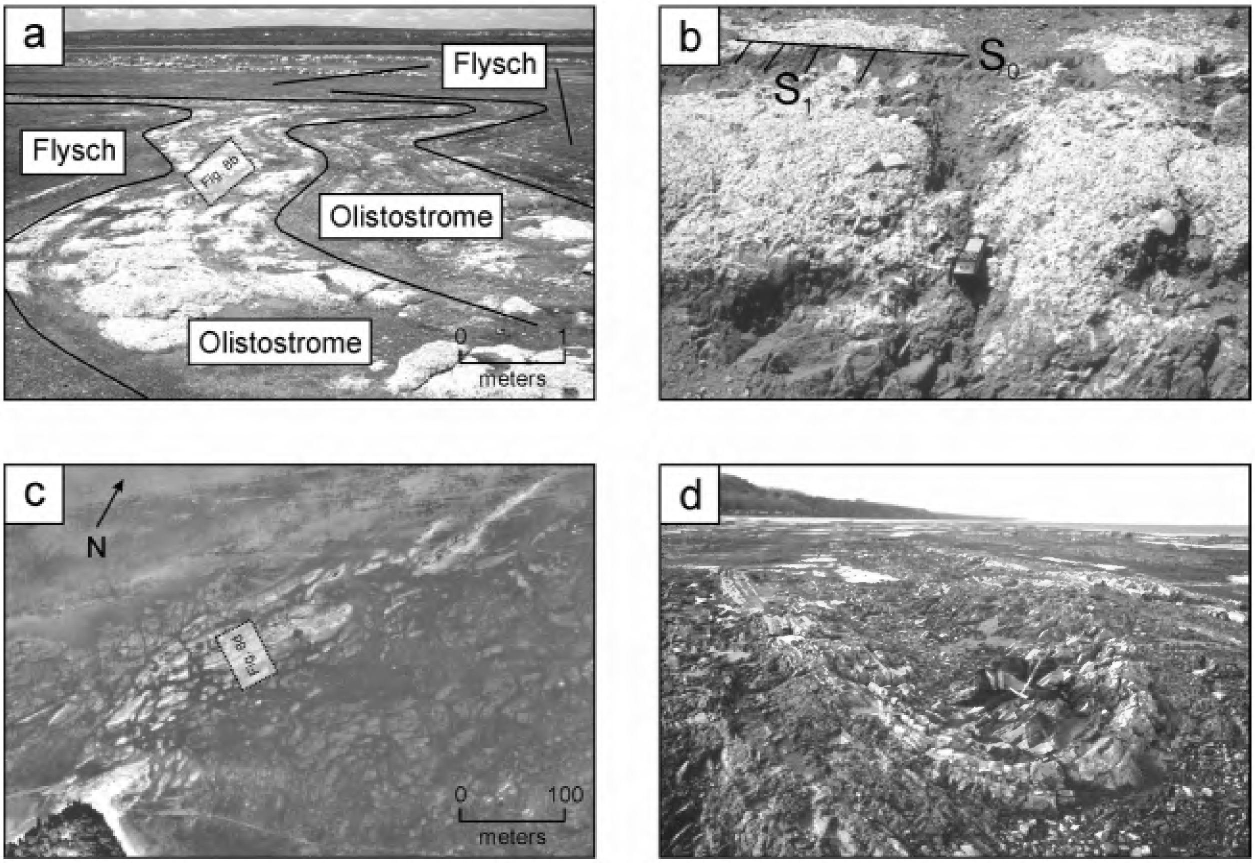

Figure 17. (a) Interbedded olistostrome zone within the flyschoid sequence of Les Fonds Formation; (b) Close up view of the olistostrome unit. A perpendicular cleavage is recognized. The GPS receptor is used as scale; (c) Aerial photography of the tectonosomes' triaxial geometry at the Pointe Aubin. (d) Folded tectonosome, area identified by the box on 17c. The backpack and the geologist hammer are used as scale.

Values of reflectance equivalent to that of vitrinite in the Pointe Aubin syncline are below 1.35% and indicate that rocks of the Les Fonds Formation are in the lower half of the mature zone. Such a low degree of maturation is very rarely observed in the St. Lawrence Lowlands and in the foreland basin sequence. Analyses in the Les Fonds Formation 7 km west of the Pointe Aubin section in the parautochthonous zone along the St. Lawrence shore, display reflectance values 0.2 to 0.3% higher (Héroux and Bertrand, 1991). This lower level of thermal maturation indicates that the Pointe Aubin section is near the top of the parautochthonous structural pile. Spatial variation of reflectance values in the Pointe Aubin successions shows a rather clear relationship with the syncline. Low values of reflectance are observed in the vicinity of the axis whereas highest reflectance values are found on both limbs of the syncline, at the base of the structural succession. This relationship indicates that the folding of the synclinal structure postdate the thermal maturation of those successions (pre-tectonic thermal maturation of Taylor et al. 1998). Maximum thermal maturation of the parautochthonous zone is thus presumably due to sedimentary and/or tectonic burial.

STOP 10. St-Nicolas – Pointe-Aubin

The northern limb of the Pointe Aubin syncline consists of a 10-20 m wide fault zone made up of a series of tectonically juxtaposed thrust slices, including distinct lithological facies and blocks of variable size and lithology, such as green silicified siltstone, bituminous mudstone, dolomitic limestone and red shale with calcarenite interbeds (Fig. 16). St-Julien (1968) included these fault slices in his polygenic chaotic unit and Globensky et al. (1993) later assigned them to the Pointe Aubin Formation. In outcrop, individual fault slices consist of tightly folded beds and sometimes highly fractured competent beds displaying internal continuity. The fault slices are of variable size, ranging from a few meters to a few hundred of meters in length along-strike (Fig. 17c), and are affected by faults and fractures fragmenting them into smaller blocks, with precise shapes, sharp outlines, and an evident triaxial geometry. All fault blocks have a common trend and a strong bed-parallel preferred orientation. The finer-grained matrix surrounding the blocks is tectonized and displays a scaly texture occurring in small cm- to tens-cm thick corridors that are parallel to the preferred alignment of the blocks. Large blocks can be lozenge-shaped, highly fractured with numerous conjugate fault planes and disposed within 10-20 meters wide corridors parallel to thrust faults. Thrust faults with down-dip striae can be recognized along the margins of the blocks. Strata within the blocks are occasionally tightly folded with axial traces parallel to the regional cleavage.

Disruption, imbrication and thrusting of the Taconian foreland basin sequence are responsible for the development of chaotic units within the turbiditic sequence of the Caradocian Les Fonds Formation (Fig. 18). These chaotic units have been termed olistostromes or tectonosomes on the basis of field criteria and following Pini's (1999) classification. Olistostromal units containing blocks of the middle mudstone (Utica Shale) and upper turbidite units (Ste-Rosalie Group) of the foreland basin and spanning the Caradocian *N. gracilis*, *C. americanus*, *O. ruedemanni* and *C. spiniferus* graptolite zones were deposited and incorporated in the Les Fonds Formation. Disruption of more competent beds of the flyschic sequence and fault stacking and slicing of older rock units occurred along major thrust faults, and now form structurally aligned corridors or tectonosomes. Graptolites and new chitinozoan data from both olistostromes and tectonosomes indicate older ages (early Late Ordovician) than the flysch units of Sainte-Rosalie Group (mid Late Ordovocian). Lithological, stratigraphic and structural criteria indicate that tectonosome slices are imbricated foreland basin rocks that are correlative to the Black River, Trenton, Utica, Sainte-Rosalie and Lorraine groups of the Laurentian platform. Thermal maturation data indicates that disruption of the autochthonous sequence, and folding and thrusting of the entire foreland basin sequence must have occurred shortly after their deposition. Contrary to what had been suggested, blocks in the olistostromes and tectonosomes were not derived from the allochthonous Chaudière thrust sheet, even though it presently marks the southern contact with parautochthonous zone. Imbrication of the foreland basin sequence must have occurred before emplacement of the Chaudière thrust sheet.

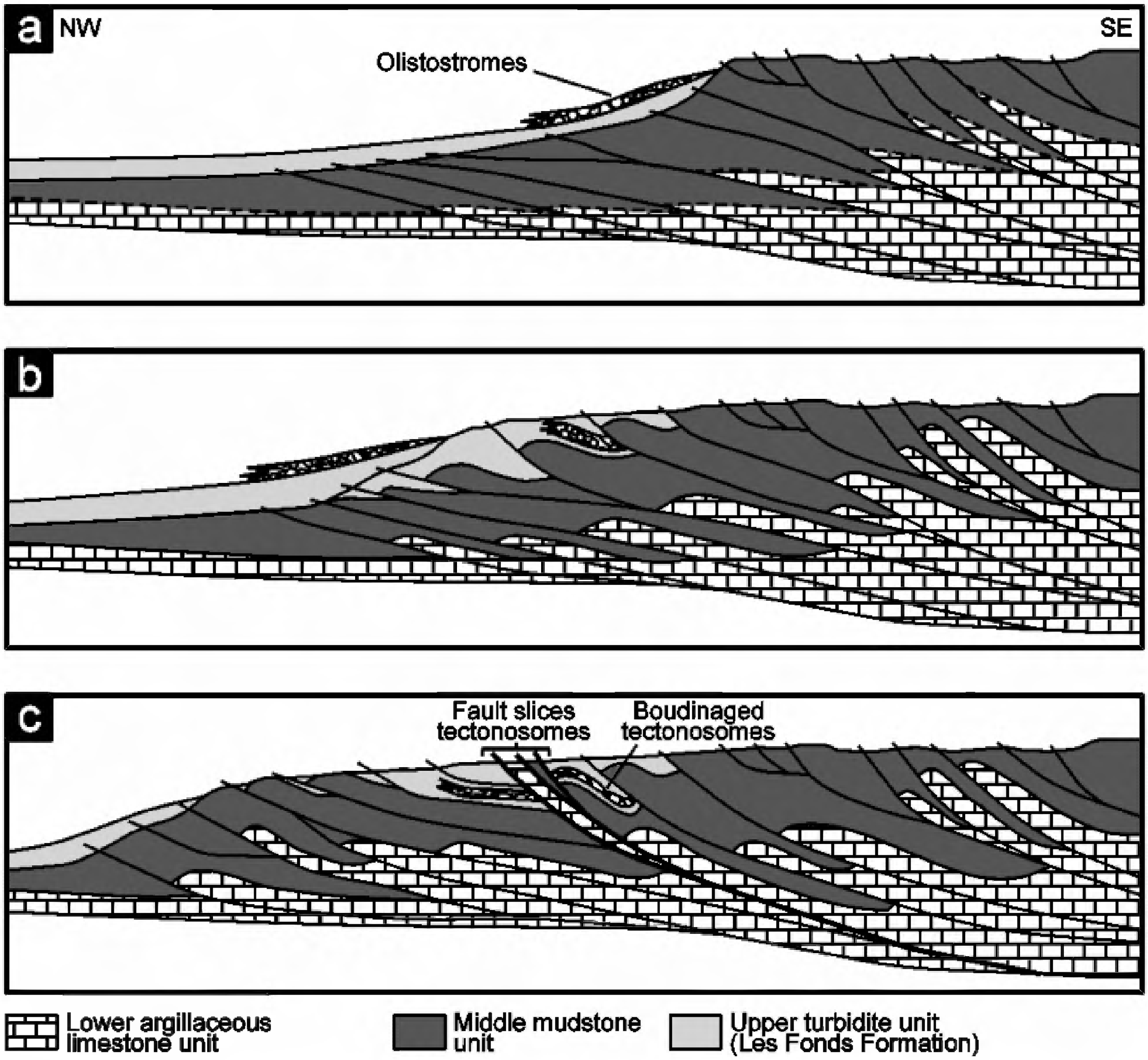

Figure 18. Structural evolution of the parautochthonous zone at Pointe Aubin. (a) Growth of tectonic wedge and deposition of olistostromes, (b) Incorporation of olistostromes within tectonic wedge. (c) Development of tectonosomes during regional folding and out-of-sequence thrusting along major thrust planes (from Comeau et al., 2004).

0.0 km	*Depart from St. Lawrence River shore outcrop*
0.0 – 0.8 km	*Take road #132 east (left)*
0.8 – 10,1 km	*Take road #171 South*
10.1 – 29.5 km	*Take Highway 20 east, towards Quebec City*
29.5 – 23.4 km	*Take exit Quebec City – Laporte bridge*
	At the north end of the bridge, take the first exit – Champlain boulevard

STOP 11. The Chaudière thrust sheet

The Chaudière thrust sheet is limited to the north by Logan's Line and associated melange units and to the south, by the Foulon Fault (Fig. 19). Sedimentary units of the Chaudière thrust sheet form the Sillery Group which consists of the Sainte-Foy, the Saint-Nicolas and the Breakeyville formations. The biostratigraphic information suggests that the Saint-Nicolas Formation is of Early Cambrian age. The Sainte-Foy Formation tectonically underlies the Saint-Nicolas Formation; the former consists predominantly of variously-coloured mudstone. The Saint-Nicolas

Formation is divided into three units: a lower massive and coarse-grained sandstone, a middle cyclic turbidite and an upper red mudstone. The Breakeyville Formation consists of two units, a lower conglomerate-sandstone and an upper mudstone-sandstone. The Saint-Nicolas and Breakeyville formations are both characterized by fining-upward trends which result from initial marine lowstand followed by transgressive events. Correlation with adjacent stratigraphic frameworks is based on the recognition of the massive lower coarse-grained sandstone unit of the Saint-Nicolas Formation in other successions. This unit is temporally well constrained and correlates with a major sea level lowstand (the Hawke Bay event) recognized along the entire continental margin of Laurentia from western Newfoundland to southern Quebec. This event marks the end of the initial rifting episode and the initiation of the passive margin. The framework also relies on correlation of the lower conglomerate of the Breakeyville with Upper Cambrian conglomerates in eastern Québec.

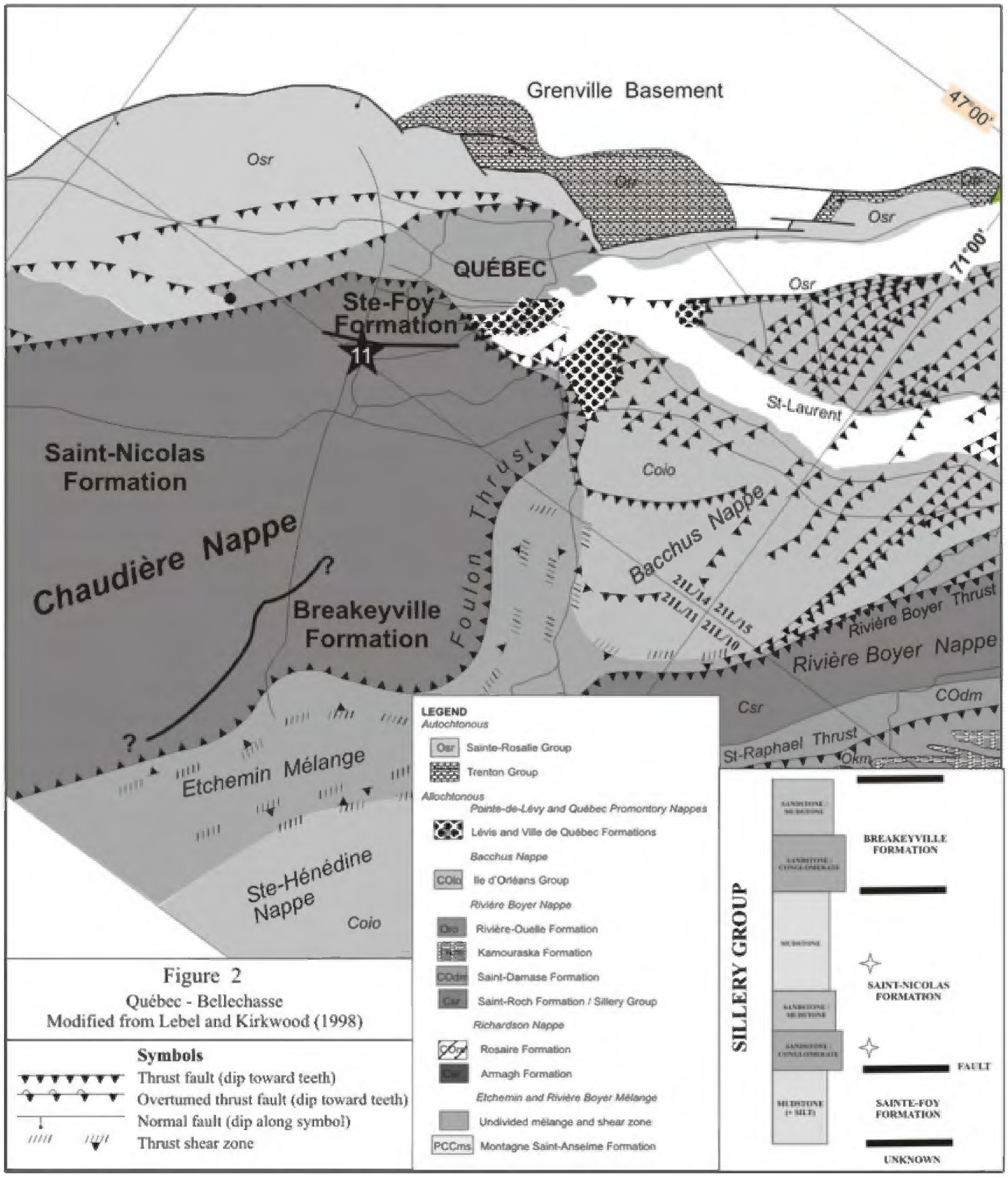

Figure 19. Simplified geological map of the Chaudière Nappe with the location of the stop. Modified from Lebel and Kirkwood (1998). The stratigraphic column locates two new ages (Early Cambrian) for the Saint-Nicolas Formation based on acritarchs.

STOP 11. Ste-Foy – Pont Laporte

At this stop, we will examine the coarse-grained facies at the base of the Saint-Nicolas Formation. This lower unit is characterized by massive beds of greenish coarse sandstones and conglomerates with subordinate red and green interbeds. The succession is cyclic (fining and thinning-upward trends) (Fig. 20a). The sandstone / conglomerate are mineralogically and texturally immature, they are rich in pink and flesh-coloured feldspars and blue quartz are locally common. Locally, small micrite clasts testify for the presence of a carbonate platform at that time. The beds are commonly graded with parallel laminations and dewatering pillar structures. Some open fractures show bitumen coatings.

In another section of that unit, the red mudstones are typified by abundant examples of the trace fossil *Oldhamia curvata* which is a key Early Cambrian element, moreover, the brachiopod *Botsfordia pretiosa* is also present in sandstone beds and also suggest an Early Cambrian age. This massive sandstone unit at the base of the Saint-Nicolas Formation is correlated with the "Green Sandstones" unit of the Saint-Roch Group and represents the slope sedimentary record of the major sea level lowstand known as the Hawke Bay Event in Western Newfoundland which, there, is recorded in the slope succession by the Irishtown Formation.

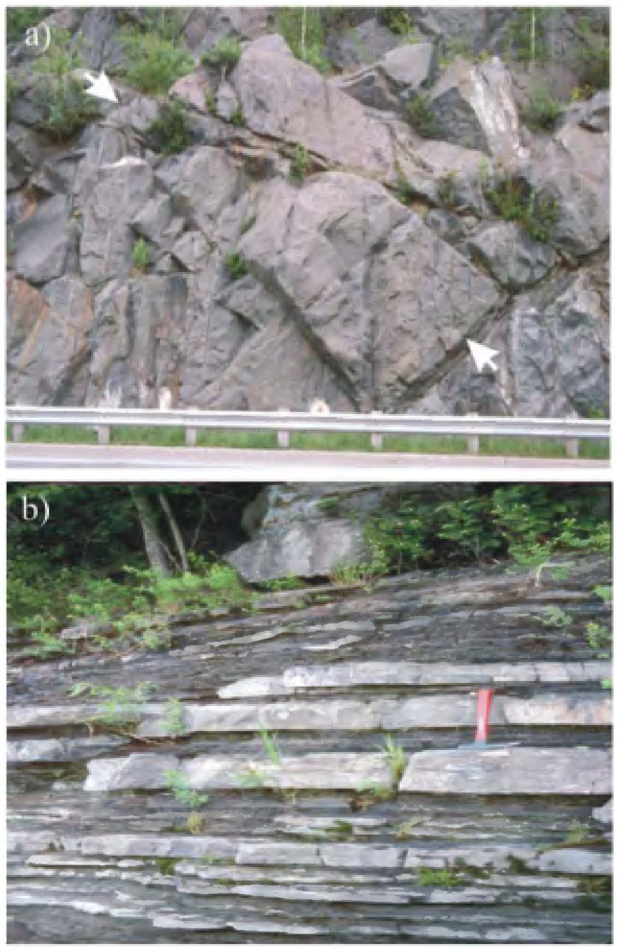

Figure 20. (a) Thick beds of immature sandstone / conglomerate at the base of the Saint-Nicolas Formation. These arkosic sandstone beds are also known as the "Green Sandstone" unit and mark the end of the rift episode. (b) Well-bedded quartzose sandstone and shale of the turbidite unit that overlies the lower massive sandstone interval. (c) Contact between the turbidite unit and the red mudstone unit at the top of the Saint-Nicolas Formation.

END OF THE FRIDAY TRIP

SATURDAY FIELD TRIP

The geology of the Québec City area is particularly rich and varied as it records more than 1,5 billion years of history of the Laurentian margin. In less than 15 km, one can visit exposures of three main geological entities, the Grenville orogen of the Canadian Shield, the St. Lawrence Lowlands or the St. Lawrence Platform and the Appalachians. The aim of this field trip is to summarize the main stratigraphic, sedimentological and structural characteristics of the Early Paleozoic shallow marine platform margin of Eastern Laurentia through visits of key outcrops located in the Québec City area. In this area, rocks of the Appalachian Humber zone lie in tectonic contact with rocks of the undeformed St. Lawrence platform (Fig. 21).

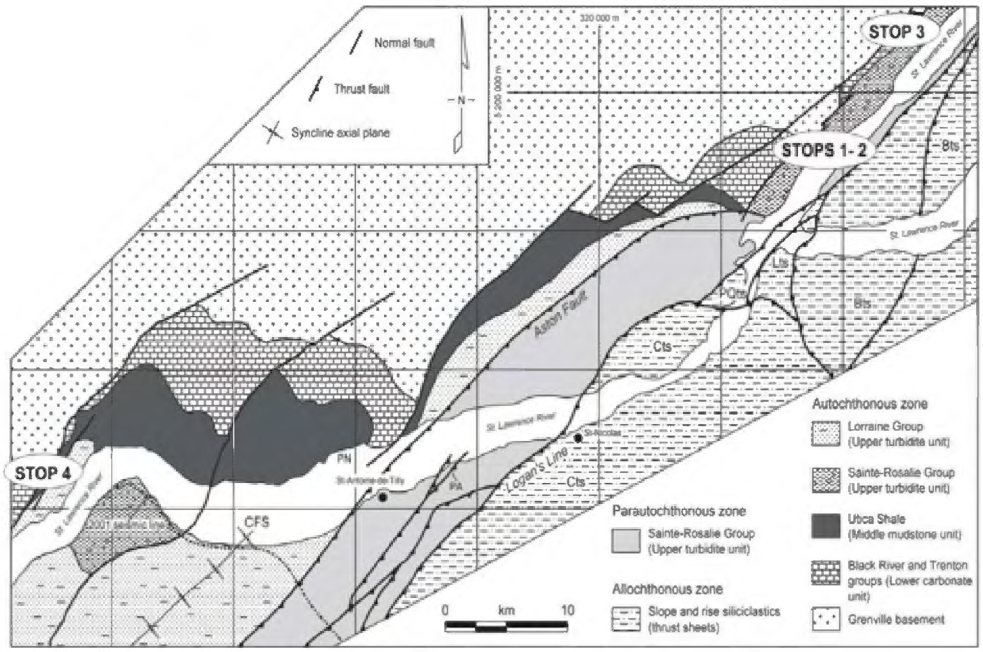

Figure 21 . Location of stops for St. Lawrence platform field trip.

THE ST. LAWRENCE PLATFORM

Geological Context

During this trip, we will visit outcrops that expose different parts of the Upper Ordovician St. Lawrence Platform. These stops will bring us to spectacular outcrops of the shallow marine platform sequence, more specifically the foreland basin carbonates of the Black River and Trenton groups.

STOP 1. Introduction to St. Lawrence Platform geology

0.0	*Departure Laval University – Geology Department – Pouliot Building*
0.0 – 6.0 km	*Highway 740 (Autoroute Robert-Bourassa, formerly Du Vallon), North*
6.0 – 17.4 km	*Highway 40 East (Autoroute Felix Leclerc), take exit 322*
17.4 – 19.1 km	*Boulevard des Chutes East to Manoir Montmorency Parking lot*

STOP 2. Montmorency Falls Park

This stop is located at the Montmorency fall, a major topographic accident that results from syn- to post-Taconian (post-Utica) extensional movement of the Montmorency fault. The upthrown block of the fault consists of Grenville gneisses unconformably overlain by Middle?-Upper Ordovician platform sediments whereas the tilted downthrown block is overlain by Upper Ordovician platform and deep marine sediments. From the parking lot, cross-back the road and descend near the river. Walk north along a trail adjacent on the east side of the river for approximately 300 metres up to a point of prominent Grenville gneisses outcrop in the river and descend to the shore.

Section starts at the southern end of the Grenville exposures. The basement consists of felsic gneiss with strong E-W mineral lineations. The Precambrian surface is very irregular and the base of the overlapping sedimentary succession is represented by a 50 cm-thick unit of buff weathering arkosic sandstone characterized by low angle cross laminations. This sandstone is glauconite-rich and its exact age is unknown. This sandstone is overlain by a 60 cm-thick fossiliferous calcirudite with sparry calcite cement (Fig. 22a). Fossils are dominated by centimetre-sized well rounded to heavily broken *Solenopora* red algae and crinoids, lithoclasts are also abundant. The calcirudite is devoid of sedimentary structures although poor preservation of allochems suggests an agitated marine environment. The calcirudite bed wedges out against the Precambrian basement and note, on the gneiss outcrop, the presence of abundant potholes and fractures filled with the calcirudite facies (Fig. 22b). Diagenetic analyses of the calcite cement indicate a complex history of marine – meteoric – marine and burial events (Ndzangou, 1997). This bed is included in the Pont-Rouge Formation. The calcirudite bed is overlain by the Deschambault Formation that consists of a 3 metre-thick coarsening-upward succession (Fig. 13a) with initial (approx. 40 cm) wavy-bedded wackestone calcilutite with thin shale partings. This first unit still wedges out on the Grenville gneiss. This first unit is overlain by a 2 metre-thick interval of thin wackestone-packstone calcarenite having abundant thin partings. This second unit transgresses over the Precambrian knoll. The uppermost unit at that locality is a 60 cm-thick interval of thickly-bedded grainstone calcarenite – calcirudite. The last three units are characterized by abundant crinoids, brachiopods, molluscs and bryozoans with the latter forming *in situ* growth thickets. The overall amount of lime mud significantly decreases upward.

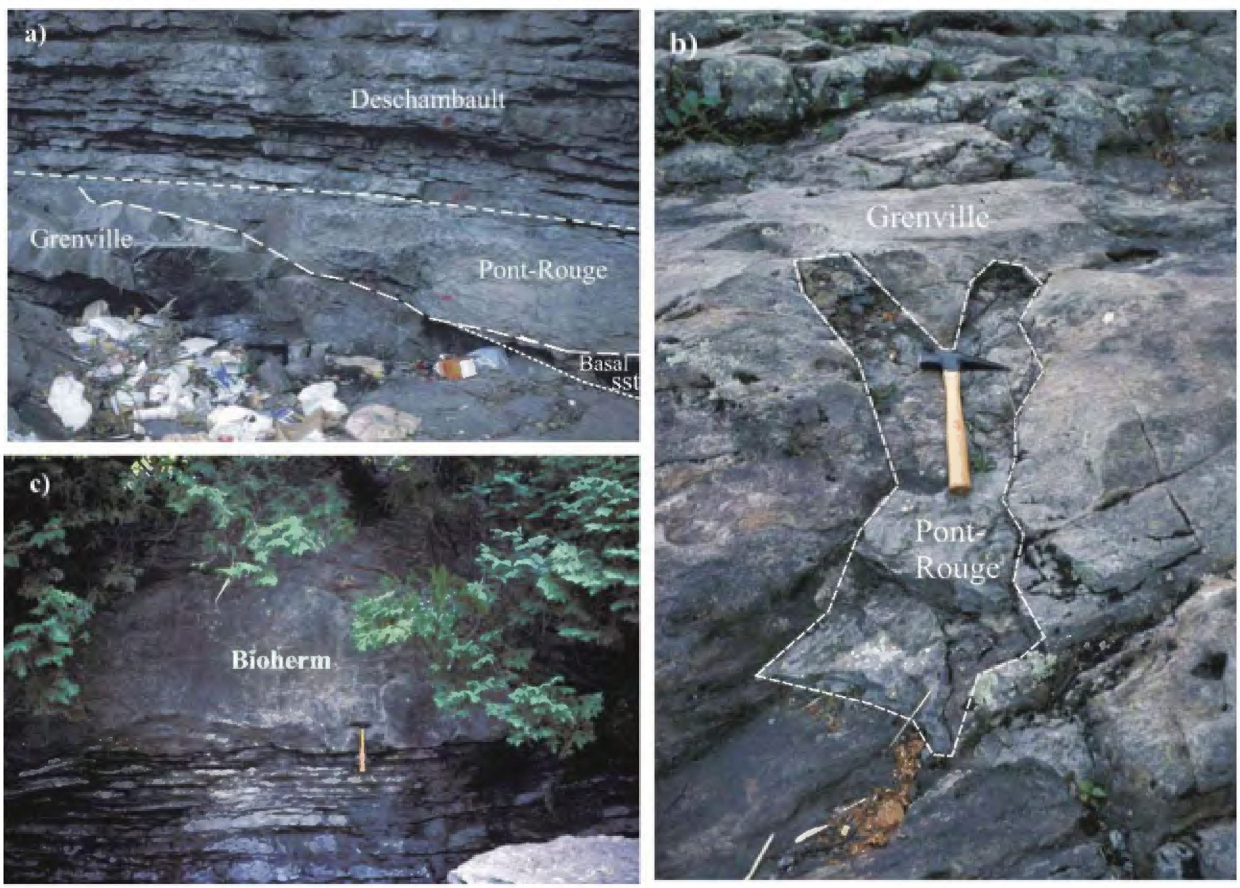

Figure 22. (a) Onlapping succession of basal sandstone (sst), Solenopora-rich calcirudite (Pont Rouge Formation) and wavy bedded limestone interval (Deschambault Formation) over the Grenville basement. (b) Pothole developed in Grenville gneiss and filled bySolenopora calcirudite. (c) Bryozoan bioherm surrounded by bryozoan and crinoid grainstone.

Higher beds can be observed at a very short distance to the north (approx. 20 m). There the section lacks the basal sandstone and *Solenopora*-rich calcirudite facies. A thinner coarsening-upward succession overlies the irregular Precambrian basement, this succession is similar to the one previously described with the exception of a thinner middle calcarenite interval. Of interest is the presence of two mound-shaped bioherms that are seen in the small cliff along the river (Fig. 22c). Note the draping of adjacent beds (bryozoan-rich packstone calcarenite – calcirudite) which suggest some small synoptic relief on the seafloor. These mounds consist predominantly of lime mud with a relatively abundant (approx 35%) well-preserved bryozoan fauna. Accessory fauna is given by crinoids, molluscs and few brachiopods. Polished slabs of the unit reveal the presence of pelletoidal crusts (cryptomicrobial?) locally surrounding and connecting the bryozoans therefore providing a bind for the structure (Ndzangou, 1997). Burrows are locally present; they are filled by burial calcite cement (Ndzangou, 1997).

Go back to the parking lot along the trail. Walk to the stairs that bring you down to the lower level at the toe of the fall. While descending, you will see grey and greenish siltstone and mudstone with fine sandstone laminae of the Upper Ordovician Lotbinière Formation (Belt and Bussières, 1981). This flysch unit belongs to the Sainte-Rosalie Group. Flysch sedimentation records the rapid foundering of the carbonate platform as the continental margin was collapsing as the result of westward migration of the Taconian allochthons, this deepening-upward trend occurred at a time of global glacio-eustatic sea level lowering.

At the base of the stairs, walk towards the fall (and be ready to get splashed), at a small observatory facility, to your right, you will see in a gully, the contact between the upper part of the platform succession (Neuville Formation, upper beds of the Trenton Group) and the overlying black shale of the Upper Ordovician Utica Group which underlies the Lotbinière Formation. Both the uppermost beds of the Trenton Group (lime mudstone calcilutite) and the shale of the Utica have high TOC content (between 1% and 3%, Bertrand, 1991) and can be considered as good hydrocarbon source rock, in particular for the black shale with high Hydrogen Index (150-250) and low Oxygen Index (OI of 15-30). The Utica shale is the assumed hydrocarbon source rock in the current round of exploration in southern Quebec, it has been recognized as the source rock for the Saint-Flavien gas field (50 km south of Quebec City; Bertrand et al., 2003) and its potential as a shale gas play is currently under evaluation.

STOP 3. Château Richer

0.0 km	*Departure from parking lot at the base of the fall*
0.0 – 4.2 km	*Highway 40 East, towards Mont Ste-Anne, exit at Church entrance at Château Richer*
4.2 – 4.8 km	*At stop, turn left on Avenue Royale, turn right at Rue du Couvent*
4.8 – 5.0 km	*Entrance of the Château Richer Municipal machinery parking lot*

Outcrops at this stop expose the upper part of the platform succession (Neuville Formation, upper beds of the Trenton Group). Rocks of the Neuville Formation consist of beds of lime mudstone calcilutite. Although the Château Richer area is located in the autochthonous zone of the Appalachians where the rocks are thought to be horizontally lying and undeformed, the exposures show imbrications and numerous faults. Fault planes are mostly subparallel to bedding planes although some are at higher angles to the bedding planes (Fig. 23). Fault surfaces display by both normal and reverse slickenlines. The geometry of the fault surfaces, fault rocks and relative chronology of slickenlines indicate that high-angle normal faults were reactivated by thrusting during the Taconian compressive event.

Figure 23. Structural features in the Neuville limestones, Château Richer municipal garage. (a) Reactivated normal fault. (b) Bedding parallel thrust fault cutting up section along a pre-existing normal fault plane. (c) Bedding parallel thrust fault. (d) Structural imbrications above a bedding-parallel thrust fault.

LUNCH

STOP 4. St-Alban – Rivière Sainte-Anne

0.0 km	*Take Highway 40 West, towards Quebec City – Montréal*
0.0 – 34.8 km	*Take exit 139-O, highway 40 for Montréal*
34.8 – 91. 1km	*Take exit #254 – Grondines – Saint Marc des Carrières*
91.1 – 97. 5km	*Highway363 North, at the northern end of Saint Marc des Carrières village, take right towards St. Alban*
97.5 – 97.6 km	*Take left at first stop*
97.6 – 100.8 km	*Just before the bridge, take entrance at left*
100.8 – 101 km	*Parking lot*

This stop is particularly significant for the superb exposure (water permitting) of the contact between the Black River and Trenton groups. From the parking space, cross the river using the panoramic bridge and follow the NE path along the escarpment for roughly 250 metres. Close to the main highway, there is a stair that brings you down to the continuous river outcrop. Be careful, water current is strong all year long. Walk back towards the SW to the lowest rock ledge (Fig. 24a). There the river makes a major west break and it is impossible to go beyond that point.

The lowest rock ledge consists of more or less dolomitic calcarenite and calcilutite with either a wackestone to grainstone texture with abundant shale seams and stylolites (Fig. 24a). These are the uppermost beds of the Black River Group (Leray Formation). The overlying beds consists of various limestone facies of the Trenton Group, with first a circa 3 metre-thick succession assigned to the Sainte-Anne Formation (= the Pont Rouge Formation of the Montmorency stop). The lowermost bed of the Sainte-Anne Formation consists of a 15 to 20 cm-thick sandy intraclastic grainstone bed that comprises various clasts of the underlying Black River beds (Fig. 24b). Over that lower bed, wackestone to grainstone bioclastic calcarenite dominates the rest of the Sainte-Anne Formation. The 13 metre-thick Deschambault Formation consists of bryozoan-rich packstone to grainstone calcarenite with locally large cross-stratifications. *Solenopora* red algae which is common in the Sainte-Anne Formation is absent in the Deschambault beds, the latter being commonly thickly-bedded and dominated by bryozoan and crinoids (Fig. 24d).

The contact between the Black River and the Trenton groups is nicely exposed and corresponds to a major sequence boundary from a major sea level lowstand. The uppermost Black River dolomitic carbonates are extensively weathered over a 30-50 cm-thick zone immediately below the irregular contact with the coarse-grained and quartz-rich calcarenite that forms a basal lag at the base of the Sainte-Anne Formation (Fig. 24b). This intensively altered zone is also characterized by multiple small fractures filled by geopetal sediments that are connected to an ancient sub-aerial exposure surface (Fig. 24c). Other evidence for subaerial exposure of the top Black River Group include: rillenkarrens, collapse-breccias, irregular topography of the upper surface and small solution-enlarged karst pits filled with laminated geopetal sediments. It is noteworthy that reported evidence of sub-aerial exposure at the contact between the Black River and the Trenton groups are rare in southern Quebec although this contact for time-correlative units in eastern USA is considered to represent a major sequences boundary (Holland, 1993; Patzkowsky and Holland, 1993).

Figure 24. (a) Lowest rock ledge on the Sainte-Anne River, looking north. The beds consist of the carbonates of the Black River Group. (b) Contact between the Black River and the Trenton groups. The hammer rests on the topmost Black River, note the intense alteration zone. (c) Laminated sediments filling in a cavity network connected to the exposed surface. (d) Thick grainstone beds of the Deschambault Formation at the Neuville quarry (20 km to the northwest).

At this locality, we can also appreciate a critical faunal change between the Black River and the Trenton groups. The upper beds of the Black River Group are characterized by the presence of large stromatoporoids and corals that are nicely exposed on bedding planes. Up to 15 species of Codiaceans and Dasycladaceans green algae have been reported from this locality (Guilbeault and Mamet, 1976). Moreover, even if not a faunal element, small beds of oolitic grainstone are present in the upper beds of the Black River Group. All these elements (fauna and particles) are common and characteristic of tropical warm-water carbonate environments, not surprisingly given the low paleosouthern setting of that part of Laurentia in early Late Ordovician (Scotese and McKerrow, 1991). A drastic turnover occurs within the Sainte-Anne Formation where all corals, stromatoporoids and green algae disappear to be replaced by a dominant red algae, bryozoan and crinoid faunal assemblage. Not a single oolite can be found in the shallow and agitated marine facies of the Sainte-Anne and Deschambault formations, Moreover, major elemental analysis of the carbonates has revealed a major increase of P_2O_5 content at that contact, with the Trenton facies showing up to 10 times the level of P_2O_5 compared to the immediately underlying Black River facies (0.03% vs 0.3% for the Black River and Trenton, respectively; Lavoie and Asselin, 1998). All these elements were used by Lavoie (1995) and Lavoie and Asselin (1998) to propose that in early Late Ordovician, upwellings of deep-marine nutrient-rich cool to cold waters were recorded along the paleo-southeastern seaboard of Laurentia and resulted in the faunal and particle turnovers.

END OF THE SATURDAY TRIP

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THE LAC PICHÉ ANORTHOSITE

by

Tomas Feininger, Département de Géologie et de Génie géologique,
Université Laval, Québec, QC G1K 7P4, Canada
Robert Dymek, Department of Earth and Planetary Sciences,
Washington University, St. Louis, MO 63130, U.S.A.

INTRODUCTION

The Lac Piché Anorthosite is the newest member of the "CRUML belt." CRUML is an acronym (<u>C</u>hâteau-<u>R</u>icher, St-<u>U</u>rbain, <u>M</u>attawa, <u>L</u>abrieville) for a group of distinctive andesine-bearing anorthosite bodies that are arranged almost linearly over a distance of 250 km northward from the outskirts of Québec City (Dymek et al., 2001; see also a general discussion on anorthosites by Ashwal, 1992). The Lac Piché Anorthosite and its encasing rocks have been mapped, and a great deal of petrochemical, geophysical, and geochronological data have been acquired. The field trip, to be held on Friday, 5 October, 2007, will be limited to 18 participants (the capacity of the two vans rented for the occasion; the roads are not suitable for the family sedan). Departure will be from the parking lot at Pavillon Pouliot, Université Laval, at 7:00 a.m. sharp. Lunches and a **detailed guidebook** will be provided. The vans will be back at the starting point before 6:00 p.m.

FIELD TRIP STOPS

The field trip consists of eleven stops (Fig. 1; if the trip runs behind schedule, Stop 6 will be omitted). Lunch, at the spectacular Chutes (falls) de la Rivière Noire, will follow Stop 5 and will be under a roof (in case of snow). With the exception of Stop 1, the trip will be within the boundaries of the Forêt expérimentale Montmorency. The circuit within the Forêt, on poor to atrocious unpaved roads, is 52 km, with a driving time of a little under two hours. Taking out an hour for lunch, this leave just over half an hour per stop. Some stops will be shorter, but we hope that others will generate lively discussion and be longer than the allotted average.

STOP 1. A hilltop (elev. ~965 m) at a Hydro-Québec communications tower is sited on fresh and recently dated mangerite. An excellent sampling site. From this stop, participants will have a fine overview (if weather allows) of the topographic setting of the Lac Piché Anorthosite.

STOP 2. The "Discovery Outcrop" of the Lac Piché Anorthosite. The sole roadcut exposure of the field trip.

STOP 3. Fresh Lac Piché Anorthosite with many interesting features well exposed. A fine site for sampling pristine andesine anorthosite.

STOP 4. "Tiger-striped norite" and labradorite anorthosite at the roof of the Lac Piché Anorthosite.

STOP 5. Leuconorite and oagnite (in what resembles an Inca fortress) overlying the anorthosite. OAGN is an acronym for **o**xide-**a**patite **g**abbro**n**orite.

STOP 6. Mangerite in a vast exposure flush with the ground surface.

STOP 7. Two varieties of mangerite and their consanguinous (?) relationship.

STOP 8. Oagnite, fresh, and the more typical rotted rock.

STOP 9. Late granite, chemically distinct from the mangerite and not related to the anorthosite.

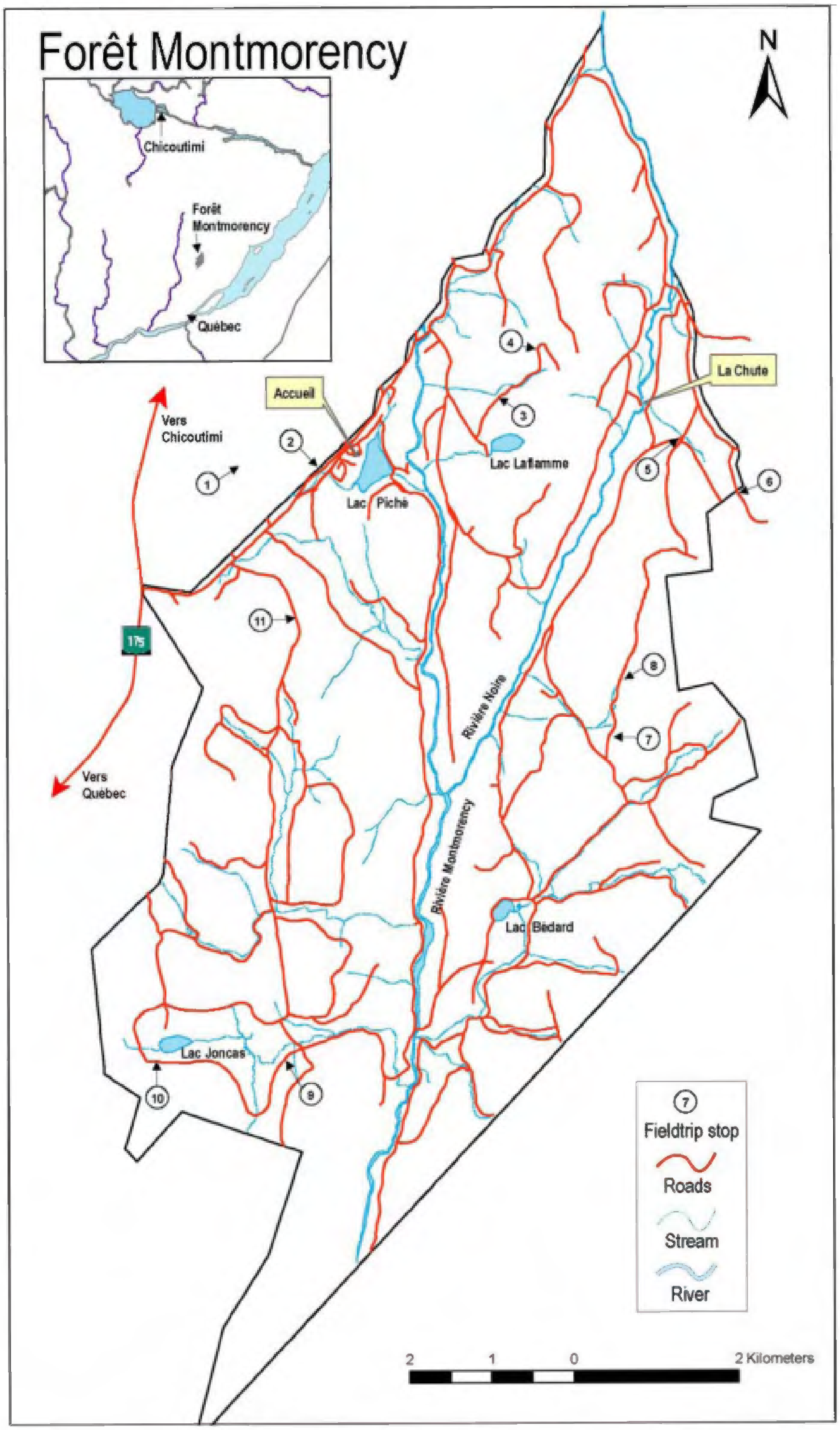

Figure 1. Stop location map, Forêt expérimentale Montmorency

STOP 10. Gabbro; along with the late granite, one of the four units in the Forêt unrelated to the anorthosite. The others, not seen on this field trip, are "featureless gneiss", and fine-grained gneisses and granofels (metavolcanic rocks?).

STOP 11. Jotunite (hypersthene-bearing monzodiorite), which in many places in the Forêt lies between the anorthosite and mangerite—a relationship commonly seen elsewhere in the CRUML belt. This stop is at a belvedere (lookout) which affords a fine view of the entire extent of the Lac Piché Anorthosite as well as Lac Piché itself (again, weather permitting).

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LATE PLEISTOCENE GLACIATION AND DEGLACIATION IN THE BEAUCE AREA, FROM SAINT-GEORGES TO VALLÉE-JONCTION

by

William W. Shilts, Illinois State Geological Survey, Champaign, IL 61820, U.S.A.
Olivier Caron and Michel Lamothe, Département des sciences de la Terre et de l'atmosphère,
Université du Québec à Montréal, Montréal, QC H3C 3P8, Canada

INTRODUCTION

Because the Quaternary geology of Eastern Québec is unique in several aspects, including the impressive thickness of Late Pleistocene sediments, with their complex stratigraphy and deglaciation history, it might prove difficult to get enough of an overview in a one-day field trip. However, the selected four stops should provide for some interesting discussions on the timing and the styles of the regional glaciations (Fig. 1). The Pleistocene stratigraphy of the Eastern Townships–Beauce area is characterized by a three till sequence, each till being underlain and overlain by glaciolacustrine sediments deposited in ice-dammed lakes during the advance or retreat phases of each glaciation. PreHolocene nonglacial sediments of the last two interglacials have been found at Rivière Grande-Coulée (MIS 7, Balescu et al., 2001), and Rivière des Plante (Massawippi, MIS5e, this field trip). The area we will visit also has a rich and puzzling lateglacial history, some elements of which will be discussed in the course of this field trip.

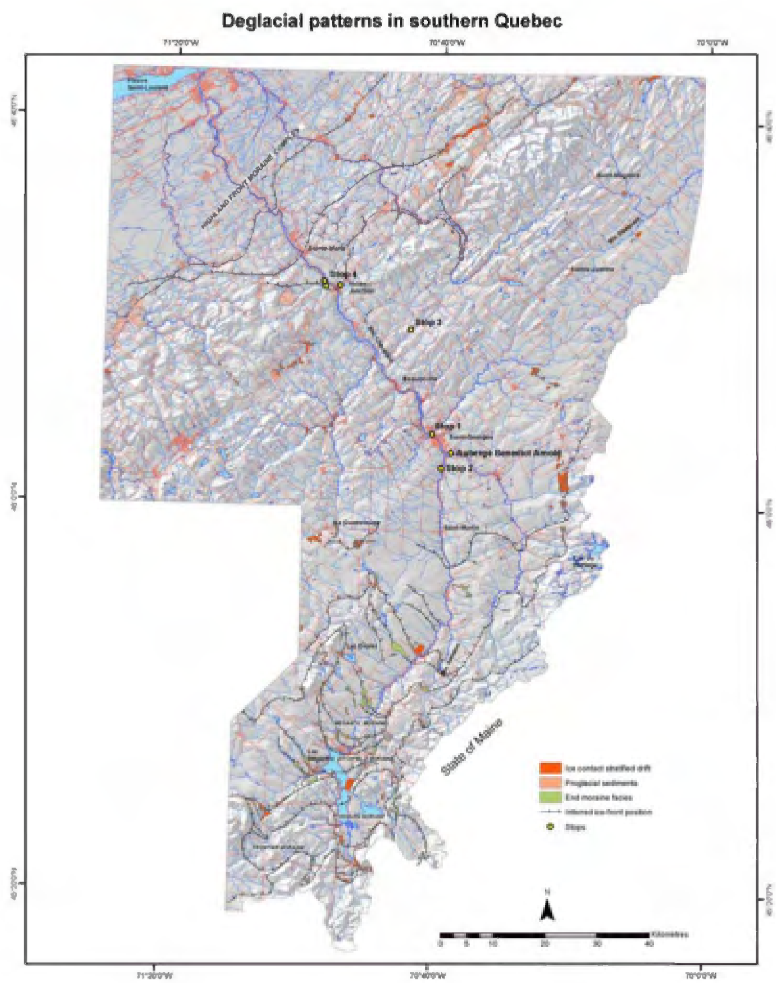


Figure 1. Regional deglaciation features in the Chaudière Valley and location of the field trip stops (from Gadd et al., 1972).

THE QUATERNARY STRATIGRAPHIC FRAMEWORK IN THE APPALACHIANS OF SOUTHERN QUEBEC

The regional stratigraphic framework records three advances of the Laurentide Ice Sheet across the southeastern Quebec Appalachians and into northern New England (McDonald, 1967; Shilts, 1970; McDonald and Shilts, 1971). These glacial episodes are represented, from oldest to youngest, by the Johnville, Chaudière, and Lennoxville tills (Fig. 2). The description of the regional lithostratigraphy is modified herein from the synthesis of Lamothe et al. (1992).

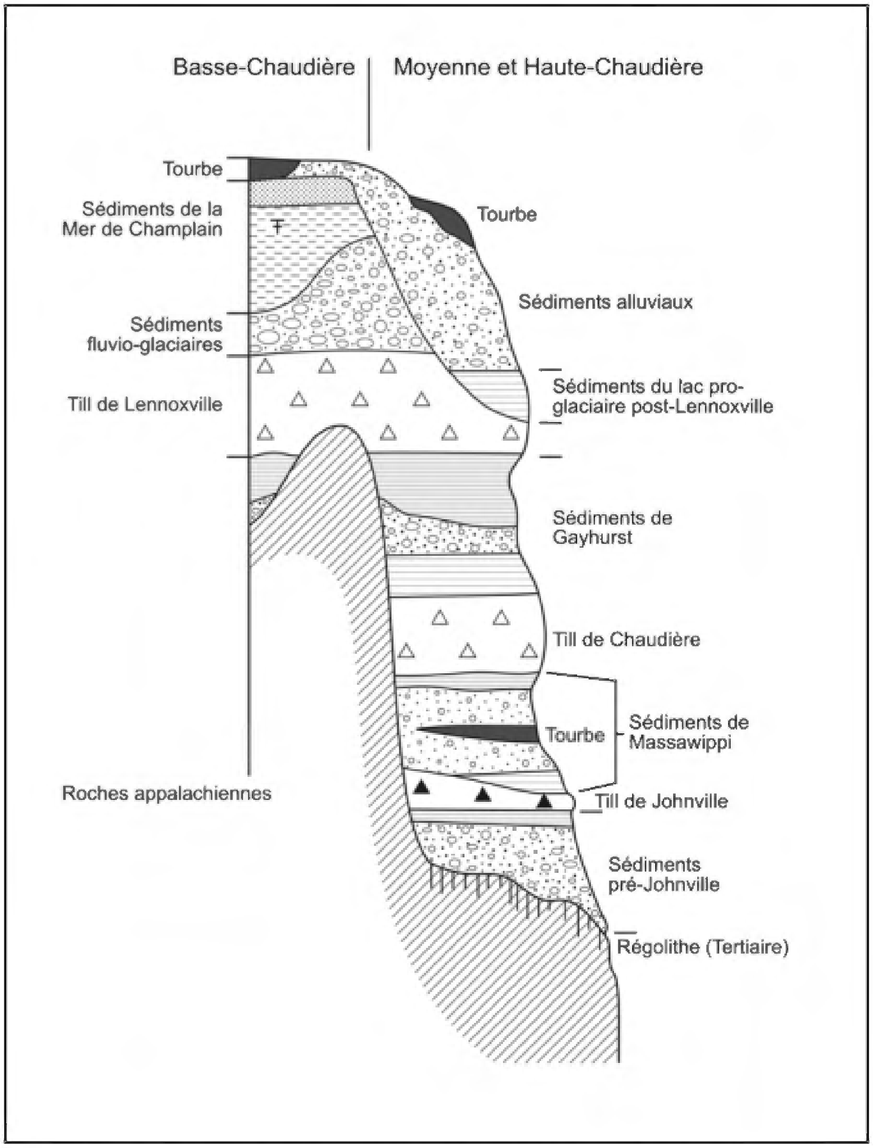


Figure 2. Quaternary lithostratigraphic framework for the Chaudière River Basin, modified from McDonald and Shilts (1971) and Shilts (1981). The elevated portion of the bedrock is a schematic representation of the Notre-Dame Mountain Anticlinorium as it marks the approximate limit between the St. Lawrence Lowlands to the West and the Appalachians to the East. A simplified stratigraphic scheme is shown for the Lower Chaudière Valley.

Pre-Johnville fluvial sediments near the base of a section on Rivière Grande Coulée have very rare crystalline pebbles that are thought to be derived from the Precambrian Shield, over 100 km down drainage from the section. If it can be established beyond a doubt that these pebbles are truly Precambrian in age, they would represent a glaciation older than the presumed Illinoian- age Johnville Glaciation, because they are stratigraphically beneath the Johnville Till and Sangamon-age Massawippi Formation in this section, and there is no process other than glaciation that could have transported them to this location. These fluvial sediments have been dated at 189 ± 20 ka by Balescu et al. (2001) using luminescence.

Fabric measurements and the occurrence of Precambrian erratics in the overlying Johnville Till demonstrate that this till is a product of Laurentide ice. Following deposition of the Johnville Till, free drainage conditions toward the St. Lawrence River were established in the region. This event is recorded by the nonglacial fluvial sediment facies of the Massawippi Formation. Pollen spectra from lacustrine facies in this unit indicate the presence of a boreal forest in the region during the later time of deposition of the Massawippi Formation (McDonald and Shilts, 1971). Radiocarbon ages obtained from disseminated organic debris concentrated from lacustrine sediments of the Massawippi Formation throughout the Appalachian region of Quebec are beyond the limit of the method. The most complete facies record of the Massawippi Formation yet known from the Appalachians is exposed at several sections along the Rivière des Plante that will be visited in the course of this field trip.

The Chaudière glaciation which follows the Massawippi interglacial interval is recognized as a complex event. During its early phase, referred to as the ''Maritime Ice Cap'' phase by Shilts (1981), local ice advanced from the east or northeast and deposited the lower portions of the Chaudière Till. In many exposures of the Chaudière Till, this lower till grades imperceptibly upward into a till with characteristics (fabric, composition) of tills deposited by Laurentide ice that flowed southward off the Canadian Shield. It is thought that this transition marks the displacement of 'Appalachian'' ice by Laurentide ice (McDonald and Shilts, 1971) or far less likely, a complex history of shifting ice-flow directions within an Appalachian-based ice cap (Parent, 1987). Directional and compositional data collected from the Chaudière Till at the Rivière des Plante and Ascot River sections, as well as observations made at surface localities are taken as evidence that, at the onset of the Chaudière glacial phase, an independent ice cap developed in the northeastern Appalachians, in Maine and/or New Brunswick. Evidence for southwestward ice flow some time prior to the subsequent (Lennoxville) ice advance comes also from the presence, at the surface, of Devonian granite erratics displaced southwest of their known outcrop (McDonald, 1967; McDonald and Shilts, 1971). They occur as scattered surface boulders at a number of localities outside of prominent late Wisconsinan southeast-trending Lennoxville dispersal trains, documented by Shilts (1973), Shilts and Smith (1989), and Parent (1987).

The end of the Chaudière glaciation was marked by a short-lived retreat of Appalachian and Laurentide ice to the Appalachian front. Glacier ice in the St. Lawrence Valley impounded glaciolacustrine waters in the northward-flowing Chaudière and St. François valleys, resulting in deposition of locally thick glaciolacustrine and deltaic sediments of the Gayhurst Formation. Only a rather unsatisfactory radiocarbon age of >20,000 yr B.P. (GSC-1137; McDonald and Shilts, 1971) has been obtained thus far from disseminated organic debris in the generally unfossiliferous sediments of the Gayhurst Formation, which is thought to be Middle Wisconsinan in age.

The last major advance of Laurentide ice resulted in deposition of the Lennoxville Till, the surface till of the region. The dominant ice flow direction during the Late Wisconsinan was towards southeast, as the ice margin reached Long Island, New York and the coast of New England. Dispersal trains are evidence that it is this phase of ice flow that is at the source of most of the glacial transport in the surface till (Shilts, 1981). The retreat of Lennoxville glacier was from south to north in the Chaudière Valley up to St.-Georges, and several lobate ice margin positions have been documented for retreat (Fig. 1). Down valley from St. Georges-de-Beauce, the late glacial erosional record becomes increasingly complex. Indeed, a spectacular reversal of ice flow is deduced from hundreds of striated outcrop where northward striae are cross-cutting the Late Wisconsinan SE flow, this resulting from the formation of the Quebec Ice Divide, an east-northeast-trending feature that extends eastward into the state of Maine, where it is called the North Maine Ice Divide. Not much glacial transport towards the north seems to have taken place, as late glacial, northward moving ice was already loaded by dispersal trains that had been formed earlier.

This Quaternary stratigraphic framework has been developed through several decades of extensive field work, including geophysics and geochemistry programs as well as systematic drilling and trenching by the researchers of the Geological Survey of Canada. An account of how this stratigraphy came into existence is found below, as a personal contribution by the senior leader of the field trip. Recently, a new phase of field and laboratory investigations has been initiated. Indeed, the Ministère de l'Environnement et du Développement Durable du Québec is funding a major hydrogeological program covering the entire Chaudière Valley drainage basin. Among other information to be produced is a drift thickness map (Fig. 3) which is the basis for a 3 D model. This is the subject of a PhD thesis by Olivier Caron from Université du Québec à Montréal. Also, over the last years, Michel Lamothe and Sanda Balescu, both from the UQAM Lux laboratory, have carried out a luminescence dating program aimed at assessing an absolute chronology for the stratigraphic framework. Sediments from Rivière Grande Coulée, Rivière des Plante, and the type section exposures of the Gayhurst Formation, as well as samples from the late glacial ice-dammed lacustrine beach sediments are being analysed. Some of these results will be reported and discussed at the field trip.

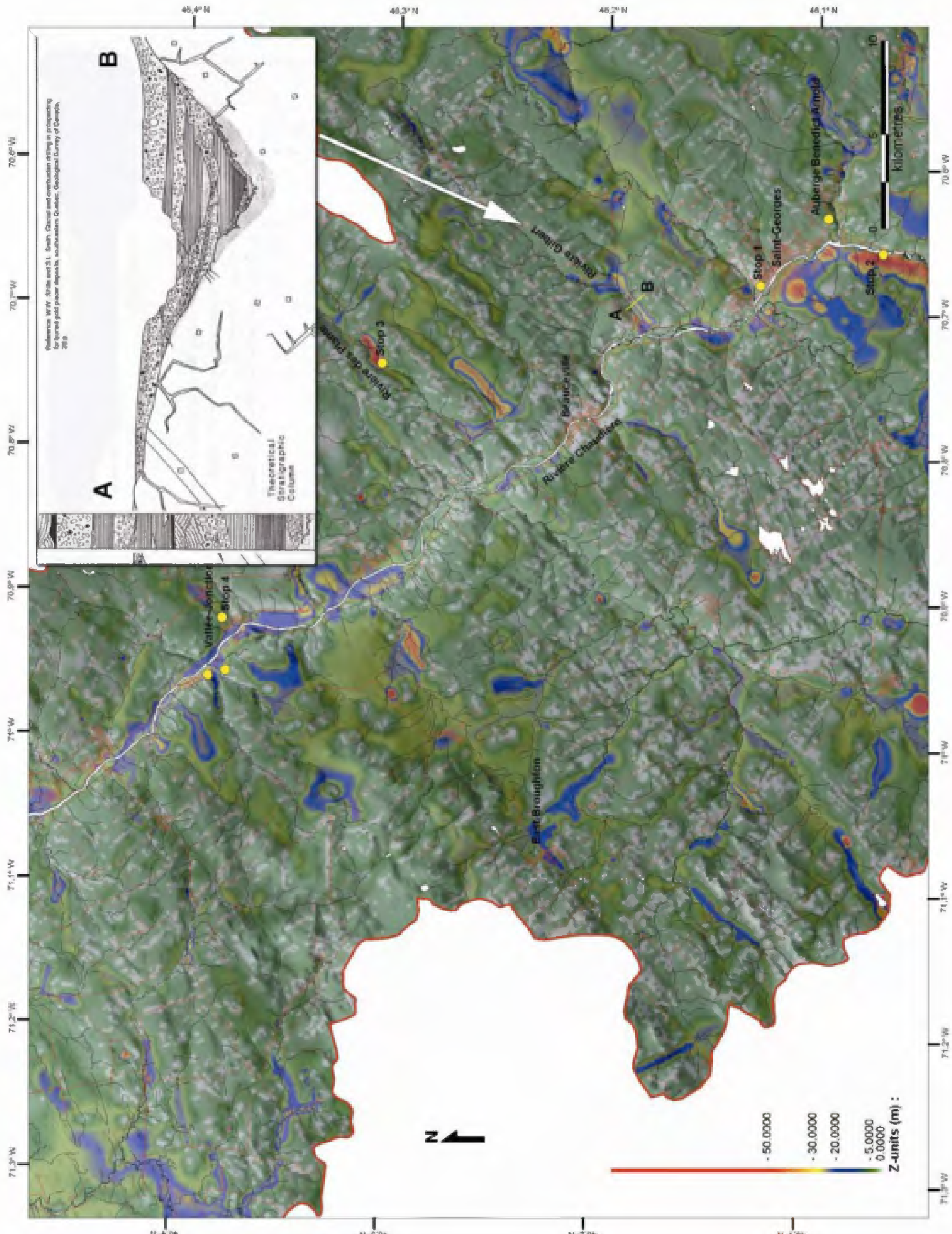


Figure 3. Drift thickness map for the Middle and Lower Chaudière Valley. In several NE-SW trending secondary valleys, drift may exceed 50 m. The Rivière Gilbert section is shown in the inset, from Shilts and Smith (1988).

A SHORT HISTORY OF THE DEVELOPMENT OF GLACIAL STRATIGRAPHIC MODELS IN THE QUEBEC APPALACHIANS: A PERSONAL PERSPECTIVE - 1964-1994

Contribution by W. W. Shilts
Illinois State Geological Survey

As a glacial geologist with a research career spanning much of the time between the development of the first modern Quaternary stratigraphic models for the Quebec Appalachians to those available in present literature, I have a personal perspective on the historical development of Pleistocene stratigraphy in the northern Appalachians. Before working in Quebec, I worked in Vermont on mapping and stratigraphic research, and for that reason feel that I can shed some light on historical linkages among ideas developed on both sides of the international border – ideas that have been freely transferred back and forth for almost four decades. This account is not complete. It reflects my work primarily and that of my close colleagues and contemporaries. Much recent work by Bouchard, Gauthier, Lamothe, LaSalle, Ochietti, Parent, and their students and colleagues is not discussed here because it does not materially alter the general picture I am presenting in this account. Parent's 1987 thesis and papers based on it should be reviewed by interested readers, however, as they present a model of ice flow history that is in many ways at odds with that presented here, particularly with respect to interpretation of the Highland Front Moraine complex and the significance of the westward-trending striae in the upper St. François River valley. Likewise, I have not discussed the detailed erosional stratigraphic work of Genes, Kite, Lowell, and Newman in northwestern Maine, which, particularly in the 1980s, produced a picture of late-glacial ice flow history which is complimentary to the sequences developed in Quebec in the '70's.

The 1950s and 1960s: the first modern stratigraphic models and the search for Appalachian Ice Caps

In the 1950s, Nelson Gadd (Gadd, 1955) and Paul Karrow (Karrow, 1957), among a few others, carried out systematic mapping and stratigraphic studies of the central St. Lawrence lowlands of Quebec and of the Appalachians to the south (Gadd, 1955, 1971). Gadd concluded that there had been at least two major glacial phases in the St. Lawrence lowlands, deposits of which are separated by nonglacial organic beds and peat older than the limit of radiocarbon dating, i.e. >52,000 years B.P. He named the till of the youngest event, which he considered to be 'classical' Wisconsin in age, the Gentilly Till, and he named the till deposited during the older phase Bécancour Till; the fluvial, lacustrine, and organic beds separating the two tills were referred to collectively as the St. Pierre beds. The original simple stratigraphy described by Gadd and Karrow in their University of Illinois Ph.D. theses on the Quaternary history of the St Lawrence Lowlands set the stage for development of the complex stratigraphic framework and glacial history that are recognized today in the Quebec Appalachians. In the early 1960s, D. P. Stewart and Paul MacClintock were involved in an ongoing project of the Vermont Geological Survey to map the glacial deposits of the state at a scale of 1:62,500, compiled at 1:250,000, and to provide a Quaternary stratigraphic framework for the state. This work is best represented by two important publications, one describing a stratigraphic model for northern Vermont (Stewart and MacClintock, 1964) and one integrating mapping and stratigraphic studies in one comprehensive volume, accompanied by a map (Stewart and MacClintock, 1969).

During the latter stages of Stewart and MacClintock's work, the Geological Survey of Canada (GSC) initiated a similar project in the Sherbrooke area, just north of the Vermont border. On both sides of the border, numerous natural and artificial sections exposing deposits representing several glacial/nonglacial cycles provided an opportunity to begin to construct a Quaternary stratigraphic framework for the northern Appalachians, based on interpretations of depositional environments of various sediment facies exposed. In 1964, R. E. Behling (Behling, 1965) carried out a detailed study of a series of well-exposed sections along Stannard Brook in northern Vermont, adding interpretive detail to the general stratigraphic framework published that year by Stewart and MacClintock (1964).

The summer of 1964 also marked the beginning of the GSC Sherbrooke project, assigned to B. C. McDonald, a Canadian Ph.D. student of R. F. Flint at Yale University. Because of Flint's long-standing interest in the possibility of the existence of and expansion of late-glacial ice caps located in the northern highlands of New England (Flint, 1951), McDonald's thesis was primarily designed to seek out and document evidence of northward flow from the hypothetical New England ice caps into southern Quebec. Flint's (and McDonald's) interest was in part driven by brief, sketchy reports of northward trending striae and northward dispersal of erratics in the area west of Sherbrooke and in the vicinity of Thetford Mines, Quebec (Clark, 1937; Cooke, 1937). Also, Robert Chalmers, in the 1890s, had recorded widespread, northward-trending striae in the Chaudière River valley, east of Sherbrooke (Chalmers, 1898). Thus, McDonald expended considerable effort in analyzing directions of striae, fabric of till, and dispersal patterns of distinctive erratics, eventually producing a thesis that at the time was a North American model for the integration of diverse quantitative data for determining ice flow history and correlating stratigraphic units (McDonald, 1967).

In the summer of 1964, McDonald, having discovered several multiple till sections along Ascot River and in several other places near Sherbrooke, visited Stewart and MacClintock in the field in northern Vermont to review their key sections and to evaluate the criteria on which they based their stratigraphic interpretations. Briefly, Stewart and MacClintock had concluded that deposits of four glaciations were preserved in sections in northern Vermont. Their chief tool for stratigraphic correlation was till fabric, and neither buried soils nor datable organic material had been found to place the glacial deposits within a temporal framework. They found that a widespread till sheet, lying beneath a surface till and generally separated from it by glaciolacustrine sediments in northern Vermont, had a fabric trending NE-SW, in contrast to the tills above and below it, which had fabric trending consistently NW-SE, parallel to the regional direction of striations and consistent with the trends of major dispersal trains in northern New England (Flint, 1957). Stewart and MacClintock had named the surface unit with NW-SE fabric 'Burlington Till' and the next lower unit 'Shelburne Till,' with its characteristic NE-SW fabric.

McDonald, primed by the work he observed on his brief visit to Vermont, returned to the Sherbrooke area and began a detailed fabric study of his best-exposed, multiple-till sections along Ascot River. He noted the same sequence of flow directions in successive till sheets as had Stewart and MacClintock and discovered, in addition, organic-rich, nonglacial (glaciolacustrine) beds beneath a thick subsurface till with the predominantly NE-SW fabric at its base. Though adopting till fabric as his primary correlation tool, McDonald made careful observations of the distribution of distinctive provenance indicators, both within tills and among surface erratics. He was able to show that, in addition to strongly developed SE-trending dispersal trains of ultramafic, granodioritic, and syenitic erratics, these erratics were also displaced as far as tens of kilometers southwest of their source outcrops. The southwestward dispersal patterns were severely attenuated by reworking during later southeastward flow of the last glaciation. At no place in the Sherbrooke map area did McDonald find any indication of the hypothetical northward flow. By the time he finished his thesis in 1967, McDonald had concluded, on the basis of what was and still must be regarded as unequivocal evidence, that glaciers had not flowed into Quebec from Vermont in late glacial time.

Flint had originally wanted McDonald to map in the Lac Megantic area, Quebec, because of its proximity to the highest parts of the White Mountains of New Hampshire and Maine, where well-developed cirques marked the former presence of mountain glaciers. Because of the political priorities of the day, the original map area had been extended westward to the more densely populated Sherbrooke area by the GSC, who was funding the project. It was planned that McDonald would begin mapping in the Sherbrooke area, using those results for his Ph.D., and would then move eastward along the international boundary to the western border of Maine, always looking for evidence of northward ice flow into Quebec. In 1966, his thesis research completed, McDonald began mapping eastward into the Rivière Eaton drainage basin in the vicinity of La Patrie, Quebec. This mapping project was in support of a hydrogeological research project being carried out by the Quebec provincial government as a part of their research contribution to the International Hydrological Decade (1965-1975). In the course of this mapping, McDonald and his students made detailed observations of numerous multiple till sections discovered along the Eaton River and its tributaries (McDonald, 1969). He also recorded abundant striation and dispersal evidence of southward to southeastward flow of the last ice sheet, southwestward flow of the ice sheet preceding the last, but no evidence at all of northward flow from the White Mountains, which form the southern border of the Eaton River map area.

When McDonald was assigned to play a significant role in "Operation Winisk," the 1967 GSC multidisciplinary project to map and work out Precambrian, Phanerozoic, and Pleistocene stratigraphy of the Hudson Bay Lowlands, the southeastern Quebec project area was turned over to the author to finish mapping the eastern part of the original map. This mapping of the upper Chaudière River valley was to serve as the basis for a Ph.D. dissertation at Syracuse University (Shilts, 1970). Like McDonald, I carefully searched the international border regions for any signs of northward flowing ice and systematically recorded and collected data on the numerous stratigraphic sections that were exposed along the Chaudière River and its tributaries. Using techniques learned from McDonald and during two summers (1964, 1966) mapping for the Vermont Geological Survey, I documented major ice flow directions and confirmed the presence of the same general depositional stratigraphy that had been described earlier by McDonald, MacClintock, and Stewart. As in the Sherbrooke area, no evidence was found of late-glacial ice flow from New England into Quebec, but westward flow from glacial centers in Maine-New Brunswick during the early phases of flow of the penultimate ice sheet was confirmed by fabric, westward boulder displacement from the Attean Quartz monzonite of Maine, and compositional disparities between the surface and lower tills. As in the Sherbrooke area, the later phases of flow of the penultimate ice sheet were inferred to be southeastward, from a

Laurentide-centered ice sheet that displaced the Appalachian ice in this part of Quebec. Abundant erosional evidence, in the form of multiple directions of striations on the slate outcrops typical of the region, clearly indicated that the last two flow events to affect the study area during the last glaciation were east and southeast, but no attempt was made to establish age relationships between these generally distinctly different directions.

Perhaps the most significant discovery made in the course of mapping and stratigraphic studies of the upper Chaudière valley was the observation of a buried deltaic facies of the glaciolacustrine deposits that separated the surface till, with provenance indicating southeastward glacier flow, from a subsurface till with fabric and provenance indicating, as in the northern Vermont -Sherbrooke-Eaton River area, west-southwestward flow followed by southeastward flow. The delta was exposed in a borrow pit excavated for a short-lived hydroelectric dam across the Chaudière River in Gayhurst Township. Several natural exposures and drilling to bedrock at the dam site indicated that the delta was built by an ancestral Chaudière River, prograding northward into the south end of a glacially dammed lake with a surface at 1300' (400 m) in the Chaudière valley (Fig. 4). Because of the strong relief in the area, it was concluded that the only possible outlets for a glacially dammed lake at this altitude were northeastward through the Famine and Daaquam River valleys, which follow a structural depression in front of the La Guadeloupe thrust fault and possibly through two smaller valleys at about the same altitude just to the south (Figure 4). This drainage ultimately spilled into the upper reaches of the St. John River (McDonald and Shilts, 1971). The altitudinal constraint imposed by the deltaic deposits on the inferred level of this interstadial, ice-dammed lake provided for the first time some concrete evidence of probable configuration and location of ice fronts immediately prior to the main late Wisconsin readvance to the Wisconsin maximum limit in New York and New England. The paleogeography and interpretation of the sequence of glacial events in the Quebec Appalachians has come to be hung on the "hook" provided by the exposures of the overridden delta and associated glacial and nonglacial sediments encountered in sections and boreholes at and near the Gayhurst dam site.

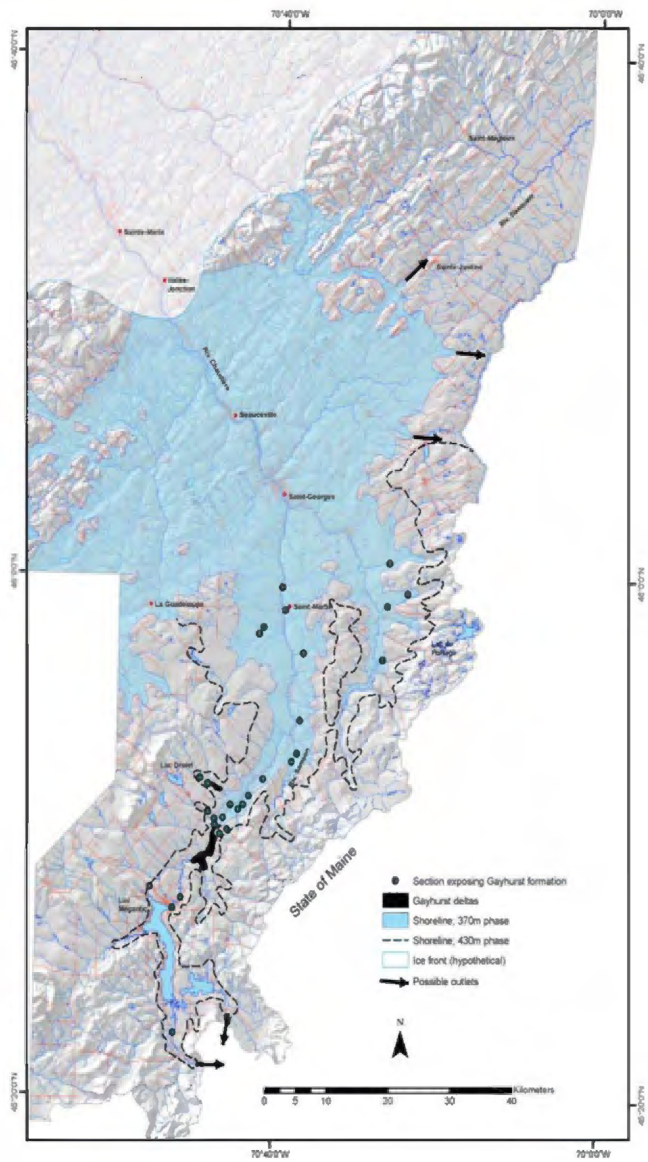


Figure 4. The maximum extent of Mid-Wisconsin Glacial Lake Gayhurst and associated deltas and outlets. As the normal drainage is from the International Border towards the St. Lawrence River, any ice expansion across the St. Lawrence Valley, and into the Appalachians would have created ice-dammed lakes, during each glacial advance and northward retreat (Shilts, 1981).

The 1970s: stratigraphic synthesis and rediscovery of evidence of northward ice flow

In 1971, McDonald and Shilts synthesized their stratigraphic observations from the Eaton, St. François (Sherbrooke area), and Chaudière River valleys in a paper that gave formal names and interpretations to the units they had identified (McDonald and Shilts, 1971). In the same paper, they presented compositional evidence for southeastward flow of the last Wisconsin, Lennoxville glacier, southwestward flow for at least some phase of the earlier, Chaudière glacier, and southeastward flow of the early Wisconsin or Illinoian, Johnville glacier. Their evidence did not indicate any late-glacial northward flow from New England. In the same paper, they presented paleogeographic reconstruction of the main phases for interstadial Glacial Lake Gayhurst, into which were deposited several facies of the Gayhurst Formation, which separates Lennoxville Till from the earlier Chaudière Till. They further suggested that the lake was confluent across a low col at La Guadeloupe within the St. François and Chaudière drainage basins. The various nonglacial, organic-rich sediment facies overlying Johnville Till were collectively named the Massawippi Formation and were correlated with all or part of the St. Pierre beds. The picture of depositional stratigraphy presented by McDonald and Shilts in 1971 has persisted more-or-less intact to the present day with some minor modifications as noted later. It should be emphasized that it grew from and was strongly influenced by a stratigraphic model worked out by Stewart and MacClintock and their colleagues in the early 60s, a model that was subjected to some criticism by other New England workers at the time it was proposed.

In 1971, however, an important discovery was made that added a wealth of detail to the understanding of events that occurred during the last glaciation and vindicated in an unexpected way Flint's original ideas about the importance of the evidence of northward-flowing ice in Quebec. Robert Lamarche of the Ministère de l'Énergie et des Ressources of Quebec, while mapping bedrock in the Thetford Mines region, noticed that a widely dispersed, unequivocal set of striations indicating northward flow was superimposed on striations indicating southeastwardly flow. He invited McDonald and the author to look at the evidence with him, and we agreed that there could be no doubt that the last ice movement in the area between Thetford Mines and St. Georges-de-Beauce, to the east, was northward, as first suggested by Chalmers (1898) in the 1890s. As a result of Lamarche's work (Lamarche, 1971, 1974), McDonald and Shilts, with Gadd's help, prepared a map and paper describing the regional pattern and timing of reversal of glacial flow for the first time (Gadd et al., 1972). In this paper, it was suggested that an independent Appalachian ice cap, formed when ice south of the Appalachian front was cut off from its Laurentide source, was isolated south of the St. Lawrence River as a result of redirection of late glacial ice flow down the St. Lawrence River and estuary.

With these observations was born the concept of "erosional stratigraphy," the technique of reconstructing by intercomparison among hundreds of bedrock outcrops a complex series of glacial flow events from cross-cutting relationships of striations on individual outcrops. Erosional stratigraphy differs from conventional stratigraphy in that individual flow events do not necessarily leave behind recognizable glacial sediments, so that the number of erosional events may far exceed the number of depositional events that can be easily recognized. Erosional events may reflect internal rearrangements or shifting of ice flow centers within a continuous ice sheet, and not necessarily flow direction changes associated with retreat, readvance, or reconstitution of ice sheets.

The 1980s: Mineral exploration and Quaternary stratigraphy

In 1985, 1:50,000-scale mapping and stratigraphic studies of the glacial geology of the lower Chaudière and Etchemin River valleys were undertaken in support of placer gold exploration research. The areas mapped joined the already mapped Lac Megantic area (Shilts, 1981), and extended northward from that area for 45' of latitude along the Maine border and westward almost to Quebec City. In this area, detailed striation measurements were made on over 900 outcrops in an attempt to understand the paleogeographic implications of the erosional stratigraphy originally described by Lamarche (1971, 1974) and later by Lortie (1977). In the middle Chaudière-Etchemin valleys, it was possible to map seven distinct striation events or phases, from oldest to youngest: (1) southwestward, (2) southeastward (135° ± 5°), (3) east-southeastward (100° ± 10°), (4) southeastward (135° ± 10°), (5) northward (000° ± 10°), (6) northwestward (340° ± 10°) or northeastward (030° ± 15°), and (7) east-southeastward (090-110°). Most of these phases are documented by hundreds of multiple-striation outcrops, and the first stop on this field trip will provide an opportunity to observe and discuss the age and extent of these erosional phases. Systematic mapping of the erosional stratigraphy in this area and adjacent areas in Maine and Quebec has added rich detail to the general picture provided by the depositional stratigraphy that was established almost 4 decades ago. It has provided insights into the disintegration style of this sector of the Laurentide Ice Sheet (LIS) by providing details of the reversal of flow and eventual isolation of an Appalachian ice cap caused by calving of the ice sheet in the lower St. Lawrence estuary as glacioeustatic sea level rose, forming a reentrant in the ice front. Finally, it documents the significance of parts or all of the Highland Front Moraine (Gadd, 1964) as the terminal deposit of a readvancing LIS just before it retreated north of Quebec City, allowing the Champlain Sea to flood the upper St. Lawrence, Lake Champlain, and lower Ottawa River valleys.

During the latest phase of mapping in the lower Chaudière Valley, a unique and complete Quaternary sequence of sediments was discovered along Rivière des Plante, northeast of Beauceville, Quebec. In three of four sections found along a half-kilometer reach of Rivière des Plante, *in situ* organic beds, correlative with the Massawippi

Formation (McDonald and Shilts, 1971) were found above Johnville Till and beneath compositionally distinct outcrops of Chaudière and Lennoxville Till in sections exposed by flooding in 1988 and 1989. These sections are thoroughly described in the notes accompanying the field trip guide. In the course of this program, a systematic drilling project was carried out during which 42 boreholes were cored. Lithologic logs and geochemistry of the glacial sediments in these boreholes have been used to document a model for the surface concentration of gold in the Rivière Gilbert placer as well as for the other placer regions of Southeastern Québec (see LaSalle, 1980 for a detailed list of sites; Shilts and Smith, 1988). The lack of discontinuity between the gold-bearing regolith and the sediments related to the advance of the Johnville glacier would suggest that the lithostratigraphic sequence shown on Fig. 2 may indeed sum the entire Quaternary history for this region.

In summary, as a result of the research carried out in Southern Quebec over the past 40 years, the stratigraphic picture of the Quaternary of the Vermont and Quebec Appalachians has been enriched and enhanced by new studies of organic beds from well-exposed sections in the Chaudière Valley and by detailed reconstruction of erosional stratigraphy. The modern picture is like a color photograph of the old "black and white" stratigraphy of the 1960s – same picture, better focus and richer detail.

THE FIELD TRIP: FROM ST. GEORGES TO VALLÉE JONCTION

The list of stops comprises a) a striated bedrock exposure in St. Georges-de-Beauce, b) a buried mid-Wisconsin subaqueous outwash fan along the west bank of the Chaudière River Valley, just a few km south of St. Georges, c) the spectacular Rivière des Plante sections with the last-interglacial Massawippi sequence, and d) a late glacial subaqueous outwash fan at Vallée-Jonction, representing the last evidence of active ice in this part of the Chaudière Valley.

ROAD LOG

Kilometer

0.0 Starting from Auberge Benedict Arnold at 18255, boulevard Lacroix, St-Georges de Beauce, Québec, G5Y 5B8, turn right on Highway 173

5.0 Turn right at red light, and park near the Canadian Tire store, (500 rue 107, St. Georges de Beauce, G5Y 8K1); the outcrop is near the southwest corner of the store, at the south side of an open field.

STOP 1. St. Georges-de-Beauce multiple striation site (30 MINUTES)

More than 900 bedrock outcrops, ornamented with glacial striations, have been examined in the Chaudière Valley over the past 20 years, and more that ¾ of these outcrops have sets of striae recording at least two discrete and distinct directions of glacial flow. This particular outcrop was selected for the field trip from among the hundreds studied because it is easily accessible and because it records not only the major southeastward to eastward flow directions of the main Lennoxville glaciation, but also the northward flow associated with the formation of the Quebec Ice Divide, an east-northeast-trending feature that lies about 10–15 km south of this site. Additionally, this outcrop of the Devonian Famine Formation comprises relatively rare bedrock lithologies for this part of the Appalachians and lies at the leading edge of a major thrust fault. The outcrop, itself, is composed of fossiliferous limestone of Devonian age, lying conformably on an arenaceous pebble conglomerate. This cratonic material was caught up along the leading edge of the northwestward-verging La Guadeloupe thrust fault, which marks a major contact between two terranes and is traceable in Quebec from Lac Memphremagog on the Quebec/Vermont border, northeastward to Lac Frontière on the Quebec/Maine border, a distance of over 260 km (160 miles). In several places along its trace, it forms the lowest point between major drainage basins, and the valley of the Rivière Famine, which joins the Chaudière at this point, lies in a depression in front of the fault for its entire length. In Ste Justine, Quebec, about 30 km to the northeast, drainage in the valley is directed eastward via Rivière Daquaam into the St Jean River from an imperceptible divide on the valley floor. The divide separates the Famine and Daquaam drainages which are both underfit streams lying in the same valley, the south side of which is formed by the face of the La Guadeloupe fault. The significance of the valley is that it served as a major outlet to Glacial Lake Gayhurst, as well as earlier and later glacial lakes, any time a Laurentide Ice Sheet advanced into the Appalachians, blocking northward flowing drainage of the southern tributaries of the St. Lawrence River. There is further discussion of Glacial Lake Gayhurst at stops 2 and 4.

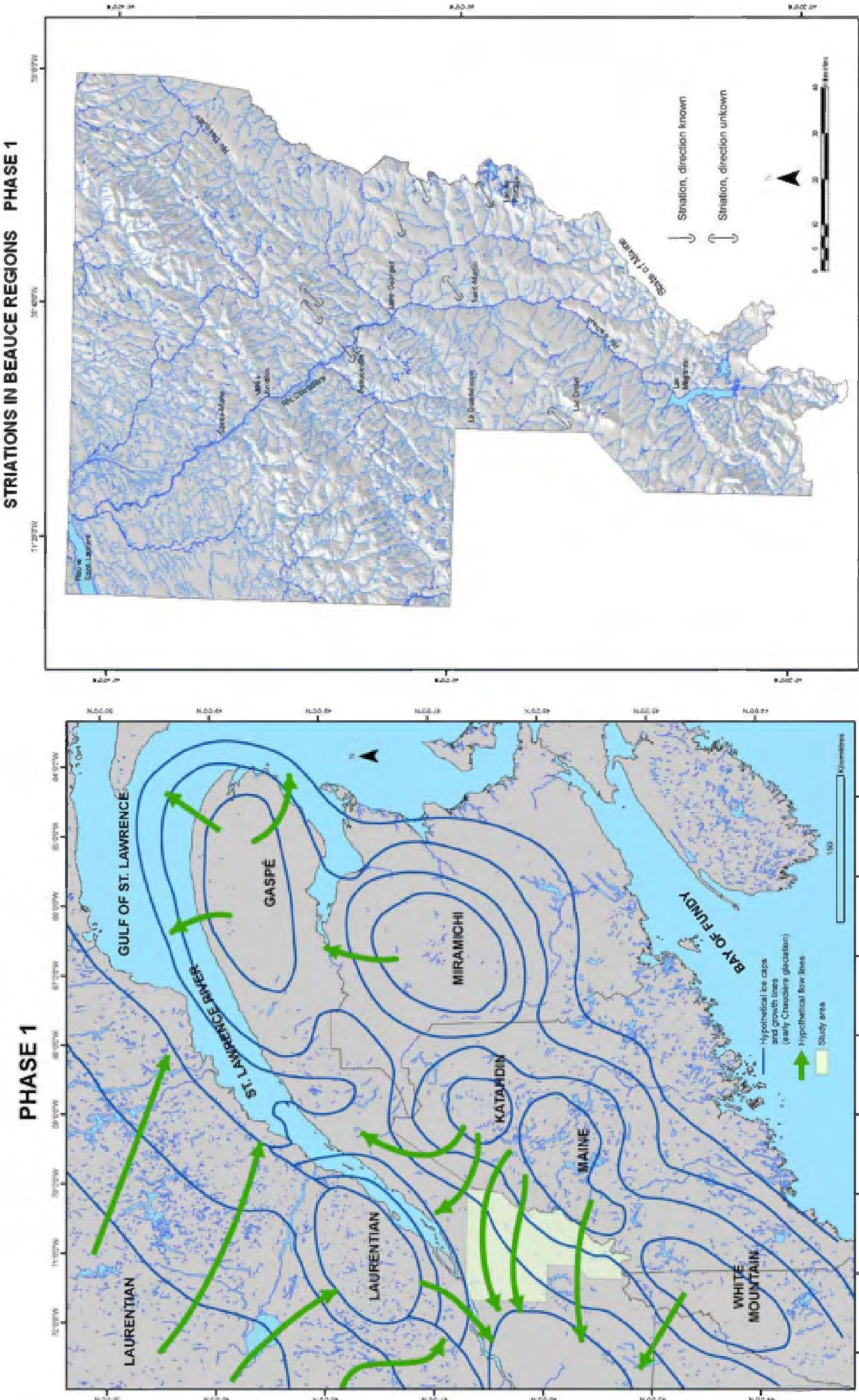
This outcrop, which has relatively unweathered, glacially polished facets, carries two prominent sets of striations. On its north-facing side, it carries the main, regional southeasterly set, 120 degrees (regional range is normally 100-120, depending on outcrop shape), formed during the Lennoxville glaciation. The second set, which relates to the late glacial reversal of flow, also during the Lennoxville glaciation, is oriented at 010 degrees, marking northward flow from the late glacial Quebec Ice Divide. Uneroded 'tails' of rock on the lee side of pebbles in the conglomerate and lack of the 010 striae on the north-facing side of the outcrop confirm both the sense and relative ages of the two phases of ice flow. This sequence is repeated on literally hundreds of other outcrops north of the ice divide in this region.

Merging data from hundreds of outcrops like this one has led to the development of a regional erosional stratigraphy. At each striation site, a chronological identifier was assigned to each direction encountered, whether or not direction and age relationships were unequivocal. However, the large number of outcrops that bear multiple striations with clear directional indicators and unequivocal age relationships make the relative age determinations very reliable. It was noted that in this region, as in the Sherbrooke area, there was very little evidence of even minor deflections of flow by either large-scale or small-scale topography. Although instances of as much as 90° of flow deflection were noted on individual outcrops, these instances were extremely rare, occurring on less than 1 percent of the outcrops examined.

There are seven distinct striation events or phases documented from this area, and they are, from oldest to youngest: (1) southwestward, (2) southeastward (135° ± 5°), (3) east-southeastward (100° ± 10°), (4) southeastward (135° ± 10°), (5) northward (000° ± 10°), (6) northwestward (340° ± 10°) or northeastward (030° ± 15°), and (7) east-southeastward (090-110°). The sites where striations corresponding to each of these phases were recorded are shown on Figures 5 through 14.

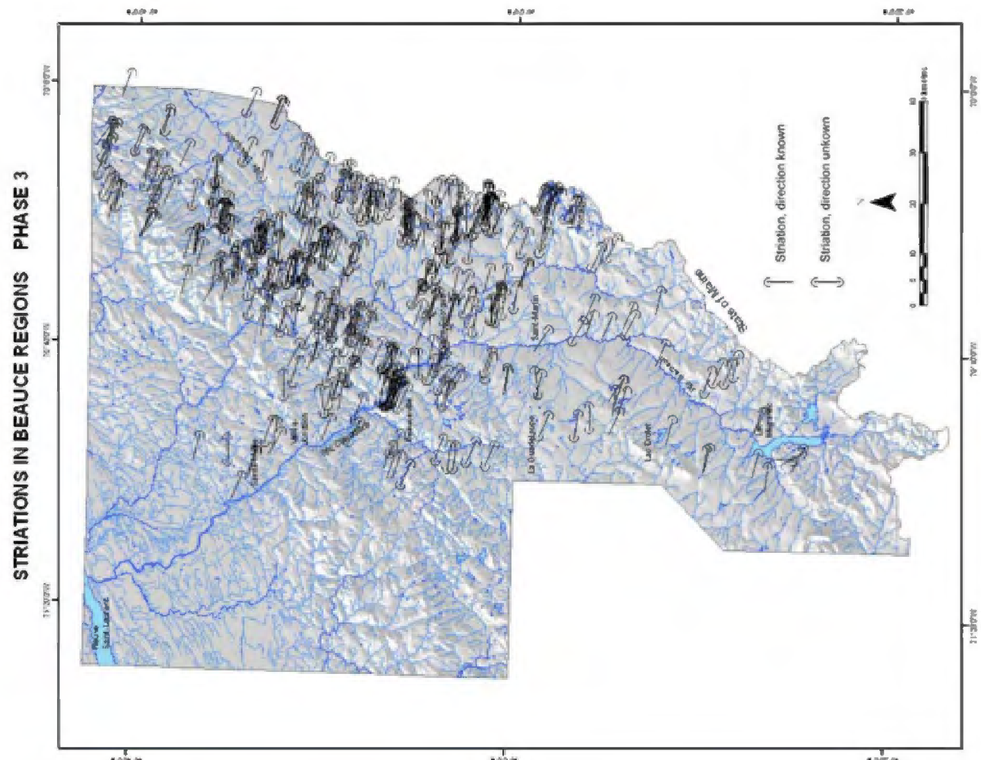
The least common striation direction in the Chaudière-Etchemin region is southwestward (phase 1). Because of its rarity and because it is found in one case on a surface protected from younger southeastward striating events, it is believed that the southwestward glacial direction may represent ice flow associated with till deposited during the early phase of Chaudière glaciation. Any glacial striae that might be preserved from older glacial events (Johnville glaciation), would be either deeply buried and inaccessible or not easily resolvable, due to the difficulty of observing clear, cross-cutting relationships and the likelihood that they would have azimuths similar to those of striations cut during the later late-Chaudière and Lennoxville glaciations.

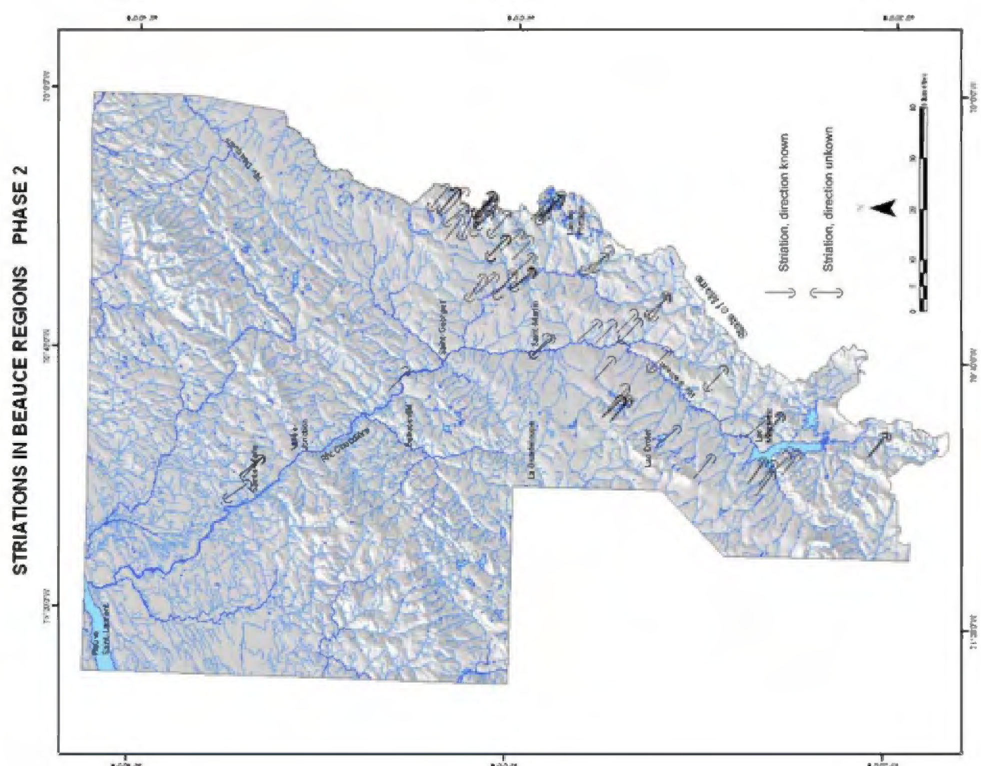
The southeastward directions can be divided into four groups: phase 2 early southeastward (135° ± 10°); phase 3 east-southeastward at 100° (± 15°); phase 4 later southeastward at 130° (± 5°) and phase 7 southeastward readvance. This fourth southeastward set of striae (phase 7) is thought to have formed when Laurentide ice readvanced to the Highland Front Moraine position and up the Chaudière Valley during a late glacial pulse (Blais, 1989; Shilts and Blais, 1989). It postdates the various sets of striae formed during the northward flow phase of remnant Appalachian ice (see Bouchard et al., 1987; Lortie and Martineau, 1987). North of a line approximating the Highland Front Moraine System, a southeastward flow phase, probably associated with the readvance, seems to have erased much evidence of northward flow. Based on cross-cutting relationships, the southeastward striae both precede and postdate the 100°, phase 3 flow. If not a product of an early Lennoxville local phase of flow, the earlier southeastward phase may date from the Laurentide (latest) phase of Chaudière glaciation. It has been identified only south of the Quebec Ice Divide (see below), suggesting that the post 100° southeastward and various northward flows have largely erased it or made it hard to recognize north of the ice divide. The divide, being a late glacial feature, obviously could have no significance in delimiting an earlier flow phase. The later southeastward striae (phase 4) may represent ice flow from the earliest position of the Quebec Ice Divide, near the Appalachian front south of the St. Lawrence River. The ice divide eventually migrated southward to the St. Georges area, at which point it provided a symmetrical equilibrium profile for the remnant ice cap.



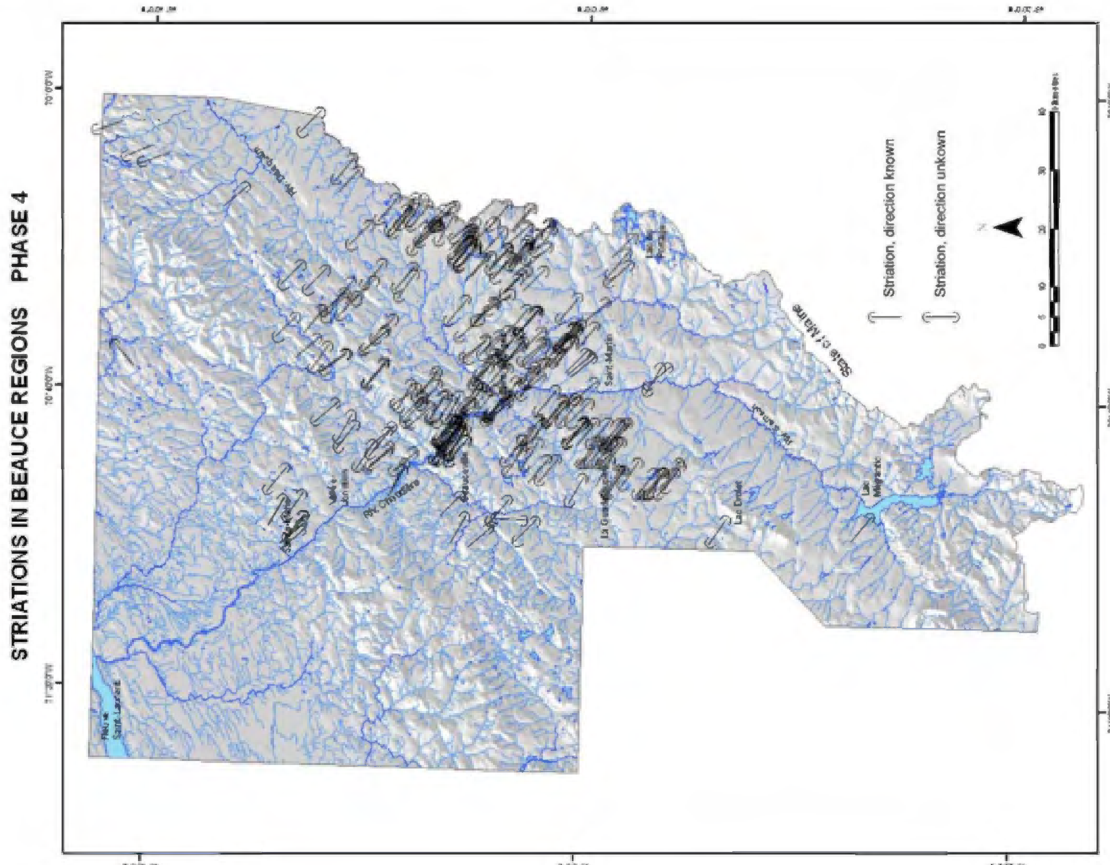
Figures 5 (left) and 6 (right). Regional distribution of striae for phase 1 and reconstruction of contemporaneous ice configuration.

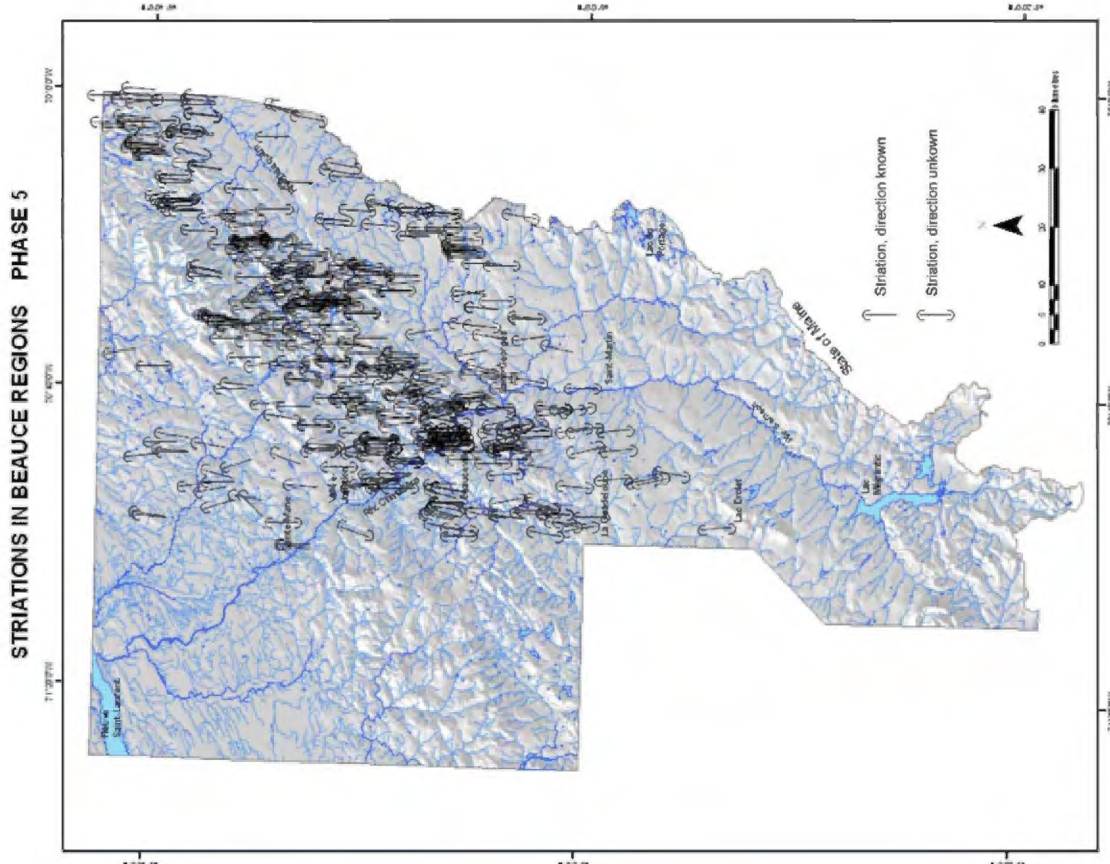
Glacial striae indicating general northward flow (phase 5) are ubiquitous north of the Quebec Ice Divide, which lies more-or-less along the southern border of the post-1985 map area. "Northward" flow directions actually range from north-northwestward to north-northeastward, i.e., 000° (± 10°). Based on cross-cutting relationships, the northward striae in the map area are consistently and unequivocally younger than the southeastward sets, except for those of phase 7. The other groups of northward striae (phase 6) at 340° ± 10° and 030° ± 10° have cross-cutting relationships that indicate that they, in turn, are younger than the 000° phase 5 group. The two sets of striations of phase 6 and the westward set noted by Lamarche (1974) and Parent (1987) in the upper St. François River valley, west and south of Thetford Mines, may be more or less contemporaneous, possibly reflecting flow of small ice streams from different sides of the isolated, shrinking Appalachian ice cap.



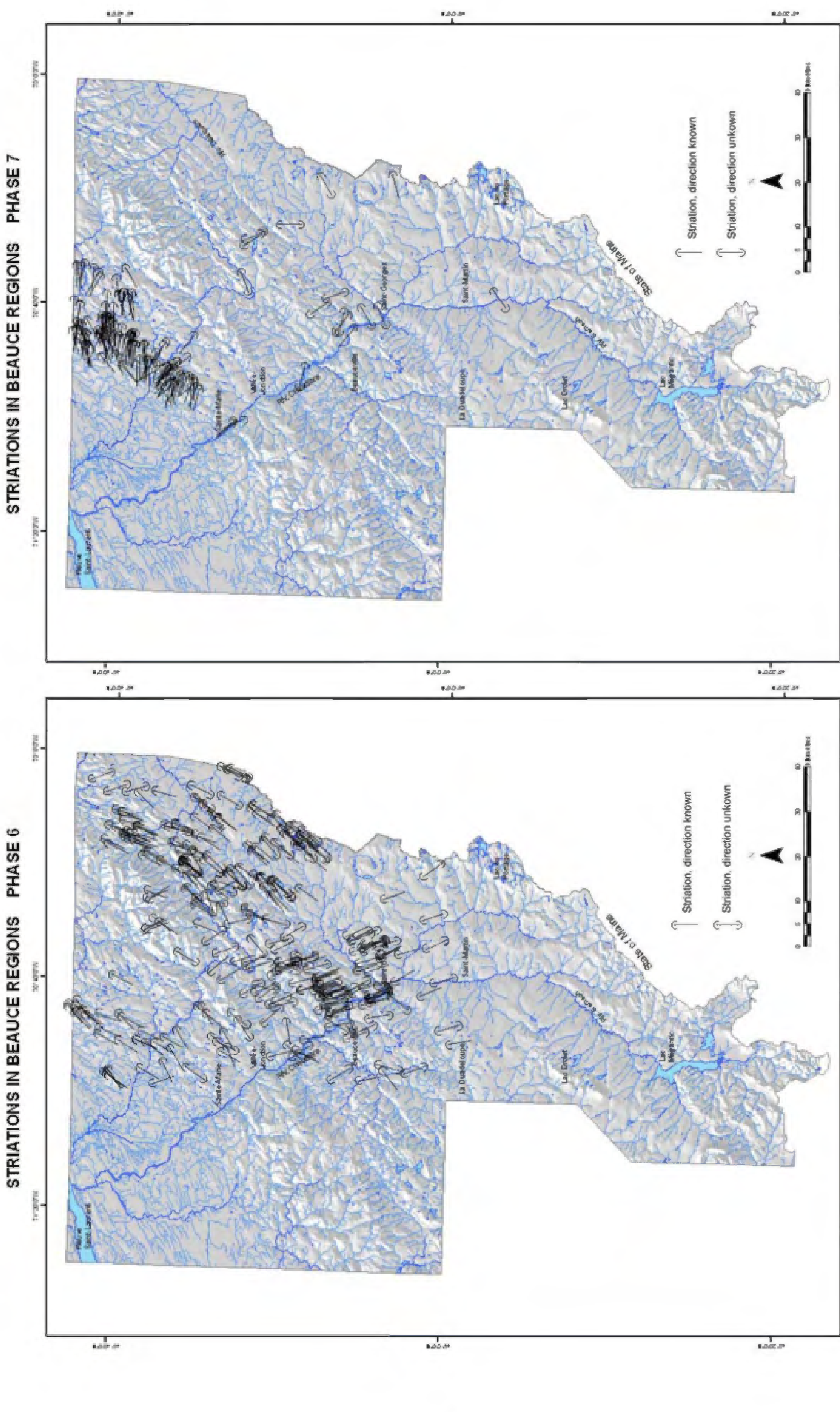


Figures 7 (left) and 8 (right). Regional distribution of striae for phases 2 and 3. See text for details.



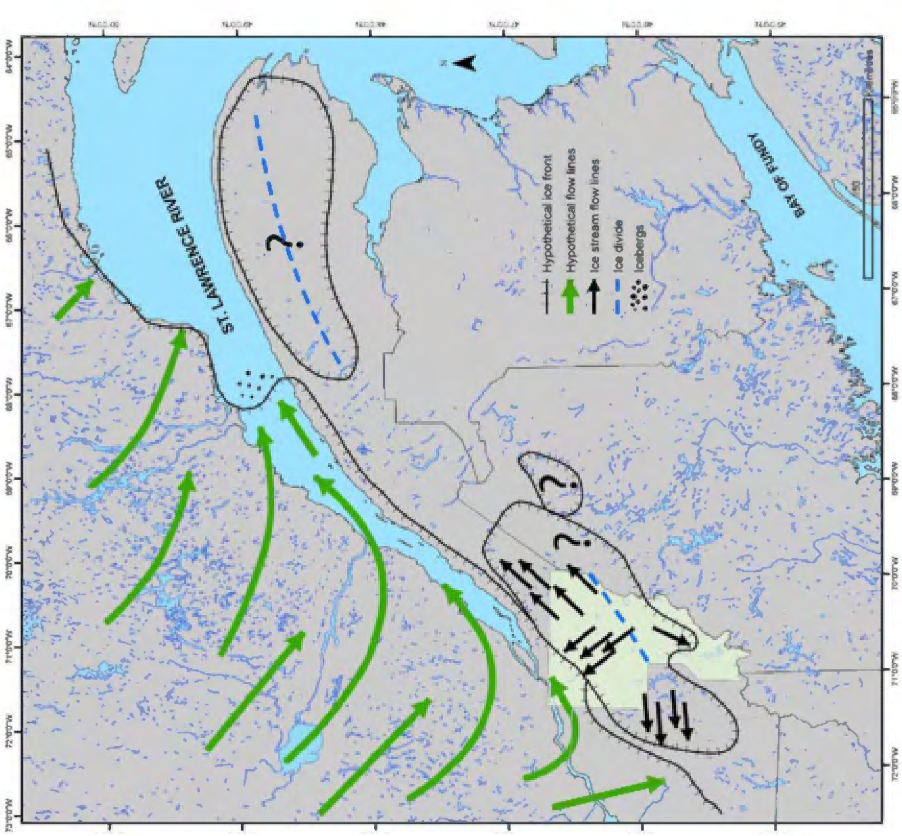


Figures 9 (left) and 10 (right). Regional distribution of striae for phases 4 and 5. See text for details.

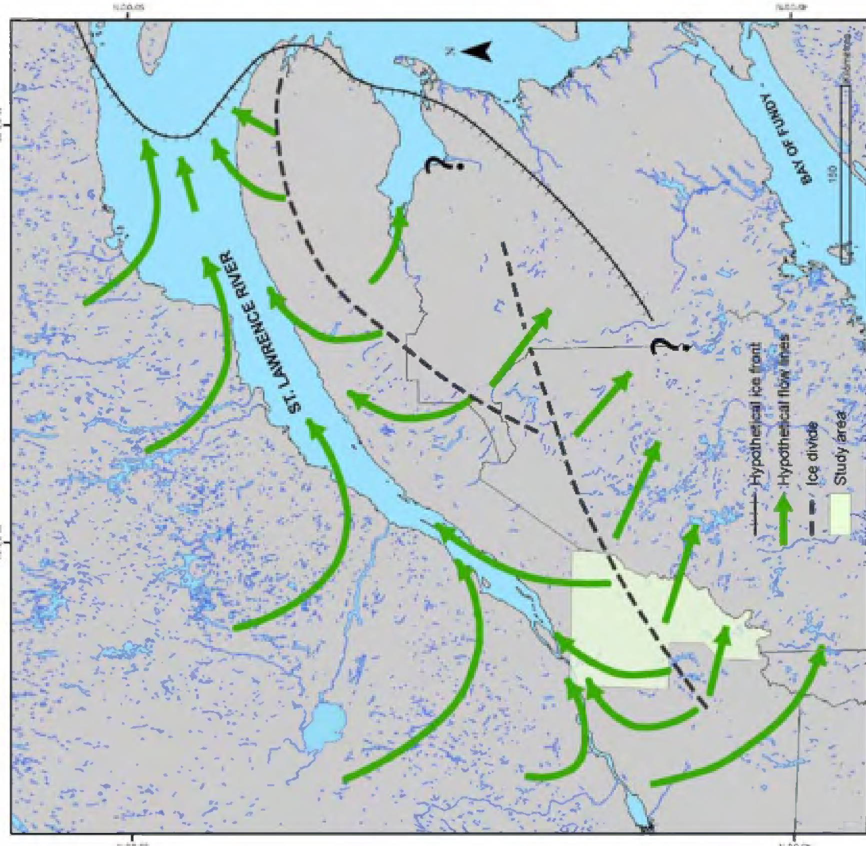


Figures 11 (left) and 12 (right). Regional distribution of striae for phases 6 and 7. See text for details.

PHASE 6



PHASE 5



Figures 13 (left) and 14 (right). Suggested regional ice configuration for phases 5 and 6

Kilometers

0 From Canadian Tire parking lot, exit towards the main highway and turn left, on Highway 173
3.75 Turn right on 1st Avenue
3.95 Turn right to cross over bridge
4.20 From the end of the bridge, drive to 6th Avenue
5.90 Turn left, and keep driving on 6th Avenue
9.1 Entrance to gravel pit. Leave the cars on the side of the road.

STOP 2. Glacial Lake Gayhurst sediments, south of St.-Georges (1 HOUR)

Excavation of this site has, at one time or another, exposed several facies of the Gayhurst Formation (McDonald and Shilts, 1971), the interstadial glaciolacustrine deposit that lies between the Chaudière and Lennoxville Tills below altitudes of 430 m asl. The top of the section and the till plain extending west from the valley side comprise Lennoxville Till, which is about 15 meters thick in this exposure. Directly below the Lennoxville Till is a thick sequence of irregular, graded, silty clay laminae and diamicton beds, representing deep-water sediment facies of the lower member of the Gayhurst Formation. At this site the sediments were deposited in approximately 200 m of water in Glacial Lake Gayhurst.

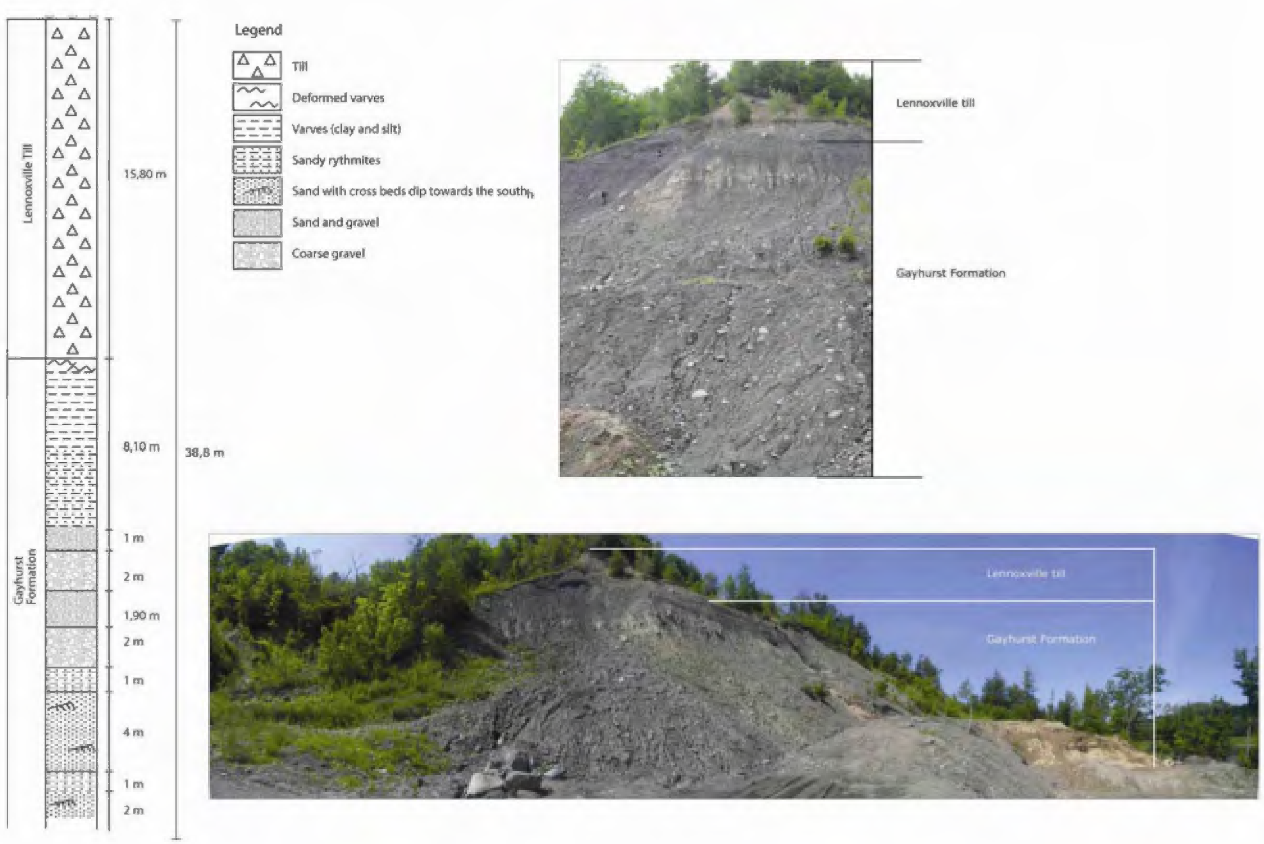


Figure 15. Stratigraphic log for the Gayhurst subaquatic outwash, south of St-Georges

Sediments of Glacial Lake Gayhurst, a large proglacial lake dammed at the margin of the retreating Chaudière Glacier and the later, advancing Lennoxville Glacier, are widely exposed in sections and have been encountered in numerous boreholes. It is assumed that Lake Gayhurst never drained during the interval between the two glaciations, since no evidence of weathering or subaerial erosion has ever been identified in any of the numerous exposures of or boreholes through Gayhurst sedimentary sequences. The Gayhurst Formation sediment package comprises fine-grained, rhythmically laminated sequences that vary in thickness from 0 to >100 m over short distances and thick (>50 m) sequences of sand and/or gravel deposited in subaqueous fans or deltas. These sediment facies commonly are interrupted at irregular intervals by silty to stoney diamictons representing mudflows from the base of the deeply submerged ice front.

Interpretation of the paleogeography and depositional environments of the Gayhurst Formation and of older and younger lacustrine sediments is constrained by the altitudes of possible outlets for ponded drainage in the Chaudière River valley: (1) 427 m a.s.l. southward into the Dead River basin of Central Maine; (2) 397 m (±) mainly via Daquaam and Famine rivers, eastward into the St. John River basin of northern Maine; and (3) westward into the St. François drainage basin via a col at ~305 m altitude in La Guadeloupe, Quebec (Fig. 4). One or the other of these outlets functioned each time ice advanced south of the St. Lawrence River or retreated toward it, damming northward drainage in the Chaudière and adjacent valleys.

Fine-grained sediments deposited in lakes dammed by <u>advancing</u> glaciers consist of evenly laminated sequences with uniformly thin (<1cm), graded couplets containing sparse and isolated ice-rafted debris. In contrast, those deposited by <u>retreating</u> glaciers are irregularly bedded in graded couplets of variable thickness (<1 cm->10 cm), and commonly are interbedded with 1 cm to 2 m-thick beds and lenses of diamicton. The contrast in sedimentation styles is related to the predominance during retreat of density underflows, in which thin sheets of sediment-laden meltwater exited glacier conduits at or near the lake bottom and pooled, perhaps even daily, in closed, proglacial depressions near the ice front. The interbedded diamictons represent slurries of basal glacial debris, released at irregular intervals by thawing of the nearby, deeply submerged ice front and subsequently flowing or slumping onto the lake bottom. In contrast, during glacial advances, sediment was more evenly dispersed distally as overflows or interflows, deposited some distance from the ice front, accounting for their tendency to be draped over irregular surfaces, their uniformly thinly laminated character, their small amount of ice rafted debris, and their lack of diamictons.

Subaqueous fans consisting of irregularly bedded sand and gravel, often draped over coarse gravels of an esker core, were deposited at retreating conduit mouths in valleys and grade outward and upward into thick, fine-grained, laminated sequences. At this site, all of the sediment assemblages of the Gayhurst Formation, except for the fine-grained, thinly laminated distal facies, were exposed by excavation at one time or another. A substantial subaqueous fan, deposited at the mouth of a conduit in the retreating Chaudière glacier, was, as was its late-glacial analogue at Vallee Jonction (Stop 4), draped over an esker that was deposited in the conduit and was exposed on the lake bottom as the conduit mouth(s) migrated with the northward-retreating ice front. Most of those coarse deposits have been removed for aggregate at this site, but some of the finer sand facies, interrupted by clay drapes, typical of subaqueous fan deposits, remain. Deposits of the Lennoxville Glaciation have obscured the morphology of this fan, but, based on exposures in sections and on borehole records, the fan is thought to extend, discontinuously southward in the Chaudière Valley for 7–8 km from this site. For additional descriptions of subaqueous fans and their morphology, see the discussion for the subaqueous fan at Vallee Jonction, which we will visit at Stop 4.

Kilometers

0	Turn around and drive along the 6th Avenue
3.2	Turn right to cross the Chaudière River
3.7	Turn left on the 1st Avenue and keep driving on Highway 173 (north).
25.7	Turn right, along the road Route du Golf (after Beauceville)
33	Turn left at Mr Gagné (910 Route du Golf)

This is a good 20 minutes walk to the next stop, along trail. If time is a constraint, vans will be used for transportation. We should take food on the way as this is a nice place to have lunch.

STOP 3. Rivière des Plante sections (2 HOURS INCLUDING LUNCH)

A series of sections along Rivière des Plante were discovered and described by Professor Jacques Locat and his colleagues from Université Laval in the early 1980's. Intensive study of the sections was carried out by the senior author and students in conjunction with a Geological Survey project designed to clarify the stratigraphic position and genesis of buried preglacial gold placer deposits of the middle Chaudière Valley. Major flooding in summers of 1987, 1988, and, particularly, in 1989, created good exposures of the lowest units of these sections.

The des Plante sections include virtually all of the major Quaternary stratigraphic units that are known in the Quebec Applachians, including well-preserved, *in situ*, organic beds. The fortuitous location of these sections, just southeast of chemically and lithologically distinctive ultramafic bedrock outcrops, permits many compositional constraints to be brought to bear on discussions of the ice flow events responsible for deposition of the various sediment facies, glacial and nonglacial, that are exposed here. Along a 600 m reach of central Rivière des Plante, four sections, A, B, C, and D, have been studied (Fig. 10). Although C has been badly slumped in the past, and will not be discussed further, A, B, and D are generally well exposed right to river level. We will visit only sections A and B in the interest of time, but section D, half a kilometer upstream from B, is easy to find and well worth visiting.

The glacial and nonglacial sediments exposed in the des Plante sections will be described from oldest to youngest (Fig. 16).

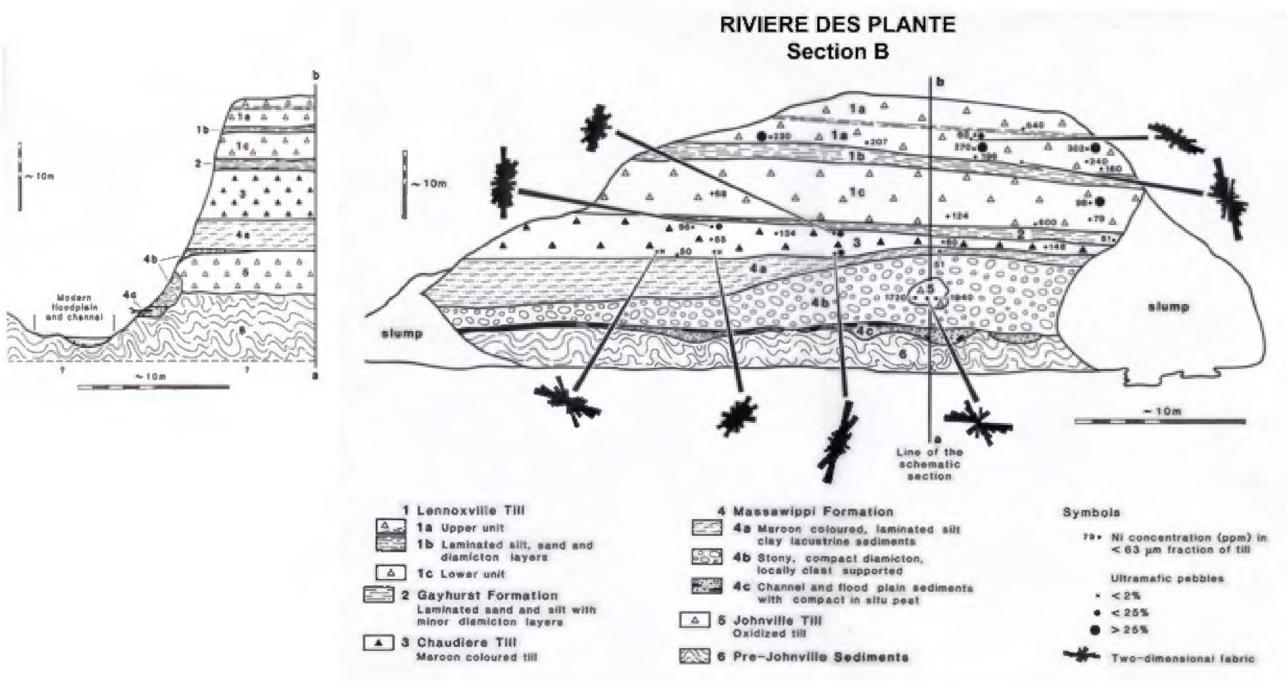


Figure 16. Stratigraphic section for Rivière des Plante section B. The Massawippi interglacial is unit 4. Unit 4b is a "fossil" slump or colluvial deposit, through a window in which the stratigraphically older Johnville Till crops out.

Pre-Johnville sediments. From these exposures and from several stratigraphic boreholes drilled nearby, two Pre-Johnville units have been identified. The first is a thick yellowish regolith that is preserved in pockets along the des Plante and similar, nearby Rivière Chaudière tributaries. The regolith was mined extensively in the 19th and early 20th centuries for the detrital gold that it contained. Compositionally, this regolith is characterized by extremely low nickel concentrations, high arsenic concentrations, high concentrations of kaolinite, abundant pseudomorphs of goethite after pyrite, virtually no mineral grains, such as epidote and garnet, typical of bedrock in the high-grade metamorphic terranes of the Canadian Shield, and in some samples, abundant secondary siderite. With these compositional characteristics, it is difficult to think that any glacial event could have affected this region before the regolith was formed. Consequently, it is likely that the Johnville Glaciation (see below) was the first glacial event to influence this area and that the older glacial events that are identified elsewhere in North America, particularly in the Midwest, did not impinge on this part of the Appalachians. This is a paleoclimate conundrum of some significance.

Immediately overlying the regolith in many nearby boreholes and underlying the Johnville Till at these sections, is a glaciolacustrine unit of evenly bedded, laminated silt and clay. In boreholes to the south, in the Rivière Gilbert drainage basin, the base of the lacustrine unit has low nickel concentrations, indicating no influence of ultramafic provenance, but about half way up the section, the sediments show an abrupt enrichment in nickel from 30-50ppm to over 150 ppm, suggesting that the Johnville glacier, which deposited the overlying till, was pumping ultramafic-rich rock flour into the proglacial lake as the first glacier to pass over the ophiolitic complex that crops out north of Rivière des Plante (Shilts and Smith, 1988).

At sections A and B, the regolith is not exposed, but the glaciolacustrine unit forms the bottom of both sections, and the interglacial fluvial deposits of the Massawippi Formation, lie in channels cut into it. At the base of section B, the silty clay is so deformed that it is virtually structureless and massive, but at the downstream end of section A, the highly deformed unit passes laterally into a deformed, laminated silty clay that can be traced downstream into a virtually undeformed, laminated sequence

The presence of the highly deformed silty clay lying beneath interglacial peat and undeformed laminae of the younger Massawippi Formation was difficult to understand until the base of these sections was washed clean by the floods of 1989. The flooding revealed that the Johnville Till had been removed from the site of the present sections by interglacial fluvial erosion that cut down through it and into its underlying, deformed, proglacial lacustrine deposits (Fig. 16; see discussion of the appearance of Johnville Till in a window through interglacial slump deposits at section B, below).

Johnville Till. Johnville Till (McDonald and Shilts, 1971) was at one time exposed in a window through a paleo-slump deposit (see below) near the base of section B. It is presumed to have been deposited by a southeastwardly flowing glacier as observed elsewhere in the Chaudière and St-François valleys. Johnville Till at section B is very compact, grey and sandier than at section D. Although we will not visit it on this excursion, Johnville Till at section D has a yellow-brown hue and contains none of the fresh sulphide grains (mainly pyrite) that are ubiquitous in unweathered tills of all ages in this part of the Appalachians, which would indicate that the colour might be related to weathering processes. However, Johnville Till does contain 10-15% kaolin (C. de Kimpe, 1990, pers. comm.), a component that is derived from reworking of the yellow-brown, preglacial, gold-bearing regolith that is preserved in pockets beneath Rivière des Plante and in nearby buried bedrock valleys (Shilts and Smith, 1988). In boreholes within 20 km of these sections, tills immediately overlying the regolith were tan or brown and contained abundant kaolinite due to reworking of the regolith. The yellow-brown, lowermost (presumably) Johnville Till from the boreholes contained both unaltered pyrite and pseudomorphs of goethite after pyrite, the latter being common in the regolith.

Besides its distinctive colour and high kaolin concentrations, the geochemical and lithological composition of Johnville Till at both section D and B is characterized by high concentrations of nickel, chromium, cobalt, and other ultramafic components. The clay (<2 micron) fraction commonly contains over 1000ppm nickel, not surprising considering that over 40% of the erratics in Johnville Till at this site are ultramafic rocks.

Massawippi Formation. In three of the four Rivière des Plante sections, organic beds were exposed by flooding in 1988 and 1989. These beds lie stratigraphically below Chaudière Till and above Johnville Till. They include fluvial gravel infilling shallow channels cut into the highly deformed and compacted laminated silty clay described above. They are overlain directly by undeformed, laminated silty clay which contains traces of organic debris.

Because of imperfect exposures of the bases of these sections, Shilts and Smith (1987) and Shilts and Blais (1989) were unable to interpret correctly the stratigraphic relationships of the exposed organic beds to the subjacent glacial and nonglacial sediments. As a result of significant erosion caused by major flooding in 1989, the modern slump covering the lower portions of all these sections was stripped and, for the first time, stratigraphic relationships became evident. In sections A and B it could be seen that the main organic deposits, compressed peats and organic silt, rested in fluvial channels and on the floodplain of an ancestral Rivière des Plante. During the Massawippi interglacial, the ancestral stream had cut down through Johnville Till and into the glacially deformed, clayey glaciolacustrine sediments underlying it, forming a floodplain about 2 m above the modern one. The present-day section has been cut back into the interglacial, Massawippi-age section, the latter having been covered with cobbly scree similar to the slump deposits that cover parts of the modern sections.

A stony diamicton, although appearing to be physically above the Massawippi Formation organic beds, is actually an almost vertical cover of slump or colluvium that rested on the interglacial section face, covering and obscuring Johnville Till and deformed, pre-Johnville lake sediments, alike. Examination of sparse, disseminated organic detritus from the stony diamicton led Matthews (1987, p. 170) to state that it contained "A rich fossil insect and plant assemblage that clearly resembles St-Pierre assemblages from the classic localities..." He concluded that during Massawippi time, this part of Quebec was covered by a spruce forest that contained some larch and a species of Alnus typical of northern boreal forests. Furthermore, the deposits contain a larger number of insect taxa than the classic St-Pierre localities, including several species that do not presently occur in southern Quebec.

Macrofossils, extracted with difficulty from the highly-compressed peat collected in 1989 from section B, were examined by Dr. Lynn Ovenden who stated that "All of the plants ... are common in boreal fens, and occur in a broad latitudinal zone from northern New England to northern Quebec. The lack of diversity and the interwoven, highly organic nature of the peat indicates (that it is) an *in situ* peat deposit. The mosses suggest a fairly calcareous, ground-water fed wetland, and the abundance of needles and wood suggest that larch and black spruce occurred in the fen." (Ovenden, pers. comm., 1989). This peat is significant in that it is one of very few *in situ* peat deposits found in the Appalachians and represents subareal conditions at this site within the Sangamon Interglacial interval, during which the Massawippi Formation was deposited.

In summary, the organic detritus in sections B and D generally suggests that the region was somewhat cooler than present during at least the latter part of the Massawippi interval (Matthews, 1987) and that these beds correlate with at least part of the St-Pierre nonglacial interval of the nearby St. Lawrence Lowlands. Organic remains in the glaciolacustrine facies that overlie the peat and fluvial deposits contain evidence of arctic flora and fauna, as do several nearby organic horizons in Massawippi (?) glaciolacustrine sediment at Vallée-Jonction (LaSalle et al., 1977), Rivière du Moulin (Matthews et al., 1987), Rivière Abenakis (Matthews et al., 1987), and Rivière de la Grande Coulée (McDonald and Shilts, 1971; Matthews et al., 1987). Tundra conditions apparently prevailed in this area as the Chaudière glacier impinged on local drainage, ponding lakes in the Chaudière Valley.

During preliminary examination of macrofossils from samples collected in 1989 from new exposures of peat and organic silt, seeds of plants presently found in and south of the Rivière des Plante were identified. Much more paleoecological work remains to be done, but these observations support the inference that the Massawippi Formation is interglacial in age, and that the tundra and boreal fauna and flora usually associated with lacustrine sediment deposited late in the Massawippi interval represent conditions prevailing just prior to the onset of Chaudière glaciation.

Overlying the peat, colluvium, and alluvium is a thin-bedded, laminated silty clay. Where well-exposed and undisturbed in section B, this unit can be seen to contain small (<1 cm-diameter) dropstones and balls of till within its upper laminae. For the most part, the laminated sequence is overlain with sharp contact by Chaudière Till, which at some spots in this section has deformed the laminae immediately beneath the contact and at others has caused virtually no deformation. The laminated sequence is also well-preserved at section A. The clay "winter" layers in this laminated sequence range from grey to maroon in colour, with maroon dominating. The maroon hues result from the incorporation of finely divided specular hematite, created by glacial erosion of red slates and shales in the St. Lawrence lowlands and Appalachian hills to the north of the sections. The overlying Chaudière Till also has a distinctly maroon tint, presumably because of incorporation of the lacustrine sediments of the Massawippi Formation.

Massawippi Formation summary. At this site the Massawippi Formation includes all of the major nonglacial and proglacial facies that might be expected during glacier-free intervals at altitudes above marine limit in this part of the Appalachians. Deformed glaciolacustrine sediments, deposited in a lake dammed by the Johnville Glacier, and Johnville Till, which overlies them, are covered by or have inset into them a variety of fluvial, palludal, and colluvial facies, representing a period of free drainage toward the St. Lawrence. These nonglacial deposits are overlain in turn by sediments deposited in a lake dammed by the advancing Chaudière glacier, which ultimately deposited Chaudière Till.

Chaudière Till. Chaudière Till forms a prominent bed across sections A and B, where it lies with sharp contact on the upper glaciolacustrine member of the Massawippi Formation. In section D, it is intercalated with Johnville Till and with deformed Massawippi laminated sediment and organic-rich gravels in a series of thrust plates. In sections A, B and D, Chaudière Till ranges in colour from grey to grey with a mauve or maroon tint and is distinguishable from Johnville Till in section D by virtue of the tan colour of the latter.

Two dimensional fabrics in Chaudière Till at sections A and B seem to strike WNW-ESE at the base swinging to NNE at the top (Poliquin, 1987). In section D the entire Chaudière and pre-Chaudière sediment sequence is intercalated in thrust plates dipping toward 005°, a direction compatible with the maxima of several fabrics measured in sections A and B. Elsewhere in SE Quebec, fabric of Chaudière Till tends to vary from WSW at the base to SE at the top. In the Chaudière Valley, fabric, measured in the few sites where Chaudière Till has been identified, ranges from SSW to 110°, the latter also being the direction of striae on the surface of Chaudière Till buried by overlying Gayhurst Formation sediments at Rivière Samson (Shilts, 1978).

On Rivière des Plante, Chaudière Till is impoverished in ultramafic clasts and in trace elements typically enriched in ultramafic outcrops, compared to underlying Johnville Till and overlying Lennoxville Till. These sections are located just a few hundred metres southeast of ultramafic bedrock within an ophiolitic complex that crops out along the northwest side of Rivière des Plante valley. The low concentrations of ultramafic debris in Chaudière Till at these sections provides strong support for a WNW to WSW to SSW sequence of shifting ice flows during the first part of the Chaudière glaciation, because only a south to east flow trajectory would have transported ultramafic erratics from the local outcrops across these sections. An additional source of low concentrations of ultramafic debris in Chaudière Till is probably sediment reworked from the underlying, ultramafic-rich Johnville Till. In sections analyzed by Poliquin (1987), ultramafic clasts, Ni, Cr, and Co also tended to be enriched near the top of the till, supporting the inference that ice flow was southerly to southeastwardly at the time the uppermost debris was deposited.

Elsewhere in SE Quebec, the shift of fabric and composition evident in Chaudière Till is taken as evidence that, at the onset of the Chaudière glacial phase, an independent ice cap grew in the eastern Appalachians, in Maine and/or New Brunswick. That ice cap was eventually overwhelmed by southeastwardly advancing Laurentide ice. The geological setting of these sections is such that such a history of ice flow is strongly supported both by fabric and by the unique constraints derived from till compositions. It should be pointed out that Chaudière Till also contains a very small percentage of Precambrian crystalline erratics, presumably derived from the Canadian Shield north of the St. Lawrence River. Elsewhere in this region it has been reported that Chaudière Till is devoid of such erratics, an observation that is often interpreted to mean that no Laurentide Ice was involved in Chaudière deposition. Poliquin (1987) has suggested that the crystalline erratics in Chaudière Till on Rivière des Plante were derived from underlying Johnville Till and Massawippi Formation sediments or were transported by Laurentide Ice from the Canadian Shield during the later phases of Chaudière deposition. It is not possible to say which of these possibilities is most compelling, and it is likely that both contributed to the presence of Precambrian clasts in Chaudière Till.

Gayhurst Formation. Because the Rivière des Plante sections are well below the lowest altitudes of Glacial Lake Gayhurst, the Gayhurst Formation at these sites consists primarily of its deep-water, laminated facies. At section D, the laminated facies is interbedded with several till-like diamictons, ranging in thickness from a centimeter to over a meter. These are interpreted as mud flows of englacial debris that melted from the submerged ice front and flowed as slurries from near its base. The intercalation of mudflows and laminated sediments is characteristic of the Gayhurst Formation throughout the Chaudière Valley (Shilts, 1981; see comment in this publication under Stop 2). The mud flows characteristically have conformable, horizontal contacts with enclosing silt-clay laminae and are thus differentiated from beds of till, which usually have erosive basal contacts and an irregular upper surface shaped by processes associated with the release from ice of the debris of which the till is composed.

At sections B and A, the Gayhurst Formation is a thin, discontinuous, laminated sandy-silt with gravel and diamicton lenses. Whether it was partially removed by the overriding Lennoxville glacier or was not deposited to any great thickness is not known.

It is characteristic of deep water facies of the Gayhurst Formation to vary from thicknesses of <1 meter to over 100 meters over short distances in boreholes and sections farther south in the Chaudière Valley. This is probably because the main source of sediment in the lake was focused on specific areas of the lake bottom by subglacial drainage exiting from ice tunnels. This internal drainage is thought to have injected large quantities of basal debris into the lake as dense, bottom-hugging slurries (density underflows) in cycles of short, perhaps even diurnal, duration. These underflows, exiting at specific localities at or near the interface between the glacier base and the lake's bottom, preferentially would have filled depressions and would have left little or no sedimentary record over the positive features of the lake bottom. Mud melting from the basal, debris-rich zones of the ice would have flowed into the depressions at irregular intervals along with the water-sorted slurries of cold, rock-flour-laden meltwater.

Lennoxville Till. Lennoxville Till caps all the sections along Rivière des Plante. It is grey, weathering brown or tan, compact, cobbly till with some lenses of gravel and numerous sub-horizontal partings that give it a fissile appearance where washed by water. The gravel lenses are thought to be dewatering channels cut into stagnant, basal, debris-rich ice from which till was released by meltout. Most of the structures seen in tills of this region are thought to have formed as a result of the release of debris by slow meltout, and not by lodgment. Prominent, section-wide beds of laminated silty sand and silty clay occur within the Lennoxville Till, particularly in section B. These are thought to have been deposited in standing water beneath the glacier when it lifted periodically off its base, admitting lake water, during deglaciation. Along Rivière Fraser, a Rivière des Plante tributary joining just downstream from these sections, a clay-rich surface till appears to overlie laminated lake sediments which, in turn, overlie Lennoxville Till, so some of the uppermost parts of the sections may be part of that sequence. A glacial/proglacial sequence that appears to overlie Lennoxville Till has been observed elsewhere in the Chaudière Valley and is thought to be related to the late-glacial southward readvance (erosional phase 7) of lobes up the Chaudière and adjacent valleys that followed the northward (erosional phases 5and 6) reversal of ice flow.

Lennoxville Till has fabric reflecting the southeastwardly flow direction of its depositing glacier, and, like the JohnvilleTill, it is rich in ultramafic clasts and geochemical indicators of ultramafic provenance. Because of similarities to the Samson River section (Shilts, 1978; Paul, 1987) has divided the Lennoxville Till into upper and lower members at section B on the basis of the presence of water-sorted sediments that occur as continuous bands in the middle of the Lennoxville sequence in both sections. At section B, two 7 m (±)-thick till beds are separated by a 2 m-thick complex of laminated silty clay, sand, diamicton lenses, and carbonate-cemented gravel. The lower part of the lower member of Lennoxville Till is grey, but becomes brown near the contact with overlying sorted sediments. The upper member is compact and oxidized to a tan-brown color. The great apparent depth of oxidation in sections B and D is probably related to the oxidizing power of groundwater flowing through the numerous sorted layers and lenses in the till.

Near the surface of sections A and B, there is some evidence of minor washing or reworking of the till, but no clear evidence of any significant post-Lennoxville glaciolacustrine or glaciofluvial sedimentation.

Till-coated ultramafic clasts. At this section, as well as at several other sections in Quebec and Vermont, the modern colluvium and alluvium at the base of the section is littered with cobbles and boulders that appear to be composed of cemented till. When these clasts are broken open, they can be seen to be cored with one or more ultramafic erratics, usually clasts of serpentized peridotite. The ultramafic erratics have apparently reacted with the matrix of the enclosing till to form some sort of cement. Tills in which this phenomenon has been noted range from slightly calcareous (<4% total matrix carbonate) in Quebec to non-calcareous in southern Vermont.

Kilometers
0 Turn around and drive back westward along the Route du Golf
7.3 Turn right on Highway 173
26.3 In Vallée-Jonction, turn left on Highway 112 to cross the Chaudière River
27 Turn right, along the road "Chemin de l'Écore Nord"
30.5 Entrance to gravel pit. Leave the cars on the side of the road.

STOP 4. A late-glacial subaqueous fan – Vallée-Jonction (1 HOUR)

Glacial Lakes in Chaudière Valley. The northward-draining Chaudière Valley was filled with lakes any time ice advanced up it and across the Appalachian Front. Because of the relief of the terrain on either side of the valley, only a limited number of lake outlets were possible. The lowest of these could have carried water westward from a lake standing at about 305 meters a.s.l. Though no evidence of erosion by overflow channels is evident in a col at this altitude near La Guadeloupe, Quebec (Fig. 3), it is possible that a lake could have existed at 305 m (±), particularly in late glacial time. Water draining from such a lake ultimately would have reached the Atlantic Ocean along a tortuous route via the Rivière Saint-François Valley, Lake Champlain basin, and Hudson River. The lack of any evidence of meltwater deposition or erosion at this altitude, however, suggests that any time the Chaudière Valley was blocked, the Saint-François Valley to the west was blocked too, forming a large lake that covered both basins to altitudes well above the La Guadeloupe col.

The next lowest outlet in the Chaudière basin is along the eastwardly trending valley presently occupied by Rivière Famine, which flows westward into the Chaudière at Saint-Georges, and Rivière Daquaam, which flows eastward into St. John River. This valley is a classic overflow channel with a wide, flat bottom, steep sides, and two under-fit rivers flowing in opposite directions from a barely discernible divide on the floor of the valley. It has already been established that this valley carried meltwater eastward into the Atlantic via the St. John River valley during the existence of Glacial Lake Gayhurst, just prior to the Lennoxville readvance. It is probable that it carried late glacial drainage, too, but the record of nearshore deposition in late glacial lakes is too poor to allow any link to be made between the col and lake levels.

The only other major outlets that controlled lake levels in the Chaudière Valley proper (many local high-altitude lakes may have been ponded in its eastern, westward-flowing tributaries) are two cols, each at approximately 429 m altitude east and southeast of Woburn in the Arnold River valley south of Lac Mégantic (Fig. 3). These outlets only functioned when ice stood south of the lower, Famine-Daquaam outlet.

Ice front deposits: Vallée-Jonction subaqueous fan. Several ice-contact sand and gravel deposits lie in the Chaudière Valley and appear to mark ice front positions from the Appalachian Front at least as far south as Saint-Georges. They all bear structures indicating southerly paleo-currents and lie well below altitudes of any of the higher two outlets discussed above. The most impressive of these is the kettled, flat-topped mass of sand and gravel which has been dissected by the modern Chaudière River at Vallée-Jonction, where we will stop.

An apparent paradox was created concerning these deposits at the time that northward ice flow was first documented in Quebec (Lamarche, 1971). These features, obviously built southward into proglacial lakes from the fronts of southward-flowing, northward-retreating ice masses, were surrounded by highlands with hundreds of outcrops on which northward or westward pointing striae clearly postdate the southeastward striae of the Lennoxville glaciation. The paradox was pointed out by Gauthier (1975), by Lortie (1977), and during the Friends of the Pleistocene excursion in 1982 at a stop to observe similar ice-contact sediments in the Saint François Valley to the west.

Shilts and Blais (1989) concluded that the ice front deposits in the Chaudière Valley, at least as far south as St-Georges, were deposited by a narrow lobe of thin ice that readvanced from a Laurentide ice front that had lain more or less passively against the northwest facing flank of the Appalachians from the time that the Laurentide and Appalachian residual ice masses separated until a time at or near the final melting away of the last vestiges of the residual Appalachian ice in the highlands. The readvance probably marks a regional climatic deterioration that caused increased alimentation of the eastern Laurentide Ice Sheet, resulting in augmented flow of ice southward across the St. Lawrence River. While not vigorous enough to penetrate very far into the foothills of the Appalachians, it was strong enough to push lobes up the major valleys, such as the

St-François, Chaudière, and Etchemin. This may have been the first of several such minor readvances that are marked immediately to the north by such deposits as the fossiliferous St. Nicholas till and the St. Narcisse Moraine.

The deposit at Vallée-Jonction is the largest of the ice front deposits that mark the retreat of a late glacial Chaudière Valley lobe. Morphologically, it has a smooth, delta-like foreslope and a level to gently rolling surface with numerous undrained depressions (kettles). To the north it becomes hummocky and passes into a ridge interpreted as an esker, deposited in the conduit that supplied sediment to the fan. On the east side of the valley, only a small remnant of the deposit was left after postglacial down cutting by the Chaudière River. This eastern remnant has been so thoroughly excavated for aggregate that its original morphology is impossible to determine.

The sediments that compose the subaqueous fan are coarse sand and gravel in large-scale foreset beds that dip gently southward and carry southward paleo-current indicators in associated smaller bed forms. In the pits on the eastern side of the valley, the coarse debris can be seen to have prograded over laminated silt and clay which has been deformed by the loading. In pits in the northern part of the deposit, bedding is much more chaotic, being faulted and deformed by ice collapse. Lithologically, the gravel has very low concentrations of ultramafic clasts even though the valley sides adjacent to the deposit are characterized by high concentrations of ultramafic erratics, according to Gadd (1978). The erratics on the valley sides were presumably transported northward from ultramafic outcrops northeast and southwest of the Chaudière River at Rivière des Plante. This suggests that in the lowest parts of the valley, ultramafic-poor debris carried southward by the readvance either covered or diluted ultramafic-rich drift deposited during northward flow.

This landform and deposit can be thought of as a late-glacial analogue of the buried subaqueous fan of the interstadial Gayhurst Formation, visited south of St-Georges at Stop 1. At least one other buried subaqueous fan has been found in the region and is inferred to have been deposited deep below the present floodplain of Rivière Samson, an eastern tributary that is confluent with Rivière Chaudière about 50 km south of St Georges. That fan would have been deposited during the retreat of the Johnville glacier, a conclusion drawn from examination of cores recovered from a deep drilling project in the Rivière Samson valley.

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DIMENSION STONE PRODUCTION AT RIVIÈRE-À-PIERRE, QUÉBEC

by

Jean-Nil Bouchard, Polycor inc., 70 Saint-Paul, Québec, QC G1V 3K9, Canada
Yves Bellemare, Ministère des Ressources naturelles et de la Faune, Québec, QC G1S 4X4, Canada

Abstract

Stone production began at the end of the 19th century in the Rivière-à-Pierre area, located 100 km (62 miles) northwest of Québec City. Today, with 17 quarries in operation, this area is the most important producer of dimension stone in Québec. Production is from the pinkish grey, brownish grey, and greenish grey farsundites and quartz mangerites of the charnockitic Rivière-à-Pierre Plutonic Suite. The first stop on the field trip is at the terraced Dumas & Voyer #4 quarry, where stone is extracted from six production benches. The stone is known as Dark Caledonia, and a part of the production is transformed in the Bordures Polycor plant, which will be visited during stop 2.

Résumé

La région de Rivière-à-Pierre est située à 100 km au nord-ouest de la ville de Québec et l'exploitation de la pierre a débuté à la fin du XIXe siècle. De nos jours, cette région est le centre d'extraction de pierre dimensionnelle le plus important au Québec avec 17 carrières en activité. Les roches exploitées sont des farsundites et des mangérites quartzifères gris rosé, gris brunâtre et gris verdâtre de la Suite plutonique de Rivière-à-Pierre, une suite de roches charnockitiques. Le premier site visité est la carrière Dumas & Voyer # 4 qui est exploitée en terrasse et possède six gradins de production. La variété de pierre extraite est connue sous le nom commercial de Calédonia Foncé (Dark Caledonia) et une partie de la production est transformée à l'usine Bordures Polycor qui fait l'objet du second site visité.

INTRODUCTION

The Rivière-à-Pierre area is located 100 km (62 miles) northwest of Québec City (Fig. 1). Quarrying began in the late 19th century, and this area has since gained an international reputation for the quality of its stone. Nowadays, it is the most important extraction centre for dimension stone in Québec with 17 quarries in activity. This is due to the aesthetic and physical qualities of the stone and the massive aspect of outcrops.

The stone is extracted to produce panels and slabs for multiple uses, such as veneer for building exteriors, tile fabrication, and custom-finished products. Other applications include monuments, stairs, and curbstone, and it was formerly used as paving stone.

A RICH HISTORY

In the beginning, quarrying was related to the improvement of the road system. In 1885, the railway connecting southern Québec to the Lac-Saint-Jean area, and which passed through the village of Rivière-à-Pierre, was completed. This led to the beginning of stone extraction at the cottage industry scale. The first major production was probably carried out by Fortunat Voyer and Joseph N. Perron in 1894. The Langelier building in Québec City is an example of a structure built with pink "granite"[1] quarried by Fortunat Voyer.

At the beginning of the 20th century, two new pink "granite" quarries were in operation near Rivière-à-Pierre. The stone in the piers of the Québec Bridge came from one of these quarries. At the time, more than two thousand wagonloads of stone were shipped to the bridge. From 1920 to 1960, new pink "granite" quarries were put into production. In 1934, a block extracted from Auguste Dumas' quarry was used to build the monolithic cross in Gaspé commemorating Jacques Cartier. The cross, weighing more than 42 tonnes, was transported by train. A

[1] The term "granite" is used in a general sense in the stone industry for all types of quarried stone.

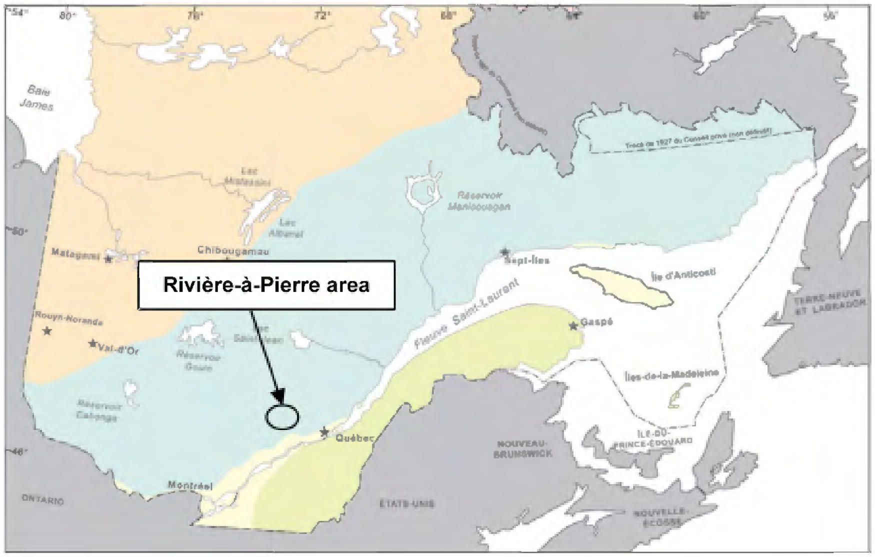

Figure 1. Location map of the Rivière-à-Pierre area

replica of this cross stands in the middle of the village of Rivière-à-Pierre. In 1938, the Arthur Dumas and Fortunat Voyer et Fils companies merged to form Dumas & Voyer Ltd.; this was a major event in the history of quarrying at Rivière-à-Pierre. During the following decades, it was the most active company, with several major projects.

The most significant quarrying phase began in the early 1960s with the opening of 18 new quarries (Fig. 2). In 1961, the White Diamond Granite company began production in the first green "granite" quarry. This stone, known as the Forest Green or Atlantic Green varieties, would later become famous in the construction of the IBM headquarters building in New York City. In 1962, the Dumas & Voyer company opened two new brown "granite" quarries; this was a significant event, since the extracted stone, the Caledonia variety, now boasts an international reputation for its aesthetic qualities.

GEOLOGY AND VARIETIES OF STONE

In the Rivière-à-Pierre area, metasedimentary and metavolcanic rocks are cut by two families of intrusive rocks. The first family, consisting of farsundites, mangerites, and jotunites, belongs to the Rivière-à-Pierre Plutonic Suite (Hébert and Nadeau, 1995). These rocks are porphyritic and coarse grained. Their basic color is grey, but their secondary tints—pink, brown, and green—give them their commercial importance. Where the texture is locally of rapakivi (or antirapakivi) type, K-feldspar phenocrysts 1–3 cm long by 1 cm wide are surrounded by albite coronas. The other family consists of diorite and grey hornblende tonalite and granodiorite, in which the feldspar is mainly oligoclase, belonging to the La Bostonnais Complex. These two families of rocks were quarried for dimension stone. Nowadays, production comes exclusively from quarries in Rivière-à-Pierre Plutonic Suite rocks.

Pink, brown, and green "granites"

In terms of volume, production comes mainly from brownish grey or orangish brownish grey farsundite and quartz mangerite. The commercial varieties known as Caledonia, Deer Brown, Nara Brown, and Canadian Caledonia are extracted from five quarries. These varieties are similar to each other, although the Nara Brown variety is much more foliated. This foliation may be due to the fact that the quarry is located near the contact with the older rocks of the La Bostonnais Complex. At the Deer Brown quarry, brownish grey farsundite is composed on average of 40% microcline perthite, 15% oligoclase (An_{20-22}), 25–30% quartz, and 10–15% green hornblende and biotite (Béland, 1982).

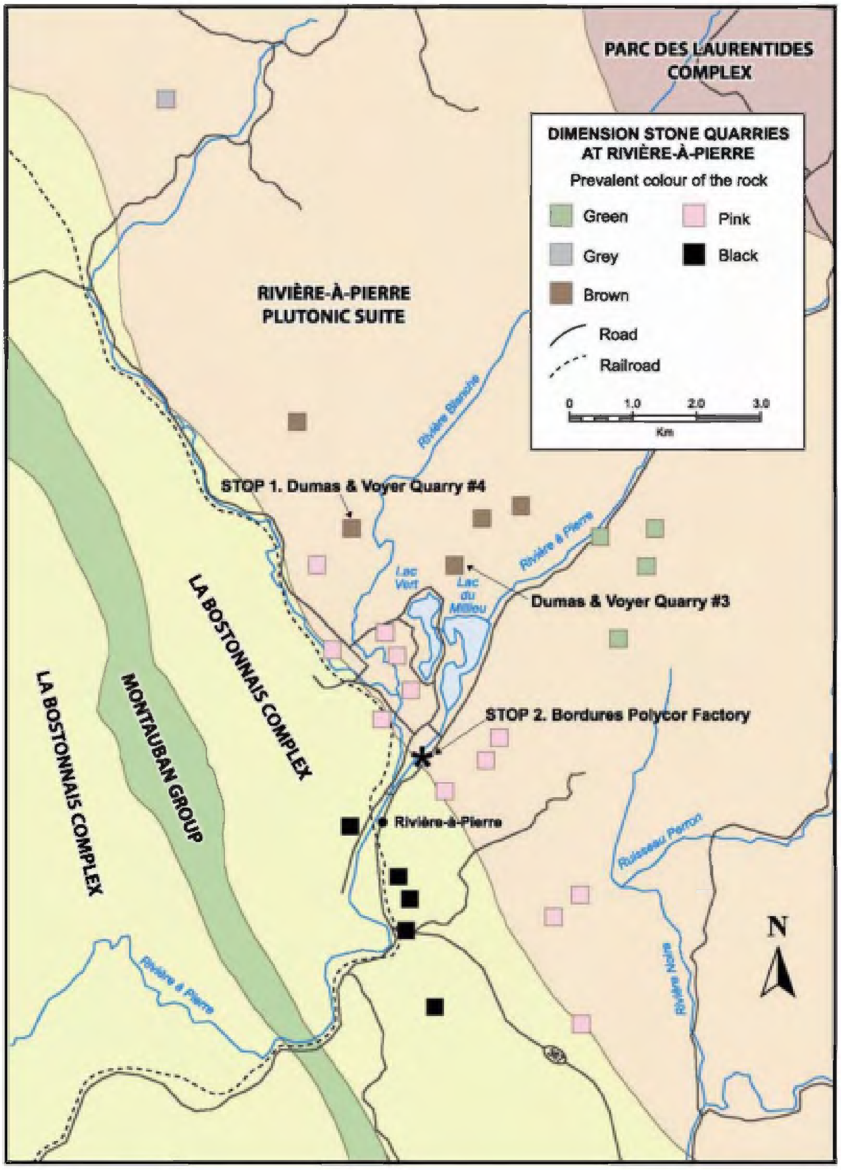

Figure 2. Locations of dimension stone quarries in the Rivière-à-Pierre area

Before 1962 in the Rivière-à-Pierre area, quarrying was mainly from pinkish grey farsundite with mineralogical and textural characteristics similar to those of the brownish grey varieties. Such pinkish rocks occur mainly in the southwestern part of the intrusion at Rivière-à-Pierre; varieties are still produced from two quarries and are known as Gris Rosé, Abbey Rose, Riviera, and New New. Near Rousseau, located 15 km (9.3 miles) southwest of Rivière-à-Pierre, medium-grained, porphyritic farsundite known as Blue Grey is also quarried.

Green "granites" belonging to the same charnockitic suite are also extracted. These include porphyritic, coarse-grained, greenish grey quartz jotunite (Prairie Green variety), greenish black quartz jotunite (Dark Steel variety), and quartz mangerite (Boreal Green variety). On outcrop surface, the rock is typically altered to a rusty-brown color. A porphyritic, coarse-grained, greenish grey farsundite (Atlantic Green variety) also occurs.

Black "granite"

Black "granite," produced mainly between 1894 and 1960, is composed of meta-igneous rocks belonging to the La Bostonnais Complex. The term includes gabbro, pyroxene diorite, granodiorite, and tonalite. These rocks are massive or gneissic and are locally migmatitic. They are medium grained and light bluish grey to dark grey in color. At the Scotstown quarry, the rock consists of 46% oligoclase (An_{29}), 4.5% microcline, 29% quartz, 10.5% biotite, and 8% green hornblende (Mattinson, 1952). Commercially known as Blue-Grey Granite and Dark Blue Pearl, these varieties were produced from three major and six small-scale quarries. The stone was mainly used to produce monuments, curbstone, paving stone, and dimension stone.

Lithogeochemical analyses

Geological mapping and data collected as a result of quarrying in the Rivière-à-Pierre Plutonic Suite have allowed at least three facies to be distinguished on the basis of the dominant color of feldspar (Table 1). Rocks of these facies, and more particularly those of the green facies, possess distinctive geochemical signatures.

Pink facies rocks, located mainly at the southwestern border of the pluton at Rivière-à-Pierre, have SiO_2, K_2O, and Na_2O contents greater than those of the green facies. Green facies rocks are characterized by TiO_2, P_2O_5, CaO, and MgO contents greater than those of pink and brown facies rocks. However, not all green facies rocks have the same characteristics. At the Deer Brown quarry, greenish grey farsundite (Atlantic Green variety) is extracted from an approximately 70 meter-wide lens in contact with brownish grey farsundite (Deer Brown variety). The transition between the two facies is gradual over a width of two meters. On outcrop surface, the two facies have the same appearance and alteration color and are very difficult to distinguish. The Atlantic Green variety possesses a chemical composition similar to that of the Deer Brown variety but is chemically distinct from the other green "granites" of the Rivière-à-Pierre Plutonic Suite; this difference confirms its specific character (Bellemare, 1999). In the area, four other quarries present the same transitional characteristics: Fletcher (Newport and Abbey Rose varieties), Marmite (Forest Green, Atlantic Green, and Atlantic Blue varieties), Atlantic Blue (Atlantic Blue and unexploited green "granite"), and Boca (Canadian Caledonia variety and a greenish grey farsundite similar to the Atlantic Green variety).

ROAD LOG

Distance in kilometers (*miles*)

0.0 (*0.0*)	Start at the intersection of De l'Église and Principale streets (in front of City Hall) in Rivière-à-Pierre. Go north on Rue Principale.
1.21 (*0.75*)	Turn left and take the bridge across Pierre River.
1.45 (*0.9*)	Turn right onto Rue Lac Vert.
3.62 (*2.25*)	Turn right onto Réserve de Portneuf road # 1.
4.51 (*2.8*)	Turn right and take the quarry road.
6.28 (*3.9*)	Stop 1, Dumas & Voyer # 4 quarry.

STOP 1. Dumas & Voyer quarry # 4

Development was first carried out in 1969 by prospectors Léo and Roger Lavoie. Commercial quarrying began in 1988 by the company Dumas & Voyer Ltd., which in 1994 became a division of Groupe Polycor. Production here has intensified over the past years, and the quarry has become the main site of extraction site for the company in Rivière-à-Pierre (Fig. 3). The quarry is developed in terraces and is located on the southeastern slope of a 100 m high hill. It consists of 6 production benches, where the height of the walls ranges from 3.5 to 5.5 m. In 2007, the monthly production from quarry # 4 is approximately 900 cubic metres of commercial blocks, with a recovery ratio of 25%. The site is equipped with 3 mobile loaders and 7 hydraulic drill units (2 Tamrocks from Finland and 5 Apaches designed in Québec). If need be, quarry # 3 is operated to satisfy additional demand.

Table 1. Lithogeochemical analyses[2] of varieties from the Rivière-à-Pierre Plutonic Suite

Quarry	Variety	Lithofacies	SiO_2	Al_2O_3	Fe_2O_3t	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	P_2O_5
Pink facies												
Newport	Abbey Rose	Farsundite	68.80	13.40	4.64	0.69	2.56	3.30	4.34	0.77	0.10	0.32
Dumas & Voyer # 1	Pinkish Grey	Farsundite	68.00	13.20	5.75	0.81	2.21	3.14	4.15	0.92	0.11	0.38
Granit Rivière-à-Pierre	–	Farsundite	66.11	13.98	5.20	0.81	2.48	3.05	4.93	0.87	0.11	0.32
Brown facies												
Deer Brown	Deer Brown D.D.	Farsundite	69.70	14.00	4.60	0.74	2.38	3.01	4.20	0.73	0.07	0.28
Dumas & Voyer # 3 and 2	Caledonia	Farsundite	68.90	13.40	5.23	0.72	2.71	3.28	4.12	0.83	0.09	0.34
Deer Brown	Deer Brown	Farsundite	67.70	13.80	4.85	0.71	2.76	3.46	4.07	0.78	0.09	0.32
Colombia 13	Nara Brown	Farsundite	66.20	14.50	5.20	0.78	2.82	3.27	4.55	0.82	0.11	0.33
Dumas & Voyer # 3 and 2	Caledonia	Farsundite	66.10	13.90	5.39	0.78	2.69	3.08	4.51	0.87	0.10	0.32
Green facies in lens												
Deer Brown	Atlantic Green	Farsundite	67.50	13.80	4.86	0.71	2.69	3.17	4.25	0.78	0.09	0.32
Lacroix et Fils 1	Atlantic Green	Farsundite	66.10	15.00	5.52	0.78	3.53	3.55	3.44	0.89	0.08	0.40
Green facies												
Martineau et Deschambault	Rivière-à-Pierre Green	Quartz mangerite	64.10	16.40	5.62	0.95	4.70	3.86	2.90	0.93	0.08	0.57
Lacroix et Fils 1	Forest Green	Quartz mangerite	63.50	11.30	10.90	1.46	4.32	2.80	2.17	1.88	0.17	0.73
Colombia 7	Prairie Green	Quartz jotunite	57.70	15.90	9.36	1.50	5.97	3.76	2.46	1.57	0.16	1.05

[2] Results are in wt.%; X-ray fluorescence – pearls.

Sales are increasing in Asia, with over 7000 cubic metres exported in 2006 to Xiamen and Shanghai in China, Taiwan, and South Korea. Approximately 4000 cubic metres are sold to Groupe Polycor's facilities and a dozen external clients for the production of landscaping slabs and stones. The latter production is decreasing strongly with the decline in curbstone sales to the United States and as a result of the decrease in the relative value of the American dollar.

The dominant rock, the Dark Caledonia variety, is a porphyritic farsundite of the Rivière-à-Pierre Plutonic Suite. The stone is coarse grained and has a brownish grey color. The brown feldspar phenocrysts are 1–3 cm long (Fig. 4). The rock is similar to the Dark Caledonia variety from the Dumas & Voyer # 3 quarry. The main detrimental characteristics are local concentrations of black minerals, inclusions of mafic gneiss and quartzite, pegmatite dikes, and the local absence of dark minerals.

Figure 3. Dumas & Voyer Quarry #4

Figure 4. Dark Caledonia variety, Dumas & Voyer Quarry #4

Distance in kilometers (*miles*)

6.28 (*3.9*)	Dumas & Voyer # 4 quarry.
8.05 (*5.0*)	Turn left onto Réserve de Portneuf road # 1.
8.93 (*5.55*)	Turn left onto Lac Vert Street.
11.10 (*6.9*)	Turn left and take the bridge across Pierre River.
11.35 (*7.05*)	Turn right onto Principale Street.
11.99 (*7.45*)	Stop 2, Bordures Polycor factory.

STOP 2. Bordures Polycor Inc. factory

This factory specializes in products for civil engineering projects. The main product is curbstone (Fig. 5), which is marketed in Québec and in the states of Maine and New York. Production is also geared to landscaping requirements (Fig. 6) in the states of Massachusetts, Maine, and Connecticut. The site has produced, among other things, enormous quantities of stone for bridge projects in Boston. The facility is equipped with large discs for primary cuts and 2 impressive guillotines for cutting curbstones.

END OF FIELD TRIP. Return to Québec City.

ACKNOWLEDGEMENTS

We thank Claude Hébert and Thomas Clark from the Ministère des Ressources naturelles et de la Faune (MRNF) for their comments on the manuscript.

Figure 5. Curbstones from Bordures Polycor Inc.

Figure 6. Cap stone of the Black Cambrian variety for the 2003 Grande-Allée redevelopment project in Québec City, from Bordures Polycor Inc.

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A FORELAND TO HINTERLAND STRUCTURAL TRANSECT ACROSS THE HUMBER ZONE SOUTH OF QUEBEC CITY, SOUTHERN QUEBEC APPALACHIANS

by

Sébastien Castonguay and Nicolas Pinet, Geological Survey of Canada, GSC-Québec,
490, rue de la Couronne, Québec, QC G1K 9A9, Canada
Alain Tremblay, Université du Québec à Montréal (UQAM), Montréal, QC H3C 3P8, Canada
Daniel Brisebois, Ministère des Ressources naturelles et de la Faune du Québec, QC G1S 4X4, Canada

INTRODUCTION

This field trip will focus on the structure of Cambrian-Ordovician rocks of the Laurentian margin (Humber zone) in the Beauce region south of Quebec City. It represents a regional section from the less deformed/metamorphosed external Humber zone to the polydeformed and metamorphosed internal Humber zone, which have been variously affected by Middle to Late Ordovician (Taconian), Silurian-Early Devonian and Middle Devonian (Acadian) tectonism. A stop in a new quarry will provide exceptional exposure of the Sainte-Marguerite Complex, a series of slivers of Grenvillian lithologies caught up along the Richardson fault zone. We will examine different structural features in the hanging wall and footwall of major faults along the Chaudière River transect, and discuss their implications regarding the tectonic evolution 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 tectonostratigraphy and structure of the paleo Laurentian margin along the strike of the Northern Appalachians.

GEOLOGICAL SETTING

The Early Paleozoic rocks of the southern Quebec Appalachians have been divided into two main tectonostratigraphic zones (Figs. 1 and 2; Williams, 1979, 1995a and references therein). East of the Cambrian-Ordovician rocks of the St. Lawrence platform and Appalachian foreland basin is the Humber zone. It represents rock units of the ancient continental margin of Laurentia that have been detached from their basement, principally displaced northwestward, and tectonically thickened and metamorphosed during the Middle to Late Ordovician Taconian orogeny (St-Julien and Hubert, 1975). This orogenic event was the result of the attempted subduction of the Laurentian margin and the accretion of various ophiolitic complexes and associated oceanic terranes (Pinet and Tremblay, 1995; Tremblay and Castonguay, 2002), collectively named the Dunnage zone, or resulting from the collision and the accretion of peri-Laurentian microcontinental terranes (Waldron and van Staal, 2001). In the Canadian Appalachians, the surface boundary between the Humber and Dunnage zones is known as the Baie Verte-Brompton line, which is loosely defined by a linear zone of discontinuous serpentinites and dismembered ophiolites (Williams and St-Julien, 1982). The Dunnage zone lies tectonically over the Humber Zone and is overlain by Upper Silurian (Pridolian) and Devonian rocks of the Gaspé Belt (Bourque et al., 1995), mainly occurring in the Connecticut Valley-Gaspé trough (Tremblay and Pinet, 2005).

The Humber Zone (Fig. 2) forms a classical foreland-hinterland succession of parautochthonous and allochthonous rock units that have mainly been deformed and metamorphosed during the Taconian orogeny, but that were also variously affected by Silurian-Early Devonian and Middle Devonian (Acadian) tectonism (Pinet and Tremblay, 1995; Castonguay et al., 2001a, 2007). The Humber zone is subdivided into external and internal zones based on contrasting structural and metamorphic characteristics (Williams, 1995b). The external Humber zone consists of latest Paleoproterozoic to Middle Ordovician siliciclastic, carbonate, and mafic volcanic rocks that are deformed into a series of imbricate northwest-directed thrust sheets comprising the Taconic allochthons. In Québec, these thrust sheets have traditionally been termed as "nappes" (St-Julien and Hubert, 1975). Rock units have attained the prehnite-pumpellyite to subgreenschist facies of metamorphism (Glasmacher et al., 2003). The internal Humber zone (Hibbard et al., 1995) is made up of greenschist facies rocks, roughly distal lithologic facies of the external zone that are mainly regrouped into lithodemic units, the Sutton and Bennett Schists, which respectively occur within the Sutton Mountains (SMA) and the Notre-Dame Mountains (NDMA) anticlinoria (Fig. 2; Tremblay and Castonguay, 2002; Castonguay and Tremblay, 2003). The latter structures are the result of complex superimposed deformation events that affected the Taconian hinterland during the Silurian-early Devonian and middle Devonian (Castonguay et al., 2001a, 2007).

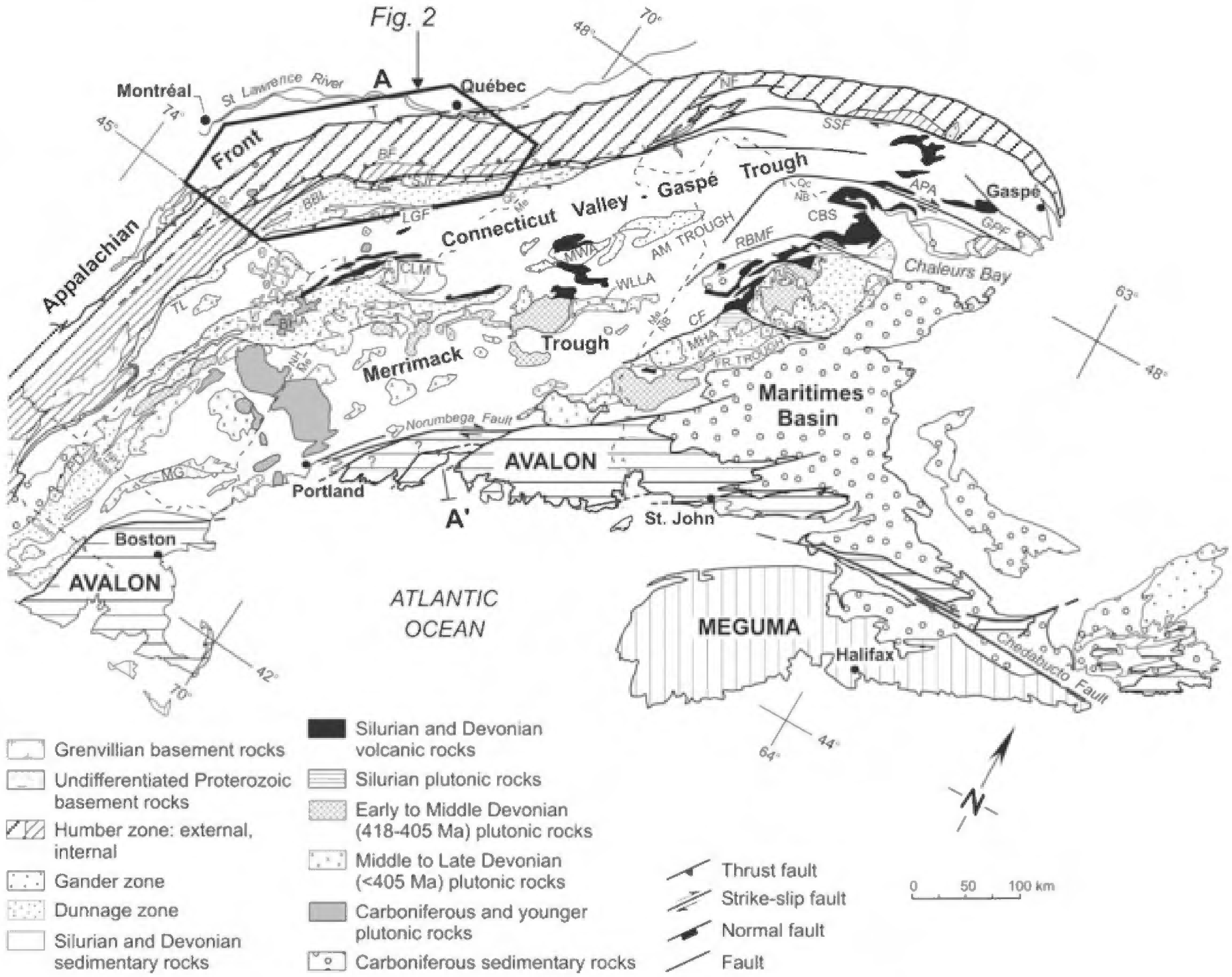

Figure 1. Simplified geologic map of the Northern Appalachians of continental Canada and New England showing major lithotectonic elements. The major Silurian/Devonian sedimentary basins are the Connecticut Valley–Gaspé, Merrimack, Aroostook–Matapedia (AM) and Fredericton (FR) troughs. Basement rocks: CLM – Chain Lake Massif; MG–Massabesic Gneiss; PD – Pelham Dome. Major anticlinoria and synclinoria: APA – Aroostook–Percé anticlinorium; CBS – Chaleurs Bay synclinorium; BHA – Bronson Hill Anticline; MHA – Miramichi Highlands Anticline; MWA – Munsungun–Winterville Anticline; 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; *CF* – Catamaran fault. State boundaries: Conn – Connecticut; Mass – Massachusetts; Me – Maine; NB – New Brunswick; NH – New Hampshire; Qc – Québec; Vt – Vermont. Note that the boundary between Medial New England (Gander zone) and Composite Avalon is approximate (see question marks). Modified from Tremblay and Pinet (2005).

REGIONAL STRUCTURAL GEOLOGY

Three generations of structures are recognized in the Humber zone of southern Québec (Tremblay and Pinet, 1994; Castonguay and Tremblay, 2003): (1) the D_{1-2} phase, a composite phase in the internal Humber zone, represents the Taconian event that is associated with foreland-propagating thrust sheet emplacement and regional metamorphism; (2) the D_3 phase comprises hinterland-directed structures and retrograde metamorphism; and (3) the D_4 phase is associated with the Acadian folding. In the external Humber zone, D_{1-2} consists of northwest-verging folds and thrust nappes (Fig. 2). Thrust faults are marked by olistostromal and/or tectonic mélanges. The regional cleavage is axial planar to close to tight folds. Piggyback thrusting has been documented (St-Julien and Hubert, 1975). Although the kinematics of D_{1-2} deformation within the internal zone are not obvious, principally due to a strong overprint, it is also thought to be dominated by northwest-directed thrust sheet emplacement (St-Julien and

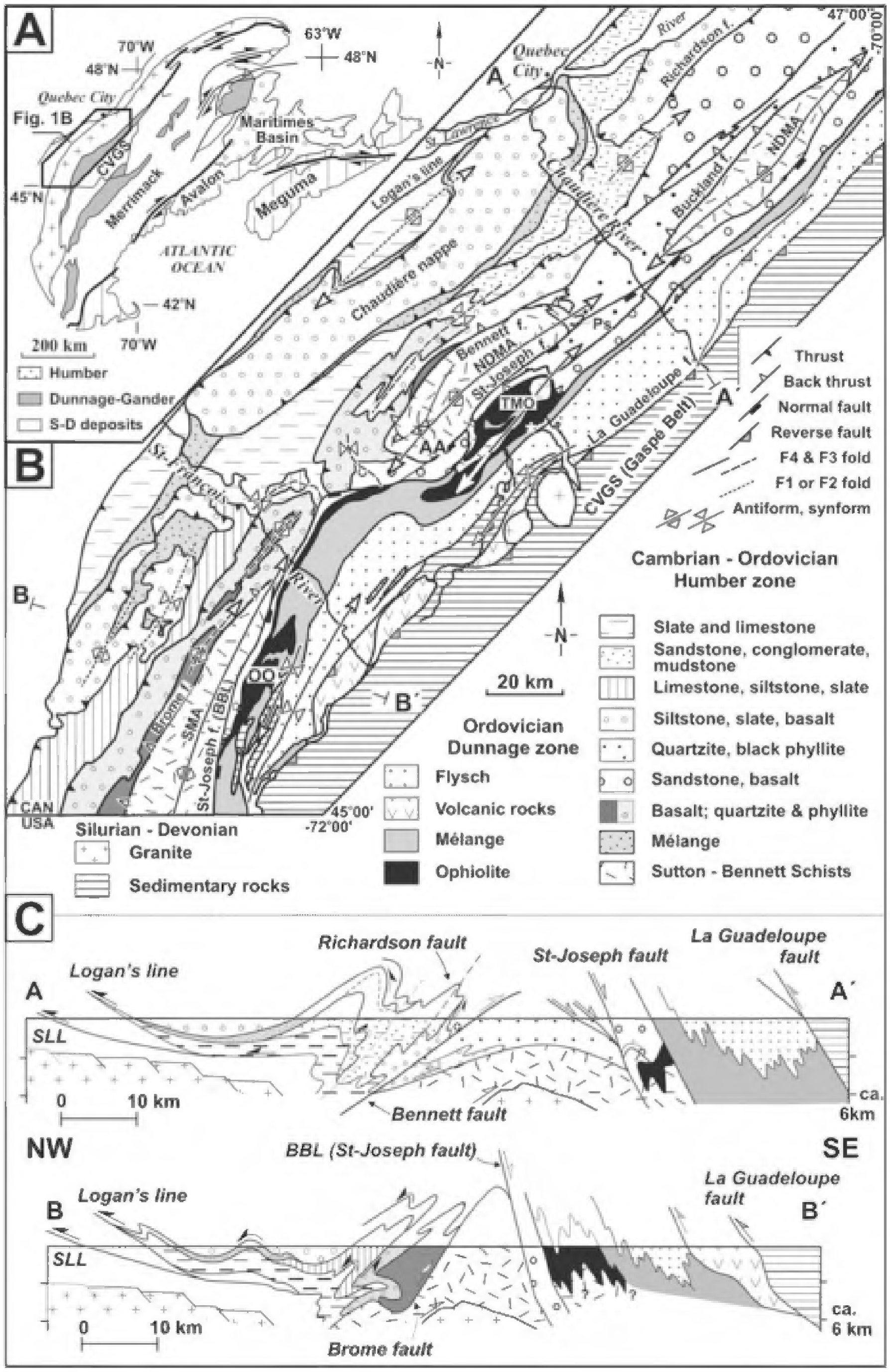

Figure 2. (A) Tectonostratigraphic subdivisions of the Appalachians in mainland Canada and New England. S-D, Silurian-Devonian; CVGS, Connecticut Valley-Gaspé synclinorium. (B) Simplified geologic map of the Humber and Dunnage zones in southern Quebec. Cretaceous intrusions are omitted for clarity. AA, Arthabaska amphibolite; BBL, Baie Verte-Brompton line; f., fault; NDMA; Notre-Dame Mountains anticlinorium; OO, Orford ophiolitic Complex; PS, Pennington sheet; SMA, Sutton Mountains anticlinorium; TMO, Thetford-Mines ophiolitic Complex. (C) Structural sections see Figure 2B for location. Cross pattern represents the Grenvillian basement, which is schematically shown. SLL, St. Lawrence Lowlands platform. Modified from Tremblay and Castonguay (2002).

Hubert, 1975; Pinet et al., 1996a).). The composite nature of the fabrics ($S_{1\text{-}2}$) is recognized in areas of limited D_3 overprint, where the S_1 schistosity is involved in curvilinear and intrafolial F_2 folds that are attributed to a progressive and continuous $D_{1\text{-}2}$ event. Elsewhere, the $S_{1\text{-}2}$ fabric is a northeast-southwest-trending composite schistosity defined by a metamorphic differentiation (Pinet et al., 1996a; Castonguay and Tremblay, 2003). A mineral and/or stretching lineation ($L_{1\text{-}2}$) is generally down-dip on $S_{1\text{-}2}$ surfaces. F_2 folds are nearly isoclinal and their axes are often curvilinear. Within NDMA, the identification of $D_{1\text{-}2}$ shear zones is rendered difficult by the intensity and homogeneity of $D_{1\text{-}2}$ fabrics and by locally intense superposed deformation (i.e., D_3). $D_{1\text{-}2}$ shear zones are however inferred in the field at stratigraphic cutoffs and along discontinuous serpentinite slivers (Tremblay and Pinet, 1994; Pinet et al., 1996a).

$D_{1\text{-}2}$ structures are overprinted by a heterogeneously-developed S_3 crenulation cleavage, that is axial planar to southeast-verging folds and associated ductile southeast-directed fault zones typified by the Brome and Bennett faults (Fig. 2; Pinet et al., 1996a; Tremblay and Castonguay, 2002; Castonguay and Tremblay, 2003). In the external Humber zone, D_3 structures decrease in intensity to the northwest and away from the Brome-Bennett faults. The northwest-dipping S_3 fabric changes abruptly from a penetrative schistosity along the fault zones, to a crenulation cleavage, until becoming a spaced cleavage less than 5 km northwest of the faults. F_3 fold asymmetry in that part of the external zone is southeast-verging, and is well exemplified southeast of Quebec City, where the Richardson fault is folded by a regional F_3 antiform (Figs. 2 and 3; Pinet et al., 1996a). In the internal zone, M_3 metamorphism is retrograde upon $M_{1\text{-}2}$ assemblage, and is dominated by chlorite and muscovite, which are more abundant near D_3 shear zones and faults (Castonguay and Tremblay, 2003). The S_3 fabric wraps around the axis of the anticlinorium (see D_4 description below) and becomes sub-horizontal and eventually east-dipping along the southeastern flank of the anticlinorium, where it is affected by moderately to steeply-dipping down-to-the-east shear bands and brittle-ductile normal shear zones associated with the St-Joseph fault, a major east-dipping normal fault (Figs. 2 to 4; Pinet et al., 1996b; Tremblay and Castonguay, 2002).

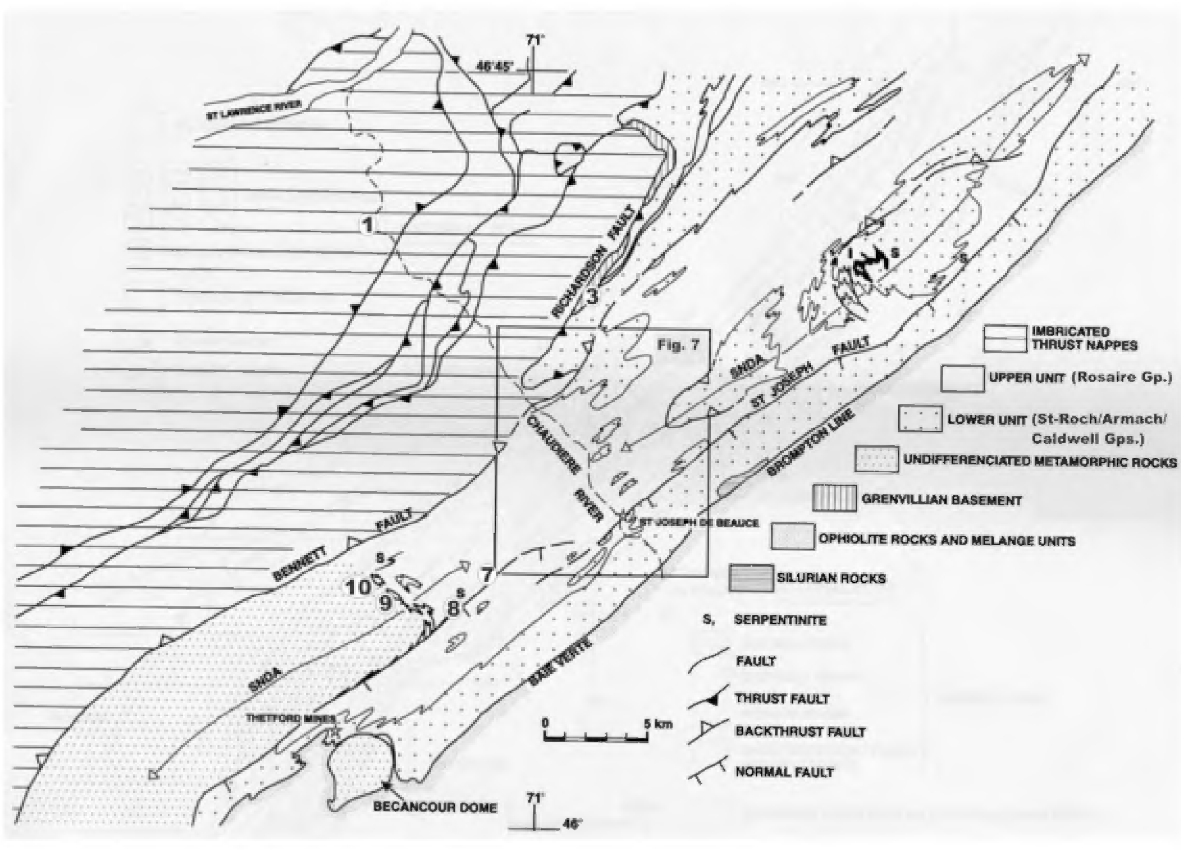

Figure 3. Simplified geologic map of the Chaudière River area, with locations of some of the stops. SNDA Sutton-Notre-Dame mountains anticlinoria. Modified from Pinet et al. (1996b).

As for the Brome and Bennett faults, the St-Joseph fault separates greenschist facies rocks in the footwall from lower grade lithologies, correlative to the external Humber zone, in the hanging wall. East of the St-Joseph fault, the internal Humber zone is locally exposed in the cores of Acadian folds structurally below the Thetford-Mines ophiolite. D_3 structures are also documented east of the St-Joseph fault, e.g., the ophiolite and underlying continental metamorphic rocks are separated from less metamorphosed rocks to the northeast by a folded backthrust fault (Schroetter et al., 2005).

D_{1-2} and D_3 structures are affected by northeast-trending upright folds (D_4) with an axial-planar fracture or crenulation cleavage along which there is no significant metamorphic recrystallization (Tremblay and Pinet, 1994). The final geometry of the NDMA and SMA is attributed to D_4. F_4 vary from open folds in the NDMA, to tight folds in the SMA, which translates into steeper dips of D_3 fabrics along the Brome fault than along the Bennett fault (Fig. 2; Tremblay and Castonguay, 2002). Axial plunges of F_4 folds remain moderate, at <20^o toward the northeast or southwest.

TIMING OF DEFORMATION AND METAMORPHISM

In southern Quebec, early stages of deformation and metamorphism along the Laurentian margin are associated with the emplacement of ophiolites (Fig. 4; Pinet and Tremblay, 1995; Whitehead et al., 1995; Tremblay and Castonguay, 2002). U-Pb zircon ages from plagiogranites of the Thetford-Mines ophiolite (Fig. 2) vary from 480 ± 2 Ma to 478 +3/-2 Ma (Whitehead et al., 2000) and define the age range of ophiolite formation. The $^{40}Ar/^{39}Ar$ amphibole age for the dynamothermal sole of the ophiolite (477 ± 5 Ma) suggests that obduction of the ophiolite occurred shortly after oceanic crust formation (Fig. 4; Whitehead et al., 1995). The ophiolite is crosscut by granites that are absent in the underlying metasedimentary rocks, indicating that the granitoids were injected prior to its final emplacement. U/Pb zircon ages from these granites are 470 +5/-3 Ma and 469 ± 4 Ma (Whitehead et al., 2000; 475-465 Ma in Fig. 4). Their chemistry and abundant inherited zircons suggest derivation by anatexis of continental rocks (Whitehead et al., 2000). The age concordance of granites and ophiolitic sole metamorphism is consistent with the hypothesis that the granites likely formed by melting of the margin due to shear heating below the obducted ophiolite (Whitehead et al., 2000).

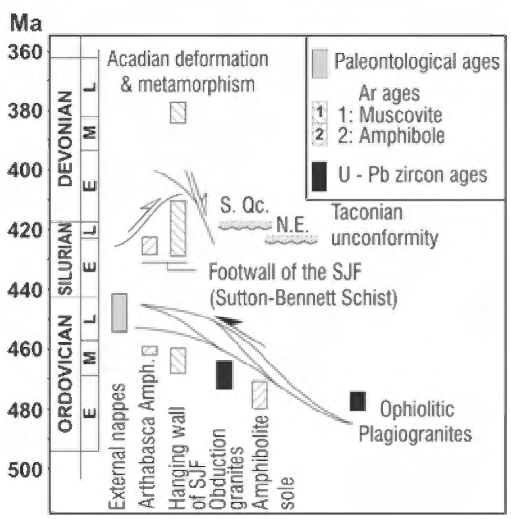

Figure 4 Diagram summarizing age constraints for the deformation and metamorphic events in the southern Quebec Appalachians. Stippled pattern refers to age of basal units of Connecticut Valley-Gaspé trough in southern Quebec (S. Qc.) and New England (N.E.). SJF- St-Joseph fault. Modified from Tremblay and Castonguay (2002).

In the Notre-Dame Mountains anticlinorium, most $^{40}Ar/^{39}Ar$ ages (amphibole and mica single-grains) vary between 431 and 410 Ma (Fig. 4, Castonguay et al., 2001a). However, Ordovician high-temperature step ages (462-460 Ma) in the Arthabaska Amphibolite (Fig. 2) suggest that the isotopic imprint of the Taconian metamorphism is locally preserved in the anticlinoria. The absence of ages between Middle Ordovician and Silurian suggests that protracted cooling of the internal zone from Ordovician to Silurian times is unlikely and that the ages correspond to distinct tectonometamorphic events (Castonguay et al., 2001a).

Southeast of the St-Joseph fault, Middle Ordovician muscovite ages ($^{40}Ar/^{39}Ar$, 469-461 Ma; Whitehead et al., 1996; Castonguay et al., 2001a) are preserved in Acadian structural outliers of Laurentian metamorphic rocks (Figs. 2 and 3). These Ordovician muscovites show no Silurian overprint and are concordant with the high-temperature amphibole ages of the Notre-Dame Mountains anticlinorium (Fig. 4). Detrital muscovites with $^{40}Ar/^{39}Ar$ ages greater than 945 Ma (Castonguay et al., 2001a) are found in very low grade continental rocks surrounding both the ophiolite and the underlying internal-zone rocks in the hanging wall of the St-Joseph fault and the Baie Verte-Brompton line. This suggests that these rocks have escaped intense Appalachian metamorphism and were subsequently juxtaposed to metamorphic units by extensional faulting. In southern Quebec, the Acadian metamorphism is dated at 385-375 Ma by muscovite $^{40}Ar/^{39}Ar$ ages in the southern part of the Dunnage zone (Tremblay et al., 2000).

In the external Humber zone, the timing of emplacement of the Taconic allochthons is based on faunal control (Fig. 4) and on recently acquired K-Ar data on thrust-related fault rocks (Glasmacher et al., 2003; Sasseville et al., in press). Graptolites in mélanges at the base of thrust nappes indicate emplacement ages from latest Middle Ordovician to Late Ordovician (Nemagraptus gracilis Zone to Corynoides americanus and Orthograptus ruedemanni zones; St-Julien and Hubert, 1975). Foreland limestones and synorogenic flysch deposits record the Late Ordovician deepening of the foreland basin. K-Ar data obtained on clay fraction from various fault rocks define four age groups at: (1) ca. 490 Ma, (2) 465 to 450 Ma, (3) ca. 410 Ma, and (4) ca. 355 Ma. Sasseville et al. (in press) attribute the first two age groups to Taconian deformational pulses (D_1 and D_2), the third group to Late Silurian-Early Devonian extensional deformation (D_3), and the fourth age group as characterizing the Acadian compression (D_4). This dataset challenges the traditional view of a gradual and in sequence NW propagation of faulting across the external Humber zone.

STRUCTURAL EVOLUTION

The proposed structural evolution of the Laurentian margin is shown in Figure 5 (Tremblay and Castonguay, 2002). The Taconian stage (ca. 480 to 445 Ma) involves stacking of northwest-directed thrust nappes (Fig. 5A). D_{1-2} deformation progressed from east to west, from ophiolite emplacement and related metamorphism in the underlying margin during 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 foreland (westward) translation of metamorphic rocks because of frontal accretion have led to progressive exhumation of deeper crustal levels of the orogen (hence preserving Ordovician isotopic ages), parts of which are now preserved below the ophiolite in the downthrown side of the St-Joseph fault. Out-of-sequence imbrication is documented in the external zone during the Late Ordovician (Sasseville et al., in press).

D_3 deformation began in latest Early Silurian time (ca. 430 Ma), and lasted until the Early Devonian (ca. 410 Ma; Fig. 5B). In the internal Humber zone, D_3 first consisted of ductile southeast-directed shear zones defining a major upper plate-lower plate (UP-LP) boundary, i.e., the Bennett-Brome fault, and culminated with normal brittle-ductile faulting along the St-Joseph fault. 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 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 fault, i.e., rocks units of the Notre-Dame Mountains and Sutton Mountains anticlinoria in the up thrown side were brought against rock units belonging to both the external and internal Humber zone in the downthrown side (Figs. 2 and 5). East of the St-Joseph fault, the D_3 event thus accounts for the presence of low grade lithologies (analogous to the external-zone rocks), their juxtaposition with ophiolites or underlying metasedimentary rocks, the presence of southeast-verging recumbent folds (originally interpreted as gravity nappes by St-Julien and Hubert, 1975). In the external Humber zone, the kinematic change in the tectonic regime during the Silurian-Early Devonian resulted in normal faulting and is interpreted to culminate in the extensional collapse of the foreland belt, coeval with SE-directed tectonic transport occurring in the hinterland (Sasseville et al., in press). D_3 is coeval with tectonism that is associated to the Salinic or Salinian orogeny in correlative terrains of Atlantic Canada (Dunning et al., 1990; Cawood et al., 1995).

Acadian compression (D_4) resulted in the folding of D_{1-2} and D_3 structures and in the passive rotation, steepening and possible reactivation or tectonic inversion of some faults east of the St-Joseph fault or BBL (Fig. 5C). In the external Humber zone, D_4 structures comprise late Devonian contractional faults, and discrete but widespread normal faults that further segmented the Taconic thrust sheets.

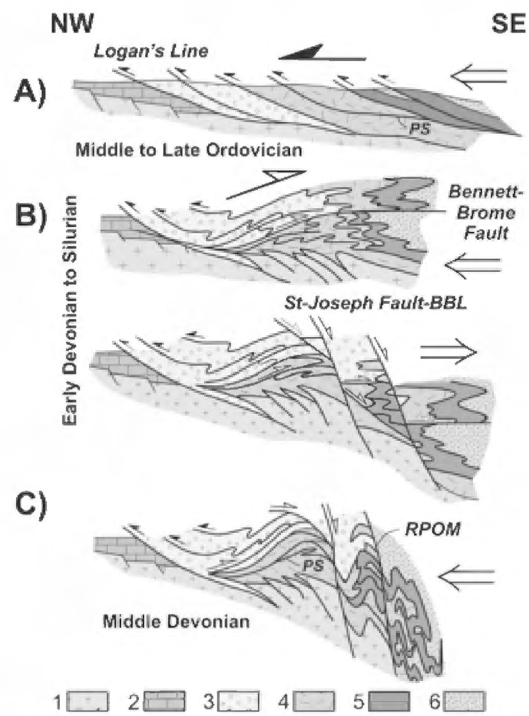

Figure 5. Schematic model for structural evolution of Laurentian margin in southern Quebec. Arrows indicate the overall crustal stress (compression or extension) for each event. See text for discussion. 1- Grenvillian basement, 2- St. Lawrence Lowlands platform, 3- External Humber zone, 4- Internal Humber zone, 5-6- ophiolites and marine sedimentary rocks of Dunnage zone. Modified from Tremblay and Castonguay (2002).

THE CHAUDIÈRE RIVER TRANSECT

Tectonostratigraphy

In southern Québec, Cambrian-Lower Ordovician continental slope deposits of the Humber zone are part of the Québec Supergroup. The succession occurs in a number of thrust nappes, most of which having distinct stratigraphic nomenclatures and are commonly separated by tectonic and olistostromal mélanges (Fig. 3 and 6; St-Julien and Hubert, 1975; St-Julien, 1995; Lebel and Hubert, 1995; Lavoie et al., 2003). From Quebec City southward along the Chaudière River valley, they are:

- The Chaudière nappe is constituted of multicolored (mainly green, red and gray) interbedded mudstone, sandstone and conglomeratic horizons of the Lower to Middle Cambrian Sillery Group.
- The Sainte-Hénédine nappe (Saint-Maxime nappe of St-Julien, 1995) is made up of interbedded multicolored (mainly green, red and gray) interbedded mudslate, siltstone, minor calcareous sandstone and polymictic conglomerate of the Sainte-Hénédine Formation. This poorly constrained informal unit has been interpreted as representing distal facies of the Ile d'Orléans Group (middle Cambrian to Lower Ordovician) occurring mainly on the island of the same name east of Quebec city (Lebel and Hubert, 1995; Castonguay et al., 2001b).

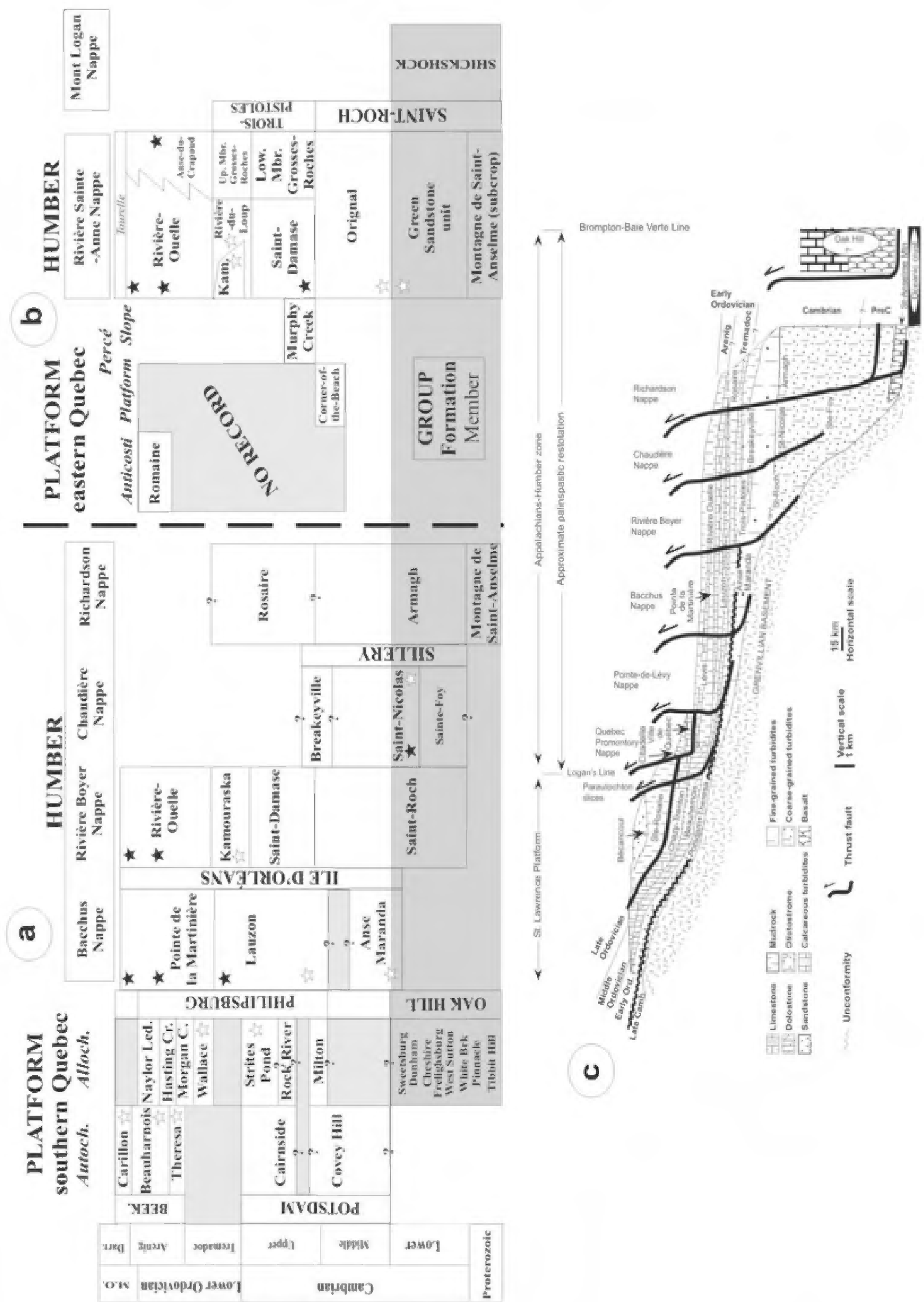

Figure 6. Rift–drift transition (dark shaded area) stratigraphic correlation of slope and platform rocks in the Quebec Reentrant in southern Quebec (a) and eastern Quebec – Gaspé (b). The interpretation for the Oak Hill Group is preliminary. Open stars are new biostratigraphic data from acritarchs and conodonts, whereas filled stars are biostratigraphic information from brachiopods, trilobites, graptolites, and chitinozoans. Pale-shaded area is for non-deposition. (c) Schematic diagram of the Humber Zone and St. Lawrence Platform showing the assumed lateral relationships of tectono-stratigraphic nappes. Note that the Oak Hill Group/nappe experienced the larger Taconian displacement. Vertical exaggeration = 15×. Alloch., allochthons; Autoch., autochthons; Beek., Beekmantown Group; Brk, Brook; C., Corner ;Cr. Creek; Led., Ledge; Mbr., Member; PreC, Precambrian. Modified from Lavoie et al. (2003).

- The Richardson nappe, the southern termination of which occurs near Sainte-Marie de Beauce, is dominantly constituted of green sandstone, locally red, with silty interbeds, and subordinate green and purple slate beds, which are correlated to the Lower Cambrian Armagh Group (correlative to the St-Roch Group; Lebel and Hubert, 1995).
- Southeast of the Bennett fault, the section corresponds to a periclinal structural depression between two anticlinoria, where only upper levels of the internal Humber zone are exposed.
    - The Rosaire Group occupies the southeastern part of the study area, northeast of the axial termination of the NDMA, and along the hanging wall of the St-Joseph fault (Fig. 3). It comprises monotonous successions of interbedded white to medium gray quarztites and medium to dark gray phyllites, both locally greenish. Occasional quartzitic siltstone and feldspathic metasandstone also occur. The matrix of some quartzite beds is dolomitic, especially in the southeastern part of the study area. Metamorphism increases from northeast to southwest within the Rosaire Group along the NDMA axis, so that rocks generally become richer in chlorite, and sericite is gradually transformed into muscovite.
    - The Caldwell Group occurs mostly to the southeast of the St-Joseph fault, either in its immediate footwall or as structural windows through the Rosaire Group. The Caldwell Group is made of alternating succession of purplish red and green feldspathic sandstone and slate, with minor quartzite beds. Regionally, volcanic rocks are also present at the base of the succession. Southeast of the St-Joseph fault (i.e., hanging wall), rock units of the Rosaire and Caldwell groups are faintly metamorphosed and have preserved primary structure, which marks a strong contrast with similar units along the footwall of the fault.
- The Bennett Schists are thought to represent distal lithologic facies correlative to the Rosaire, Caldwell and Oak Hill groups that have been polydeformed and metamorphosed at the greenschist facies, to locally epidote-amphibolite facies. The metasedimentary rocks consist of quartzite, phyllite, and quartz-albite-muscovite-chlorite±biotite schist. Metavolcanic rocks consist of chlorite-epidote-actinolite±hornblende (locally barroisite) schist with local amphibolite.

Structure

The Chaudière nappe is limited by the Foulon fault, a major thrust fault cutting underlying fabrics and delineating a klippen that represents the upper most thrust sheet of the Taconic allochthons overlying the foreland fold and thrust belt (Fig. 2; St-Julien, 1995). Its emplacement has been interpreted as out of sequence in relation to the underlying thrust sheets. The footwall of the Foulon fault is marked by the Rivière Étchemin Mélange, a chaotic unit of tectonic origin containing sheared fragments and blocks of neighboring units in a shaly matrix (Lebel and Hubert, 1995; St-Julien 1995)

The Sainte-Hénédine nappe is exposed in the core of a regional-scale F_3 fold, which is clearly delineated by the Richardson fault (Figs. 2 and 3). Based on similar lithostratigraphy and equivalent structural position, the Sainte-Hénédine nappe may be the lateral continuation and trailing edge of the Bacchus nappe exposed mainly on the Ile d'Orléans.

The Richardson nappe is underlain by the Richardson fault, which is a major D_{1-2} thrust that is marked by a tectonic mélange (Rivière Boyer mélange; Lebel and Hubert, 1995) and the Sainte-Marguerite Complex (Fig. 3; Vallières et al., 1978). The latter represents a series of thrust slices made up of high-grade metamorphic rocks that have been interpreted as Grenvillian basement caught up within the fault zone. The Richardson fault outlines a series of overturned F_3 folds that occur in the hanging wall of a southeast-directed shear zone, which is interpreted as the northeastern extension of the Bennett fault (Figs. 2 and 3; Pinet et al., 1996a, 1996b; Castonguay et al., 2001b). In Ste-Marie area, the Richardson fault is truncated by this shear zone (Figs. 2 and 3). The latter is better delineated to the southwest where it juxtaposes parts of the Oak Hill Group in its hanging wall against the higher grade Bennett Schist in the core of the Notre-Dame anticlinorium. Along the northwestern portion of the internal zone (i.e., NW limb of the NDMA), the S_3 crenulation cleavage is northwest-dipping and is attributed to southeast-verging structures. Across the axis of the anticlinorium, the S_3 fabric is a southeast-dipping cleavage paired with an anastamosing network of brittle-ductile low- and high-angle normal faults and associated boudins and folds genetically related to the St-Joseph fault (Figs. 2 and 3; Pinet et al., 1996b).

As mentioned earlier, the Chaudière River area (Figs. 2 and 3) is located between two anticlinoria with opposing plunges, northeast of the periclinal termination of the NDMA. There, D_{1-2} and D_3 fabrics are folded and wrap around the axis of the anticlinorium. At the crest of the structure, most fabrics are sub-horizontal and folds are recumbent. In that area, the sub-vertical S_4 cleavage and upright open F_4 folds are occasionally observed. D_4 fabrics do, however, become apparent and more penetrative to the southeast and southwest.

Along the southeast limb of the anticlinorium, the fabrics mainly dip southeastward and increasingly affected by moderate to steep southeast-dipping brittle-ductile shear zones that have been interpreted as footwall structures related to the St-Joseph fault (Figs. 2, 3, 7 and 8; Pinet et al., 1996b). The latter occur near the village of St-Joseph-de-Beauce; it represents a steep SE-dipping normal fault juxtaposing lithologies of contrasting structural and metamorphic characteristics. The St-Joseph fault is better delineated to the southwest where it is outlined by sheared and folded serpentinite slivers that comprise parts of the Pennington sheet.

ROAD LOG

The field trip is a section between Quebec City and St-Joseph-de-Beauce, principally along the Chaudière River Valley, with complementary stops to the southwest (Figs. 2, 3 and 7). It focuses on the structural characteristics of the external and internal Humber Zone. Stops are located in Figures 3 and 7. Figure 8 illustrates an idealized structural cross-section of the transect.

STOP 1. The external humber zone: Thrust faults and folds of the Chaudière nappe

Location. From Quebec City or from highway 20, take highway 73 South. After ca 7 km, take the exit 124 (Saint-Etienne-de-Lauzon), and turn left on c*hemin St-Grégoire* for ca. 1.2 km. At the intersection with route 171 (*route St-André*), turn left and drive for ~6 km. There is a park-rest area on the left side of the road ("Parc du détroit de la Chaudière"). The outcrop is along the Chaudière River just behind the rest area.

Geological setting. The Cambrian and Early Ordovician passive margin sedimentation in the Québec reentrant is mainly recorded by siliciclastic slope and rise deposits preserved in the Humber zone (Fig. 2). Sedimentary facies consist of four principal successions; 1- Lower - Middle Cambrian red and green shale, green feldspathic sandstone and some carbonate; 2- Upper Cambrian black mudslate, white quartzite and polymictic conglomerate; 3- Lower to Middle Ordovician red, green and black mudstone with subordinate feldspathic sandstone and limestone conglomerate (slope deposits); 4- Upper Middle Ordovician flysch deposits.

In this region, the external Humber zone is bounded to the NW by Logan's line, and by the Bennett fault to the SE (Fig. 2). Within the external zone, the regional deformation is mostly characterized by west-directed thrust faults and folds, and by a regionally-developed cleavage (S_{1-2}).

Field description. The lithologies exposed at this outcrop are part of the Lower to Middle Cambrian Sillery Group (Breakeyville Formation) and consist of a sequence of green sandstone, locally up to 2-3 meters thick, interbedded with red mudslate and minor, thinly-bedded limestone (Fig. 9). The outcrop exposes a series of thrust faults and related folds within the Chaudière nappe. Thrust faults are sub-horizontal or slightly inclined to the east or southeast, and marked by cm- to meter-thick zones of cataclastic breccias 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-directed fault kinematics. Asymmetrical tight to isoclinal folds are nicely exposed in the hanging wall of thrust faults (Fig. 9). K-Ar data from various fault rocks of this locality yielded ages between 471±9 Ma and 451±8 Ma (Fig. 9), which are interpreted as the age of the main movement along these faults (Sasseville et al., in press).

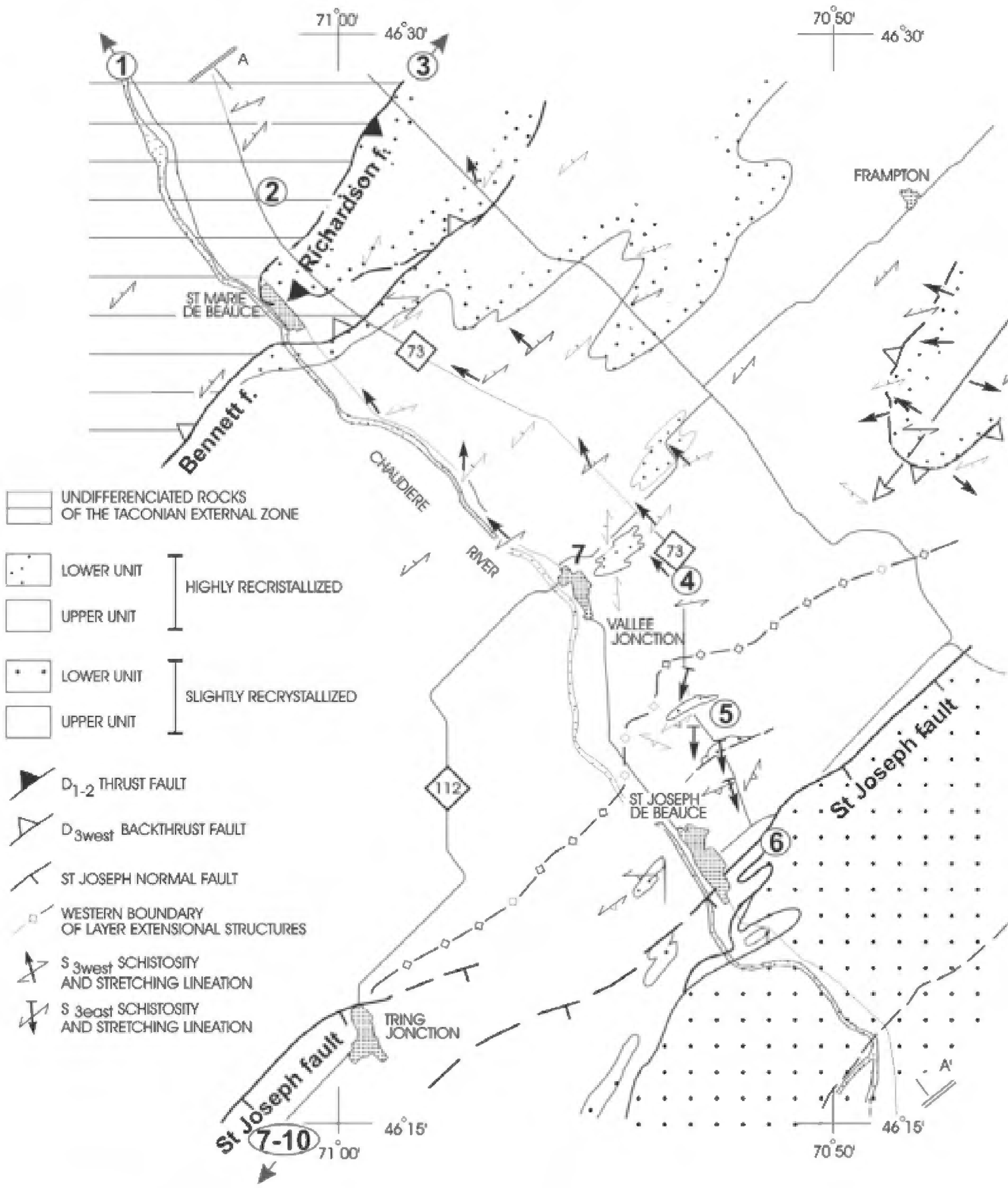

Figure 7. Simplified geological map of the Ste-Marie/St-Joseph-de-Beauce area. The lower unit is Caldwell Group and equivalent; the Upper unit is the Rosaire Group. Modified from Pinet et al. (1996b).

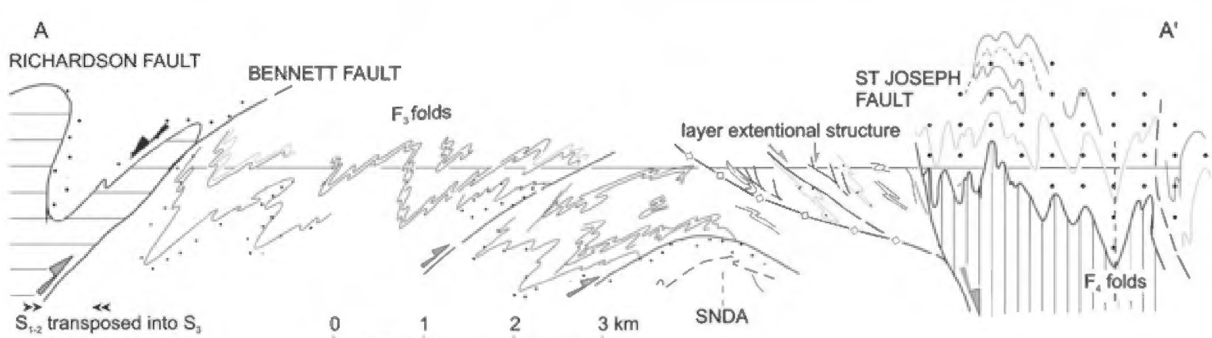

Figure 8. Schematic structural profile of the Ste-Marie/St-Joseph area. See Fig 7 for location. SNDA- Sutton-Notre-Dame mountains anticlinoria. Modified from Pinet et al. (1996b).

Regional implications. The external Humber zone consists of sub-greenschist, fine- to coarse-grained, mainly siliciclastic and calcareous rocks of Late Cambrian to Middle Ordovician age. Overall, the external Humber zone forms an east-dipping imbricate fold and thrust belt that was deformed during the late Middle to early Late Ordovician. The Chaudière nappe is limited by a major thrust fault cutting underlying fabrics and forms a klippen that represents the upper most thrust sheet of the Taconic allochthons in Québec (St-Julien, 1995). Its emplacement is probably out of sequence in relation to the underlying thrust sheets.

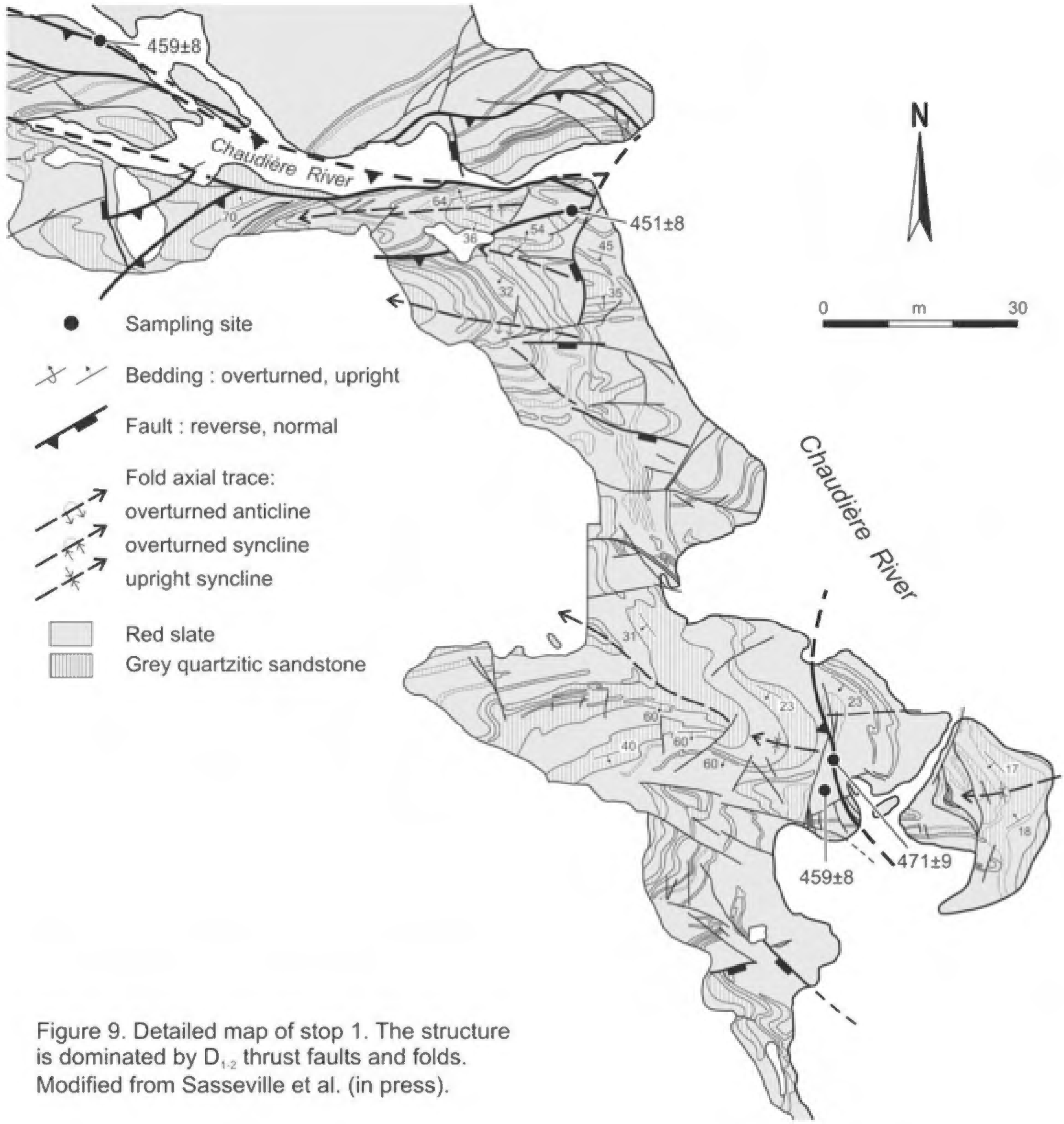

Figure 9. Detailed map of stop 1. The structure is dominated by D_{1-2} thrust faults and folds. Modified from Sasseville et al. (in press).

STOP 2. External humber zone: Polyphase deformation in the hanging wall of the Bennett fault

Location. Leaving the rest area, turn left and continue southward on route 171 for 3.8 km. At the traffic lights (intersection with route 218), turn left on *rue du Pont* and cross the bridge; continue for ca 1.5 km and take highway 73 South. Follow the highway 73 South for ~25 km and take the exit 95 (Sainte-Marie-de-Beauce*; route Cameron*). Turn left on *route Cameron*. After the overpass turn right and take highway 73 north (toward Québec city). The outcrop is a road cut on the right side of the highway, ca. 900 m from the highway entrance.

Geological setting. Along the Chaudière River transect (Figs. 2, 3 and 7), the Chaudière nappe structurally overlies different rock units belonging to various nappes. This outcrop is located within the Ste-Hénédine nappe (Lebel and Hubert, 1995; St-Maxime nappe of St-Julien, 1995) that is essentially made up of red, green and gray slates and siltslates with subordinate sandstones and polymictic conglomerates that are attributed to the Ile d'Orléans Group (Lebel and Hubert, 1995; Castonguay et al., 2001b) or Sainte-Hénédine Formation (St-Julien, 1995). This locality is situated in the inverted footwall of the Richardson fault a northwest-directed D_{1-2} thrust fault (Tremblay and Pinet, 1994). Along the Chaudière River valley, the Richardson fault is folded (inverted) and overprinted by D_3 deformation.

Field description. From NW to SE, exposed lithologies are: (1) purplish-red and green siltstone and slate; (2) polymictic conglomerate 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 meter in diameter; graded-bedding clearly indicate an inverted polarity; (3) dark grey siltstone and slate with lighter grey quartzite beds; the transition with unit 2 is gradual and several conglomeratic horizons are present at the base of unit 3.

The dominant fabric is the NE-trending S_{1-2} foliation that is overprinted by a NW-dipping crenulation cleavage (regional S_3), which is 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 F_3 anticline.

Regional implications. Fabrics and structures, formed during the emplacement of Taconian thrust nappes (D_{1-2}), have been overprinted by D_3 SE-verging folds and backthrust faults during the Silurian (Pinet et al., 1996a; Castonguay et al., 2001b, Castonguay and Tremblay, 2003).

STOP 3. The Sainte-Marguerite complex: Fault slices of Grenvillian affinities

Location. continue on highway 73 north and take the (next) exit 101 (Scott). Turn right on route 173 and drive for ca. 1 km. Turn right on *rue Desjardins* towards Sainte-Hénédine. At the village, turn right on route 275 (*rue Langevin*) to Sainte-Marguerite. Drive for ca. 4.5 km and turn left on a quarry access road. The access road is marked by big cement blocks; a truck scale/weighing facilities can be seen from the main road. The quarry is located at the end of the road ca. 2 km. Note the access road conditions may not be suitable for small vehicles.

Geological setting. In the late 1970s, a series of slices of high-grade metamorphic rocks was recognized along the Richardson fault (Fig. 3 and 10; Vallières et al., 1978; Lebel and Hubert, 1995), a major D_{1-2} thrust fault of the Québec allochthons. These tectonic slices, known as the Sainte-Marguerite Complex, include granitic gneisses with pegmatitic dykes and amphibolite that are interpreted as Grenvillian basement. Vallières (1978) obtained an Rb/Sr age on biotite of 954 ± 40 and K/Ar ages on amphiboles of 835 ± 7 to 900 ± 7 Ma. They interpreted these results as representing the minimum age of Grenvillian metamorphism at ca. 900 ± 50 Ma. More recently, Castonguay (2000) obtained an Ar/Ar data on a single-grain of biotite that yielded a plateau age of 949 ± 4 Ma, thus corroborating the former data.

Field description. This is a relatively new quarry and, thus, only preliminary geological observations are available. This quarry provides excellent exposures of the various and spectacular rocks assemblages of the Sainte-Marguerite Complex. Overall, a strong strain and metamorphic gradient may be observed across the outcrop, but locally, differentiating fabrics and structures of Appalachian and Grenvillian origin is tenuous. Three different lithologic packages can be observed, from northwest to southeast:

1) Green and red phyllitic slate, siltslate, sandstone, and quartzitic conglomerate belonging to the typical sedimentary succession of the Ile d'Orléans Group (Lebel and Hubert, 1995). These lithologies are brecciated and sheared, and exhibit 2 fabrics: a sub-vertical S_{1-2} foliation (here mostly sub-parallel to S_0) and a NW-dipping (ca. N240°/35°) S_3 cleavage, axial-planar to SE-verging F_3 folds.
2) A median zone made up of sigmoidal-shape tectonic blocks with steep east-dipping contacts. As a whole, the zone consists approximately of 30% of quartzite, 20% of red phyllite and 50% of «greenish» rocks. These rocks are strongly recrystallized, sheared and more metamorphosed than the previous packages. They commonly show two different generations of tectonic fabrics. A stretching lineation is weakly developed and only locally visible.

3) A sequence of garnet-biotite amphibolite and granodioritic gneiss with centimetric garnet porphyroblasts that are commonly strongly retrogressed. Pegmatitic feldspath-quartz dykes are also apparent, and metadiabase dykes have been also documented (Lebel and Hubert, 1995). All lithologies are strongly recrystallized. Fabrics clearly postdating the Grenvillian foliation correspond essentially to brittle fractures filled by quartz and epidote. The eastern contact of the gneiss is not exposed.

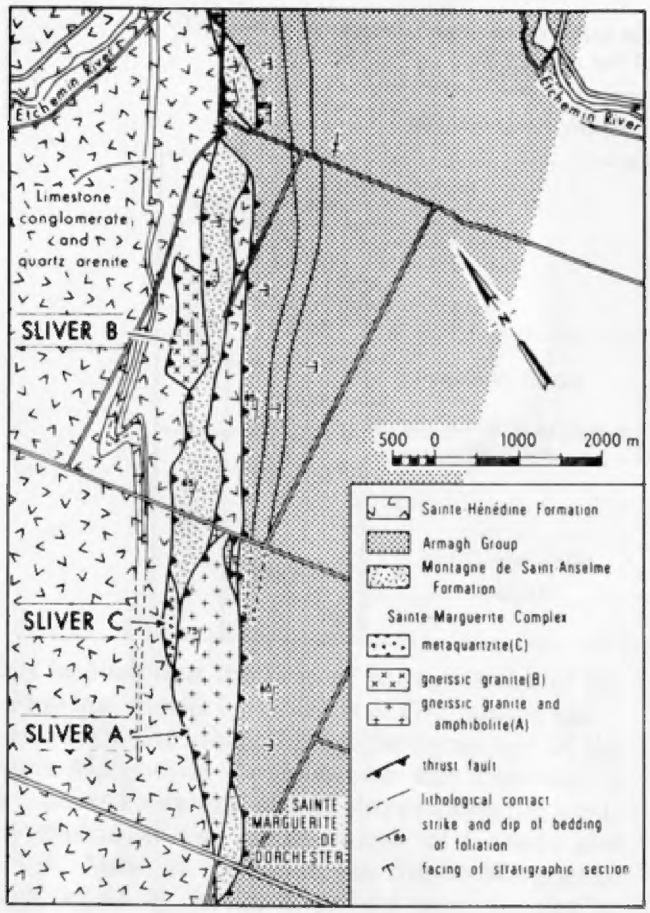

Figure 10. Detailed geological map of the Richardson fault zone and Ste-Marguerite Complex. From Vallières et al., (1978).

Regional implication. The contact between the typical sedimentary succession of the Sainte-Hénédine nappe and the Grenvillian basement slice is clearly tectonized. The lithologies that form the median zone most likely belong to the sedimentary cover sequence; lenses of quartz-rich material may correspond to sheared quartzite beds or to quartz veins. The «greenish» rock sequence probably represents sheared remnants of green sandstones, probably of the St-Roch or Armagh groups, which, together with the Montagne St-Anselme Formation (basalt and sandstone), represents the basal units of the Humber zone in the area. This interpretation is substantiated by the local occurrence of conglomeratic facies with some clasts of probable Grenvillian origin.

The occurrence of Grenvillian basement slices and of the deepest units of the sedimentary cover sequence along the Richardson fault zone implies that the latter represents a deep-seated D_{1-2} décollement. The contrasting tectonostratigraphy on both sides of the fault also implies considerable displacement along the Richardson thrust. Vallières et al. (1978) have suggested that the Richardson thrust sheet may have decapitated and incorporated basement topographic highs during its progression, which are now represented by the Ste-Marguerite Complex.

STOP 4. The internal Humber zone: The crest of the Notre-Dame Mountains anticlinorium

Location. From the quarry access road, turn left and drive 1.4 km toward the village of Sainte-Marguerite. Turn right on route 216 (*route St-Martin*) toward Ste-Marie and drive for ca. 8 km. Turn left on *rang St-Gabriel Nord*, and drive for 3.5 km, then turn right on *route Carter*. Drive 1.2 km, turn right and take highway 73 south. Continue on Highway 73 south for ca. 11 km. The stop is a road cut on the highway (Fig. 7).

Structural setting. Four generations of structures occur along the Notre-Dame mountains anticlinorium (NDMA). The regional foliation is a NW-SE striking S_{1-2} composite schistosity, axial-planar to F_2 isoclinal folds and which is associated with NW-SE trending stretching lineation. D_{1-2} fabrics and structures are folded by tight to isoclinal F_3 folds that are associated with a S_3 fabric that vary from a weakly-developed crenulation cleavage to a penetrative foliation. Regional F_3 folds are SE-verging and are associated to SE-directed fault and shear zones. All structures are affected by NE-SW trending, upright open folds (F_4) associated with the final development of the NDMA. An axial planar S_4 fracture to a crenulation cleavage is observed across the anticlinorium.

Field description. The outcrop exposes lithologies of the Rosaire Group. It consists of dark grey, massive quartzite beds and black and rusty pelitic phyllite. Quartz veins are abundant both in the quartzite and the pelites. The dominant schistosity is subhorizontal and axial-planar to recumbent folds. A discrete but well-developed series of SE-dipping normal-sense shear planes is also observed.

Regional implications. Foreland (D_{1-2}) and hinterland (D_3) verging structures are refolded by NE-SW trending upright open folds (F_4) that have been attributed to the Acadian development of the Sutton and Notre-Dame mountains anticlinoria (Tremblay and Pinet, 1994). The NDMA defines a doubly-plunging anticlinorium in the core of which are found the highest grade metamorphic rocks of the region (the Bennett Schists). In the Thetford-Mines area, the anticlinorium is bounded by folded D_3 backthrust faults and by the St-Joseph fault to the east. The Chaudière River area is, however, located NE of the periclinal termination of the NDMA, and exposes shallower levels 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 on highway 73 South. The next stop is a road cut located ca. 3 km south of stop #5 (Fig. 7).

Structural setting. In the Chaudière River area, the St-Joseph fault (Pinet et al., 1996b) is interpreted as a major normal fault. The fault strikes NE-SW and separates correlative rock units that have recorded different structural and metamorphic histories. Metamorphic rocks of the footwall are characterized by polyphase structural fabrics. Rock units of the hanging wall are less metamorphosed and generally display less strain than those of the footwall; they are found in normal or inverted position (Fig. 8). 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. We will observe well-developed extensional fabrics that are found in the footwall of the St-Joseph fault.

Field description. In this outcrop, two rock packages are recognized, (1) to the NW, light grey to greenish siltstone and sandstone that are attributed to the Caldwell Group, and (2) to the SE, black pelite and quartzite that belong to the Rosaire Group. Near the contact between these units, a 1.5 meter-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 meter- to decimeter-spaced, SE-dipping (30-70^{o}) 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 ambiguous. The folds 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, however, suggest that all these structures have been generated during a SE-verging deformational event.

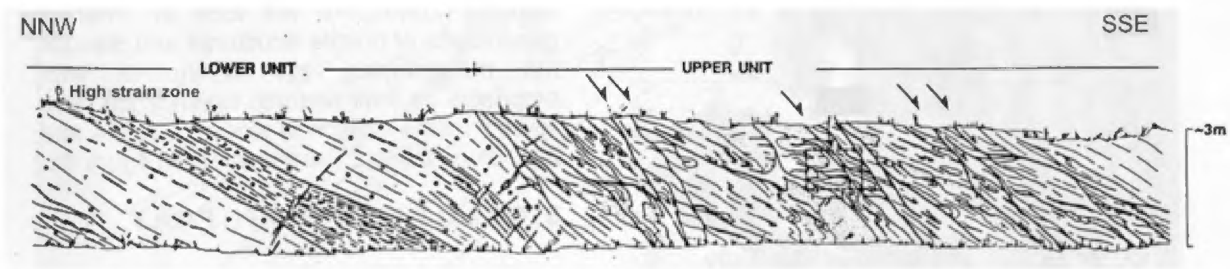

Figure 11. Sketch of the NE side of the road cut showing brittle/ductile extensional shear zone affecting D3 fabrics. Modified from Pinet et al. (1996b)

Regional implications. The St-Joseph fault (Pinet et al., 1996b) is interpreted as a late-D_3 structure active mainly during the Late Silurian-Early Devonian (Castonguay et al., 2001a; Castonguay and Tremblay, 2003). In southern Québec, the St-Joseph fault conspicuously separates two geochronologic domains of $^{40}Ar/^{39}Ar$ data: Middle Ordovician ages in structural windows of its hanging wall and predominantly Silurian-Early Devonian ages along its footwall, within the SMA and NDMA. The combination of $^{40}Ar/^{39}Ar$ results and distinct metamorphic and structural styles across the St-Joseph fault indicate a significant contrast in tectonometamorphic level between rocks of its hanging wall and footwall: upper crustal (external Humber zone equivalent) units of the Caldwell and Rosaire groups along its hanging wall against correlative metamorphic units (e.g., Sutton-Bennett Schists) that have acquired many of their characteristics at deeper crustal levels prior and during the Silurian-Early Devonian. The St-Joseph fault and related down-to-the southeast structures provide the necessary structural and crustal framework for the formation of the successor basins of the Gaspé Belt, which in terms of chronology and nature of the rock sequence is a suitable recipient for the product of tectonic denudation and erosion of the internal Humber zone.

STOP 6. The hanging wall of the St-Joseph fault: Low grade Humber zone

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 access road to highway 73 North. The outcrop is a road cut that is accessible via a construction road that is the southward continuation of Highway 73. Note that the access to this outcrop will be modified once the highway prolongation is open to traffic.

Structural setting. In the hanging wall of the St-Joseph fault (Figs. 2, 3, 7 and 8), rock units belonging to the Caldwell and Rosaire groups (St-Julien, 1987; Cousineau, 1990) 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 sandstone and red-and-green shale of the Caldwell Group. Note that these lithologies are very similar to some of the sedimentary sequences observed in stops 1, 2, and 3. A NE-SW trending sub-vertical foliation is axial-planar to upright folds. Locally, however, graded-bedding and cross-laminations in sandstone beds indicate that the sequence is up-side-down. This relationship implies the presence of a pre-existing phase of folding. Regional constraints suggest that the main fabric and superposed upright folding are Acadian-related (D_4), and that pre-existing recumbent folds probably belong to the SE-verging folding phase (D_3), documented in the footwall of the St-Joseph fault.

Regional implications. Although the St-Joseph fault is interpreted as a late D_3 structure juxtaposing contrasting pre-Acadian tectonometamorphic levels, it also lies in the region separating a northwestern domain (most of the Humber zone) where the Acadian fabrics (D_4) are weakly-developed, with a southeastern domain (Dunnage zone and Gaspé belt) where the S_4 foliation is penetrative and locally dominant (Tremblay and Pinet, 1994).

STOP 7. The St-Joseph fault: Panoramic view of the St-Joseph fault zone – Rang 5 Nord quarry

Location. Take highway 73 North to Vallée Jonction. Take exit 81 and follow route 112 south toward Thetford Mines. Continue on route 112 to Vallée Jonction, you will cross the Chaudière River, and drive through the villages of St-Frédéric and Tring Jonction. Roughly 4 km past Tring Jonction, turn right on *rang 5 Nord* (north), which is a dirt road. Drive for 1.3 km until you reach an abandoned quarry turned into a fishing pound, on the right side of the road.

Structural setting. The St-Joseph fault is recognized over a distance of approximately 200 km from Thetford-Mines to the Québec-Maine border in the northeast (Fig. 2). In the Thetford-Mines area, 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 approximately 70° toward the southeast.

Figure 12. Rang 5 Nord quarry showing high-angle ductile/brittle normal faults

Field description. Structures related to the St-Joseph fault are exposed in this quarry (Fig. 12). The footwall of the serpentinite consists of polydeformed grey phyllite to graphitic schist and quartzite attribute to the Rosaire Group. The immediate hanging wall rocks locally consist of dark chlorite schists (“blackwall”) that have been interpreted as the result of fault-localized metasomatic alteration of the host rock during regional deformation and metamorphism. To the SE, the unaltered host rock consists of pelitic and quartz-sericite phyllites interbedded with siltstone and sandstone also attributed to the Rosaire Group.

Abundant shear bands, SE-verging folds and “en echelon” sigmoidal quartz veins clearly attest for normal-sense motion (down to the southeast). Serpentinite in the fault zones is most commonly scaly. In this quarry, a series of high-angle ductile/brittle normal faults are clearly visible on the NW wall (Fig. 12). The serpentinite was preferably exploited where it was structurally thickened by folds and extensional faults.

Regional implications. Structures related to the St-Joseph fault are apparently late in relation to the regional S_3 foliation and SE-verging folds (F_3). This suggests that normal faulting mostly postdates back thrusting, and excludes the possibility that the St-Joseph fault is a rotated backthrust. Southwest of Thetford Mine, the St-Joseph fault merges with the BBL on both side of which similar metamorphic and structural contrasts occur. Structural evidence also indicates the predominance of southeast-dipping extensional faulting along the BBL. In northern Vermont, the

BBL merges into the Burgess Branch fault, also recognized as a normal fault (Kim et al., 1999). Northeastward into northwestern Maine, the St-Joseph fault merges into an unnamed normal faults system mapped at the boundary between the pre-Silurian rocks and the Connecticut Valley Gaspé trough (e.g., Osberg et al., 1985). This suggests that, from northern Vermont to northwestern Maine, the St-Joseph fault is part of an extensively developed normal fault system that extends for more than 400 km. We suggest that evidence for extensional deformation has been better preserved in the Québec reentrant because this segment of the orogen has suffered less intense Acadian deformation and metamorphism than elsewhere along the northern Appalachians.

STOP 8. The St-Joseph fault: Panoramic view of the St-Joseph fault zone in East-Broughton quarry

Location. Turn back to the intersection with route 112 and turn right. Drive through East-Broughton (ca. 3 km) and turn right on *rang 7 Nord*. Drive for ca. 1 km to the entrance of a quarry on the left side of the road.

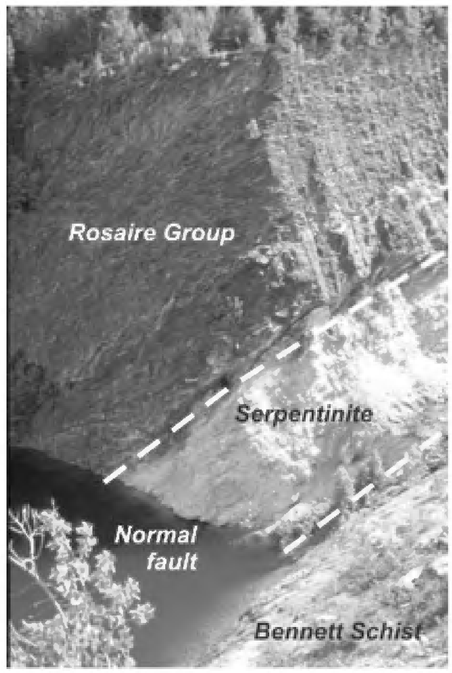

Figure 13. Rang 7 East-Broughton quarry exposing the Pennington sheet, which delineates the St-Joseph fault. From Castonguay et al. (2003).

Structural setting. See stop 7.

Field description. Again in this stop, the trace of the St-Joseph fault is delineated by the Pennington sheet, which has been exploited for asbestos and talc (Fig. 13). This quarry is rich in steatite. This talc-rich rock is exploited as blocks of "soapstone". The immediate hanging wall rocks consist of altered Rosaire Group lithologies ("blackwall"), whereas the Bennett Schists occur in the footwall.

Regional implications. See stop 7.

STOP 9. The internal Humber zone: The Bennett Schists

Location. Drive back to route 112 and turn right. Drive for ca. 6 km and turn right on *rang 11*. Follow this road for 4.7 km. The outcrop is a road cut located on the right side of the road in front of a big farm.

Structural setting. Rock units of the Notre-Dame Mountains anticlinorium belong to the Bennett Schists which represent metamorphic and polydeformed equivalents of the Rosaire, Caldwell and Oak Hill groups. As described above, three phases of regional deformation affect these units (Taconian D_{1-2}, Silurian-Early Devonian D_3, and

Acadian D_4). These rocks have been mainly metamorphosed during the Taconian orogeny (M_{1-2}). Subsequent events have variously recrystallized and retrogressed the Taconian paragenesis.

Field description. In this outcrop, two rock packages are recognized and are separated by a thin serpentinite sliver associated with the Pennington Sheet. Northwest of the serpentinite, quartz-sericite pelitic schist and metasiltstone are attributed to the Rosaire facies of the Bennett Schists. To the right of the sliver, quartz-chlorite-sericite±biotite schist and quartzofeldspathic metasandstone are associated with the Caldwell facies. Two generations of structural fabrics can also be observed. A steeply-dipping S_{1-2} schistosity represents the metamorphic differentiation or layering and a weakly to moderately developed crenulation foliation (S_3), roughly oriented N280°/25°. S_3 is axial-planar to close to tight F_3 folds. An intersection lineation (L_{2-3}) is locally well-defined. This locality is located near the NE termination of the NDMA, where the structure is more strongly influenced by the NE plunge of the regional F_4 folds.

$^{40}Ar/^{39}Ar$ analyses from metamorphic rocks of this locality yielded a plateau age of 422.3±0.8 Ma on muscovite and 420.5±0.6 Ma on biotite (Castonguay et al., 2001a) which have been attributed to the maximum age of D_3 overprint on the M_{1-2} metamorphic paragenesis.

Regional implications. Although locally strongly overprinted, the synmetamorphic D_{1-2} structures of the internal Humber zone are correlated to the NW-directed thrust sheet emplacement in the external Humber zone. This phase is associated to the Taconian Orogeny. In the internal Humber zone, the age of peak or near-peak metamorphism is dated at 465±5 Ma (Castonguay et al., 2001a). The D_3 phase is associated to SE-directed tectonic transport and metamorphic retrogression between 430-410 Ma. D_4 structures (sub-vertical crenulation cleavage, doubly-plunging open to close folds and final formation of regional-scale anticlinoria) are related to the Acadian orogeny. In this area, the Acadian overprint is constrained at ca. 387-376 Ma.

STOP 10. Ultramafic rocks of the internal Humber zone: The Pennington Sheet

Location. Continue on *rang 11* for ca 1.2 km. The outcrop is located in the farm field on the left side of the road (Fig. 3).

Structural setting. The Pennington Sheet delineates an early (D_{1-2}) fault zone within the Bennett Schist. The NW-SE trending branch of the Pennington Sheet is characterized by mylonitized and brecciated serpentinite that is affected by the regional D_3 and D_4 structures, whereas the SE portion of the ultramafic sheet is truncated by the St-Joseph fault. Similar serpentinite sheets outlining early faults have been recognized elsewhere in southernmost Québec (Colpron, 1990; Rose, 1993), Vermont (Stanley and Ratcliffe, 1985) and in the Newfoundland Humber zone (Hibbard, 1983).

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 a mineral lineation. 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. As in the previous stops, two generations of structural fabrics can be observed.

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 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.

This marks the end of the Field trip. There are two itineraries to drive back to Quebec City. You may either drive back to Vallée Jonction and take highway 73 north (the fast and easy way) or, for the back country route, continue on rang 11 through the village of St-Pierre-de-Broughton. Turn left on rang 16 toward route 271. At the intersection, turn right on route 271 and drive to St-Jacques-de-Leeds. At the intersection, turn right on route 269. Follow route 269 (which eventually becomes route 116) for ca. 47 km to St-Étienne-de-Lauzon. Here you may turn left on *chemin Lagueux* (at the traffic lights) to reach highway 20 or to return to the Parc de la Chaudière, turn right on *rue du Pont* (route 171) which becomes *chemin Ste-Anne Est* and *route St-André* and drive for ca. 3.7km. Turn left on *chemin St-Grégoire* and drive ca. 2 km. Take highway 73 north and take exit 130 toward Parc Chute de la Chaudière.
Cheers

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CU-NI-PGE-AU DEPOSITS IN A GRENVILLIAN MESOPROTEROZOIC MAGMATIC ARC

by

Anne-Aurélie Sappin and Marc Constantin, Département de Géologie et de Génie géologique, Université Laval, Québec, QC G1K 7P4, Canada
Thomas Clark, Ministère des Ressources naturelles et de la Faune, Québec, QC G1S 4X4, Canada

INTRODUCTION

The Portneuf-Mauricie Domain is located north of the city of Trois-Rivières (Québec, Canada), in the south-central part of the Grenville Province (Fig. 1). This domain consists of metasedimentary rocks and metatuffs of the Montauban Group (1.45 Ga; Nadeau and van Breemen, 1994), which are intruded by plutons of the La Bostonnais Complex (1.40–1.37 Ga; Nadeau and van Breemen, 1994). This assemblage was formed in a magmatic arc setting (MacLean et al., 1982; Nadeau et al., 1992; Bernier and MacLean, 1993; Gautier, 1993; Nadeau and van Breemen, 1994; Corrigan, 1995; Corrigan and van Breemen, 1997; Nadeau et al., 1999). The sequence was injected by differentiated mafic-ultramafic intrusions hosting several Ni-Cu±PGE (platinum group element) deposits; of these, the Rousseau and Lac Nadeau deposits will be visited during this field trip (Fig. 1). The intrusion containing the Lac Nadeau showing (West zone) has been dated at 1396 +6/–5 Ma by the U-Pb method on zircons (Sappin et al., 2004). This age, interpreted as an emplacement age, falls within the age range for the La Bostonnais Complex. The mafic and ultramafic rocks hosting the Lac Nadeau and Rousseau deposits have a magmatic arc trace-element signature as indicated by negative anomalies in HFSE (Ta, Hf, Zr, Ti) relative to REE (Sappin et al., 2006a; Figs. 2a, 2b). The arc-related geodynamic setting of the Portneuf-Mauricie Domain's Ni-Cu±PGE showings is unusual for such magmatic sulfide deposits. A few relatively recently discovered Ni-Cu-PGE deposits in the world are currently interpreted to be associated with magmatic arc settings. An understanding of the origin of this new type of deposit—the Ni-Cu-PGE deposits of the Portneuf-Mauricie Domain are good examples of this type—is necessary for effective exploration for Ni-Cu-PGE. Also, sulfides in Portneuf-Mauricie Domain deposits have the particularity of showing relatively high concentrations of base and precious metals compared with sulfides in many other Grenvillian deposits. The Ni, Cu, PGE, and Au contents of sulfides (recalculated to 100% sulfides) are as follows: 8–16 % Ni_{100} (i.e., Ni at 100% sulfides), 5–9% Cu_{100}, 3–65 g/t $(Pd+Pt)_{100}$, and 1–30 g/t Au_{100} (Sappin et al., 2005).

DEPOSIT DESCRIPTIONS

Lac Nadeau deposit

The Lac Nadeau deposit comprises three mineralized zones: (1) the West zone, corresponding to the Lac Nadeau showing (sensu stricto); (2) the East zone; and (3) the Kéno zone (Fig. 3; Sappin et al., 2004). The mineralized zones are located in three, genetically associated mafic to ultramafic plutonic bodies, separated on surface by country rocks. Three rock assemblages make up the contiguous country rocks of the three intrusions (Fig. 3): (1) a unit of mainly granodiorite and diorite, (2) a unit of mainly leucocratic granite, and (3) a unit composed mainly of biotite paragneiss and quartzite. The external contacts of the three intrusions are generally parallel to the foliation in the country rocks (Fig. 3). These mineralized intrusions are not tabular with regular layering, as interpreted by Poirier (1988); rather, they are zoned. The three intrusions result from multiple injections and perhaps mingling of different magmas, intruded in no particular order. They are composed mainly of lherzolite (± plagioclase), plagioclase-bearing harzburgite, websterite (± olivine, ± plagioclase), plagioclase-bearing orthopyroxenite, gabbronorite (± olivine, ± quartz), norite (± quartz), and quartz-bearing gabbro. Mafic rocks are most abundant. Locally, the rocks of the three intrusions show partially preserved cumulate textures. Olivine and plagioclase are essentially cumulus minerals, but they also locally intercumulus in olivine-rich gabbronorite. By contrast, orthopyroxene and clinopyroxene are intercumulus minerals, but in olivine-rich gabbronorite they may be cumulus.

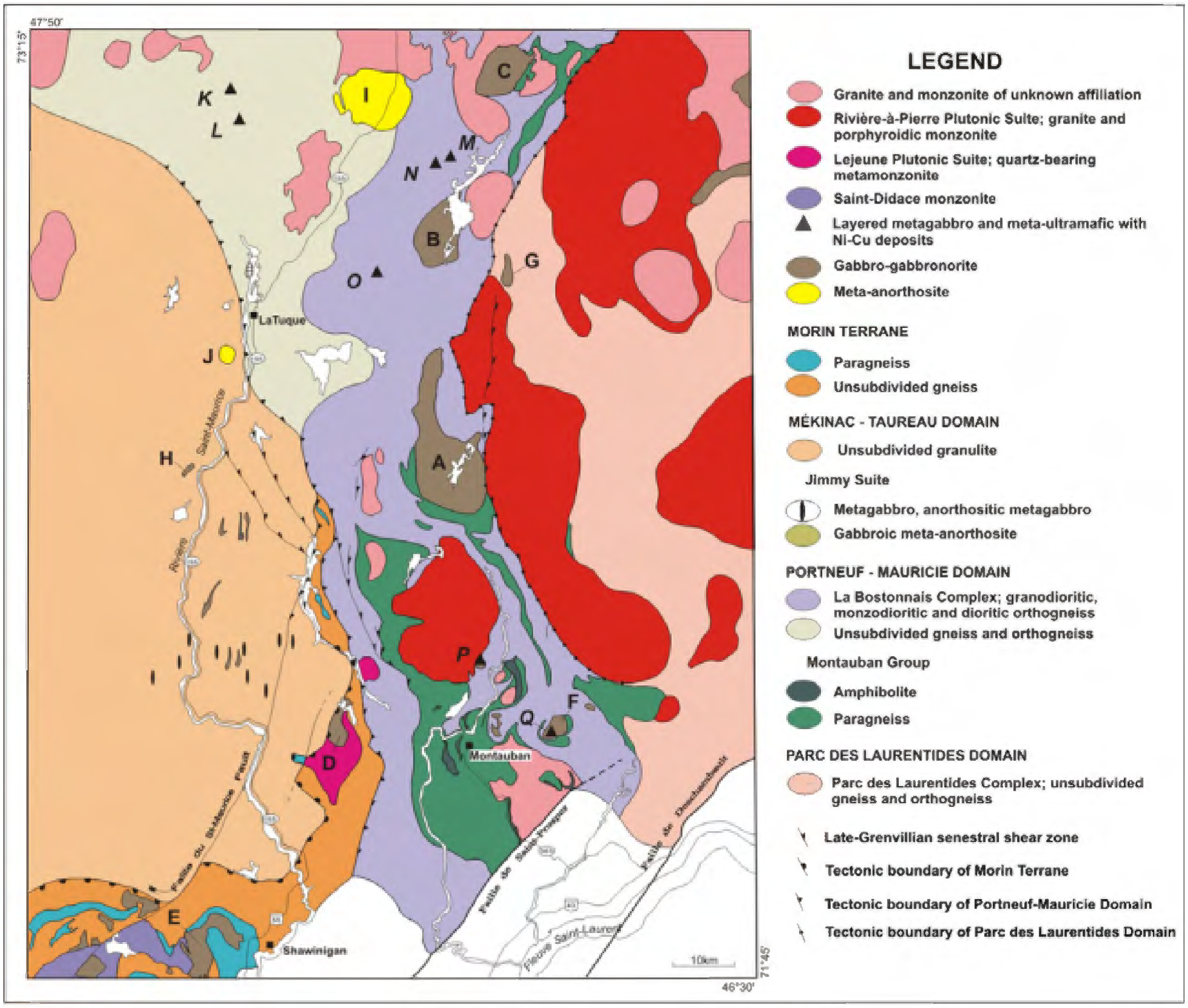

Figure 1. Simplified geology of the Portneuf-Mauricie region (modified from Nadeau and Brouillette, 1994, 1995). Gabbro-gabbronorite intrusions and meta-anorthosites: A – Lapeyrère; B – Édouard; C – Étoile; D – Lejeune; E – Shawinigan; F – Montauban; G – Sandford; H – Wessonneau; I – Langelier; J – La Tuque. Mafic-ultramafic intrusions and associated Ni-Cu showings: K – Lac Matte; L – Lac Kennedy; M – Lac Édouard; N – Boivin; O – Rochette Ouest; P – Rousseau; Q – Lac Nadeau.

The **West zone** intrusion measures 290 m by 150 m. The composition of the rocks well mineralized with disseminated sulfides varies from melanocratic norite and gabbronorite (± olivine) to plagioclase- and olivine-bearing websterite. The **East zone** intrusion, which measures <600 m by 300 m, includes weakly mineralized lherzolite–harzburgite (± plagioclase) and websterite (± olivine, ± plagioclase). Finally, disseminated sulfides in the **Kéno zone** are hosted in an intrusion 150 m thick and of unknown length. The well-mineralized lithofacies of this zone are gabbronorite and olivine- and plagioclase-bearing websterite. The abundance of sulfide in the three mineralized zones varies from <1% to 10%. The grain size of the sulfides is variable, locally reaching 1 cm. The sulfides are mainly pyrrhotite, with some pentlandite, chalcopyrite, and locally pyrite. Both gabbroic and ultramafic rocks contain disseminated sulfides. The West zone contains the largest number of mineralized outcrops, as well as the sulfides with the highest concentrations of base and precious metals. The sulfides in all mineralized zones display a close association with olivine-rich mafic and ultramafic rocks. The forsterite content of olivine in the rocks

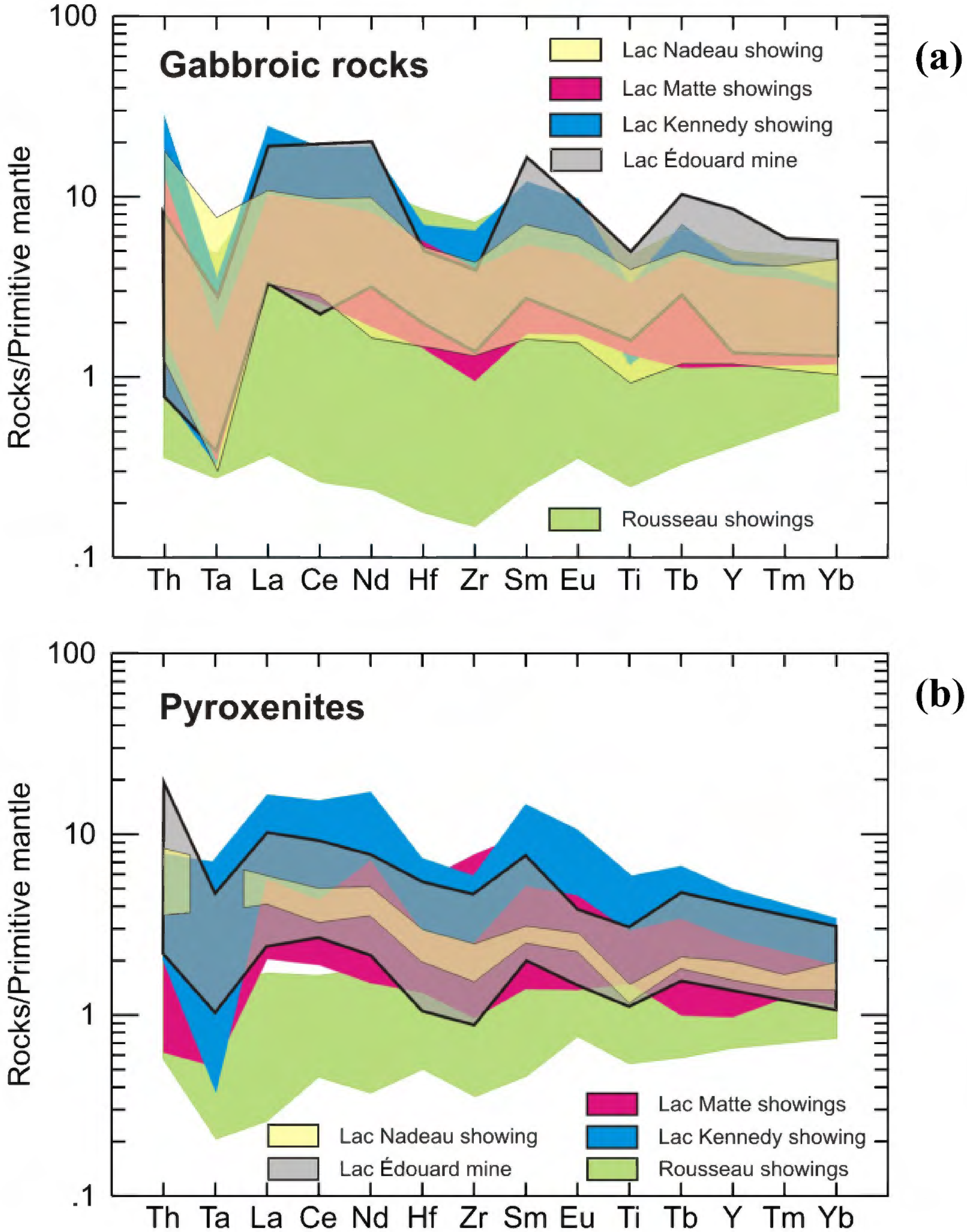

Figure 2. Multi-element diagrams normalized to primitive mantle for sulfide-rich and sulfide-free mafic and ultramafic rocks of the Porteneuf-Mauricie Domain: (a) gabbroic rocks, (b) pyroxenites. Primitive mantle values are from Palme and O'Neill (2004). For analytical methods, see Sappin et al. (2005) and Constantin (2006).

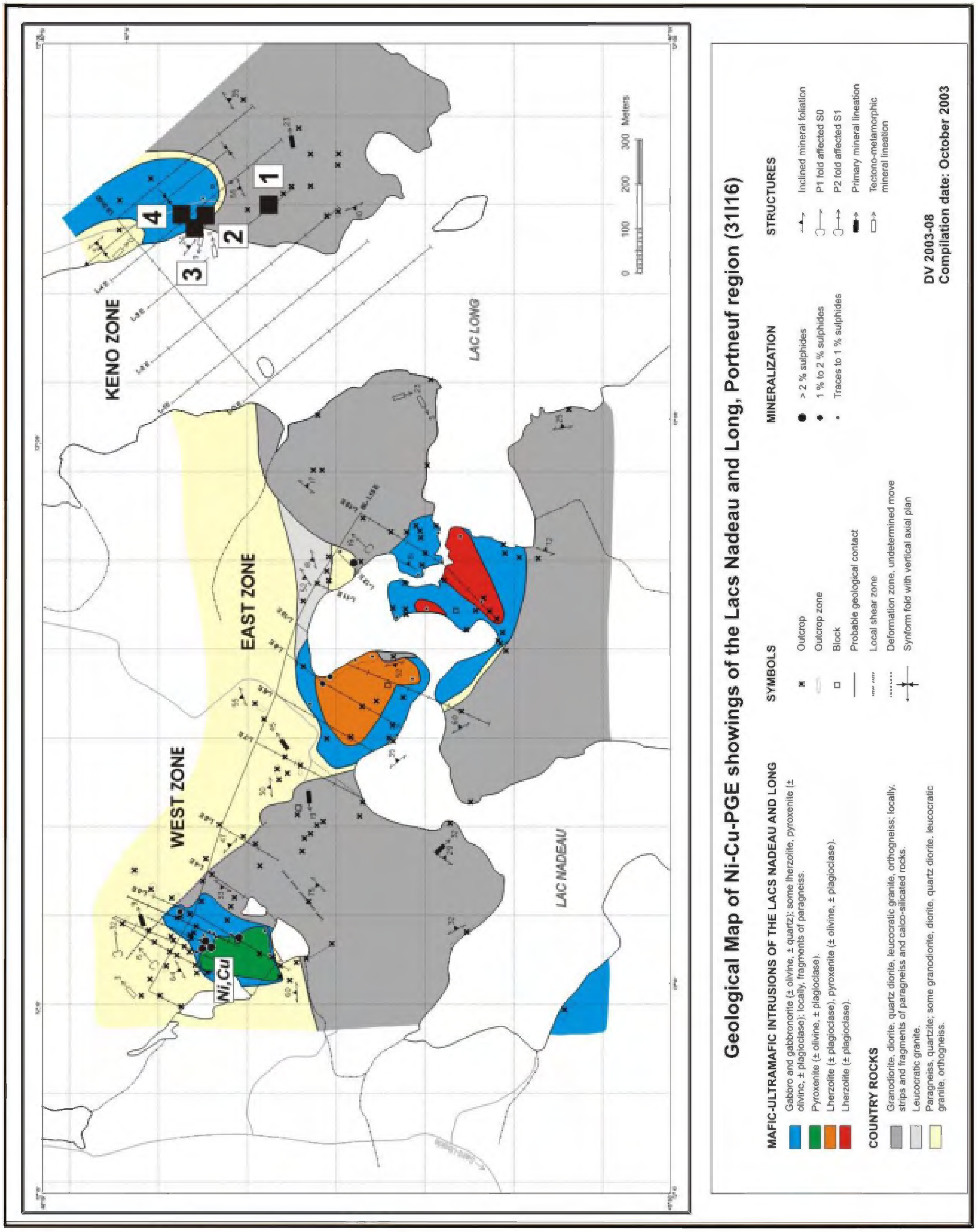

Figure 3. Geological map of the Lac Nadeau area and its Ni-Cu-PGE showings (modified from Sappin et al., 2003). The locations of Stops 1 to 4 are shown.

ranges between Fo70 and Fo83 (Sappin et al., 2006b). The parent magmas were fairly well differentiated, and their source was probably the mantle (Sappin et al., 2006b).

Unfortunately, the West and East intrusions will not be visited during this field trip because of problems of accessibility. We will however see the Kéno intrusion and, aided by typical mineralized samples from the other two intrusions, will make comparisons among them. The Kéno intrusion has the particularity of displaying, at least superficially, a different structural context than the West and East intrusions. The external contact of the mafic-ultramafic intrusion is, as in the West and East intrusions, parallel to the foliation in the paragneiss. However, the Kéno intrusion is deformed as an open, synformal fold plunging at a small angle to the north (Fig. 3). The Kéno pluton is not zoned, layered or banded, but we can see some evidence of multiple injections, as in the other two intrusions.

Rousseau deposit

The Rousseau showings are hosted in the Lac à la Vase intrusion, a mafic-ultramafic body elongated in an E–W direction (Fig. 4). This intrusion is about 3 km long. Its width varies between 1.8 km in the central section to 800 m at its eastern end. In the north, west, and south, the pluton is bounded by an assemblage, rarely gneissic, of monzonite–monzodiorite (± quartz, ± pyroxene) and granite. Pyroxene-bearing diorites (rarely gneissic) occur to the northeast. A locally gneissic assemblage of granite and granodiorite, quartzite, and late quartz-bearing diorite occurs to the southeast and the southwest. The Lac à la Vase intrusion is mostly concordant with the country rocks.

The Lac à la Vase pluton is zoned (Fig. 4). The outer zone is mainly mafic and is composed of leucocratic to melanocratic gabbronorite and norite. However, it also contains minor plagioclase-bearing websterite and hornblendite. These rocks are locally amphibolitized. The core of the intrusion contains two main olivine-bearing zones composed essentially of ultramafic rocks. One of the zones (150 m by 150 m) is located in the western part of the intrusion and the other (~800 m by 400 m) in the central part. The olivine-rich rocks include lherzolite, wehrlite, and harzburgite (all ± plagioclase); mesocratic and melanocratic olivine gabbronorite and olivine norite; and olivine orthopyroxenite and websterite, both of which may contain plagioclase. All rocks in the intrusion show quite well-preserved cumulate textures, with cumulus olivine and intercumulus plagioclase. In the olivine-free rocks, orthopyroxene and clinopyroxene are cumulus minerals. However, in the olivine-rich rocks, these pyroxenes can be cumulus or intercumulus. The mafic and ultramafic rocks of the intrusion show abundant evidence of multiple magmatic injections. In the outer zone, the ultramafic rocks crystallized from magmas that were younger than those from which the mafic rocks crystallized; in the core zone the opposite order prevailed.

The Lac à la Vase pluton contains four Ni-Cu showings called the Rousseau showings (Fig. 4). The first is located in the western part of the intrusion, more precisely at the northern contact of the western olivine-bearing zone. This showing is hosted in olivine- and plagioclase-bearing websterite. The second showing is also located in the western part of the intrusion, just northeast of the first. The sulfides occur in olivine- and plagioclase-bearing orthopyroxenite. In these showings the sulfides are net textured. The third showing is located at the north end of Lac à la Vase. There, disseminated sulfides occur in a meter-scale dike of plagioclase-bearing meta-orthopyroxenite injected into gabbronorite. Locally, the sulfides are net textured. The fourth showing occurs on the south shore of Lac à la Vase in olivine metawebsterite. The sulfides in this showing occur as "droplets" and locally as disseminated aggregates. All four showings contain 3 to 7% sulfides composed of pentlandite, chalcopyrite, pyrrhotite, and pyrite. The sulfides in the Rousseau showings are closely associated with olivine-rich mafic and ultramafic rocks. The relatively high olivine forsterite content (Fo82–Fo88) in these rocks indicates that they crystallized from relatively primitive, MgO-rich, mantle-derived magmas (Sappin et al., 2006b).

Participants on this field trip will observe the multistage character of the mafic-ultramafic intrusions containing the Lac Nadeau and Rousseau showings. They will examine the styles of mineralization. An important aim of the field trip is to present the deposits in light of some of the characteristics of world-class Ni-Cu deposits: (1) an association with MgO-rich magmas, favoring the crystallization of olivine; (2) sulfide-bearing country rocks; (3) evidence of interaction between the magmas and the country rocks; and (4) common multiple intrusions of magma, suggesting that the sulfides could have reacted with and been enriched by other pulses of magma after their formation.

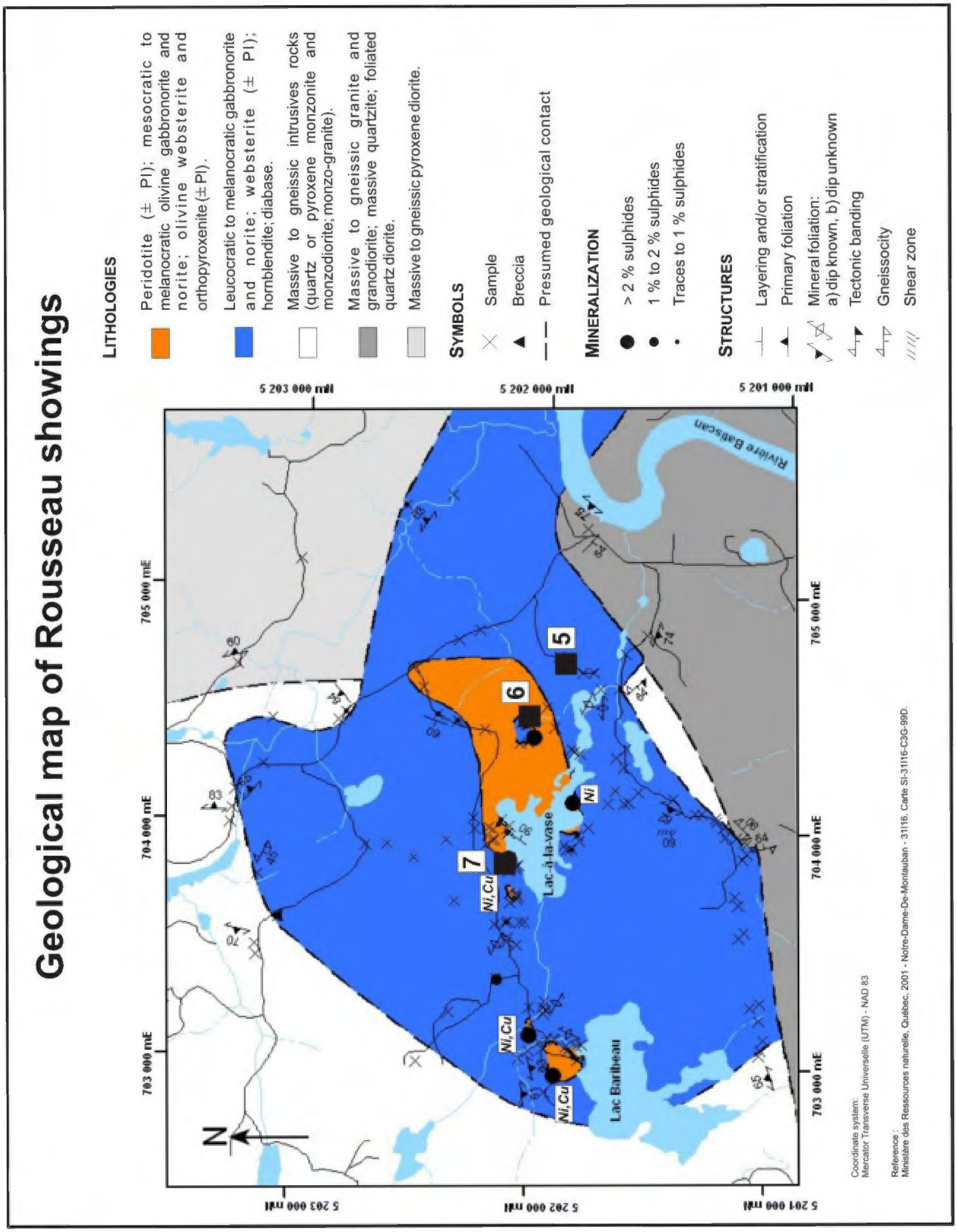

Figure 4. Geological map of the Lac à la Vase area containing the Rousseau Ni-Cu-PGE showings. The locations of Stops 5 to 7 are shown.

ROAD LOG

Distance (in km)

0.0 Start at the parking lot of the town park of Rivière-à-Pierre, on Rue Principale. This park is located between the town hall and the St-Bernardin church. Turn right onto Rue Principale.
0.6 At the Y intersection, continue on Rue Principale.
2.0 At the end of Rivière-à-Pierre do not turn right. Cross the railroad track and continue on route 367 south.
9.2 Turn right onto a gravel road indicated "Camp Kéno."
17.4 Straight ahead. Do not turn right to Association Recréative Abenaki.
18.4 Straight ahead. Do not turn right to St-Alban.
20.2 At the Y intersection, keep right.
21.5 Turn left into the Camp Kéno parking lot and park your car here.

STOP 1. Parking lot, Camp Kéno (40 min)

This stop is located in the country rocks hosting the Kéno mafic-ultramafic intrusion, in a unit of mainly granodiorite and diorite. Here, we are in the axial zone of the synclinal fold affecting the Kéno intrusion. The outcrop is located at the north end of the Camp Kéno parking lot (Fig. 5a). It is oriented NE-SW and measures approximately 15 m x 4 m. The main unit is medium- to coarse-grained biotite granodiorite, cross-cut and interbanded with pegmatite. The granodiorite is porphyritic, porphyroclastic, foliated (orientation of the foliation is variable), and gneissic. The pegmatite is banded, boudinaged (Fig. 5b), and porphyroclastic. This assemblage, including the gneissosity, is folded (Fig. 5c). Much of the deformation was absorbed by the pegmatite. Rippling on the outcrop probably resulted from the folding (Fig. 5c). Locally, the granodiorite contains centimeter- to decimeter-scale enclaves of fine-grained, foliated, granoblastic diorite, which are locally porphyritic in plagioclase. Rarely, the granodiorite contains centimeter- to meter-scale enclaves of fine-grained, foliated, granoblastic biotite paragneiss.

Assimilation by the mafic magma of sulfide-bearing country rocks would have led to contamination of the magma by sulfur, thereby causing saturation of the magma in sulfide. This is a characteristic that is common to major magmatic sulfide deposits. Here, the country rocks are not mineralized, so they are not a good source of sulfur; therefore, the sulfur originated elsewhere.

In order to identify assimilation of the host rocks by the magma, we use field and geochemical evidence. The field evidence suggesting interaction of magma and country rocks will be examined at Stop 2. The geochemical evidence includes the comparison of sulfur isotope ratios ($\delta^{34}S$) and selenium-sulfur ratios (Se/S x 10^6) in samples of country rock and mineralized mafic-ultramafic rock (Sappin et al., 2006b). In the case of the Lac Nadeau and Rousseau showings, the $\delta^{34}S$ values from the country rocks are similar to the $\delta^{34}S$ values from the mineralized mafic-ultramafic rocks. The $\delta^{34}S$ values from the country rocks are also typical of mantle values. The Se/S ratios from the country rocks are less than or equal to the ratios from the mineralized rocks. Thus, we cannot demonstrate unambiguously from these geochemical data that the sulfur in the showings originated from assimilation of country rocks.

Distance (in km)

0.0 Exit the Camp Kéno parking lot at its north end and turn right.
0.01 Take the trail named "Sentier de la Paix" and walk 200 m generally in a NW direction.

STOP 2. Camp Kéno, "Sentier de la Paix" (15 min)

This stop displays the contact between the Kéno intrusion and the country rocks. The study of the contact zone between the intrusion and the country rocks is important for identifying evidence of interaction between the silicate magma and the country rocks. Such evidence informs us about the contamination of the magma by crustal rocks and/or about the assimilation of sulfur by the silicate liquid. Both mechanisms are essential for the formation of world-class Ni-Cu±PGE deposits.

To the northwest, the outcrop is composed of fine- to medium-grained gabbronorite containing plagioclase interstitial to orthopyroxene and clinopyroxene. To the southeast, we observe gneiss composed mainly of quartzite

(±garnet, ±biotite) interbanded with minor biotite paragneiss. The paragneiss seems to be intruded by a decimeter-scale band of medium-grained, foliated biotite granodiorite. The contact between the intrusion and the country rocks is oriented at 110–115°. In this contact zone, we can see centimeter- to decimeter-scale quartz- and garnet-rich metasedimentary enclaves, suggesting possible contamination of the magma by country rocks.

Figure 5.

(a) View of the parking lot outcrop composed mainly of granodiorite interbanded with pegmatite.

(b) Close-up of gneissic structure.

(c) Boudinaged pegmatite dike.

Distance (in km)
0.0 Walk northwest 20 m along the trail.
0.02 Turn left to the area named "Le Rocher."

STOP 3. Camp Kéno, "Le Rocher" (20 min)

The cliff on the water's edge is more than 5 m in height. A very fine- to fine-grained massive mafic rock (with traces of pyrrhotite) is in sharp, subconcordant contact with foliated, fine- to medium-grained biotite-sillimanite-garnet paragneiss (upper amphibolite facies metamorphic assemblage). The mineral foliation in the paragneiss is oriented at 305°/26°. The metapelitic gneiss and the mafic rocks show a mineral lineation (82°/11° E for the gneiss and 280°/09° W for the mafic unit). A chilled margin of tholeiitic basalt composition (Figs. 6a, 6b), about 10 cm thick, occurs at the contact between the mafic-ultramafic rocks and the structurally underlying metasedimentary rocks. The composition of this chilled margin may represent the composition of the parental magma of the Kéno intrusion. This magma displays negative anomalies in HFSE (Ta, Hf, Zr, Ti) relative to REE (Fig. 7). These anomalies are typical of magma associated with a magmatic arc environment. Moreover, the TiO_2 content (0.85%) indicates that the mantle source of this magma was not depleted by a previous melting event.

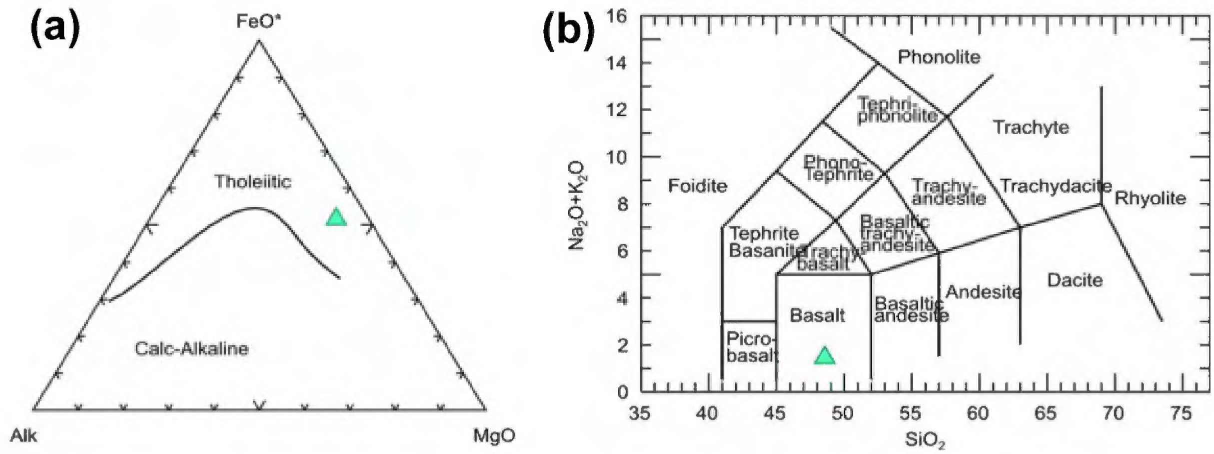

Figure 6. AFM (a) and alkali–silica (b) diagrams confirming the tholeiitic and basaltic affinity of the chilled margin of the Kéno intrusion.

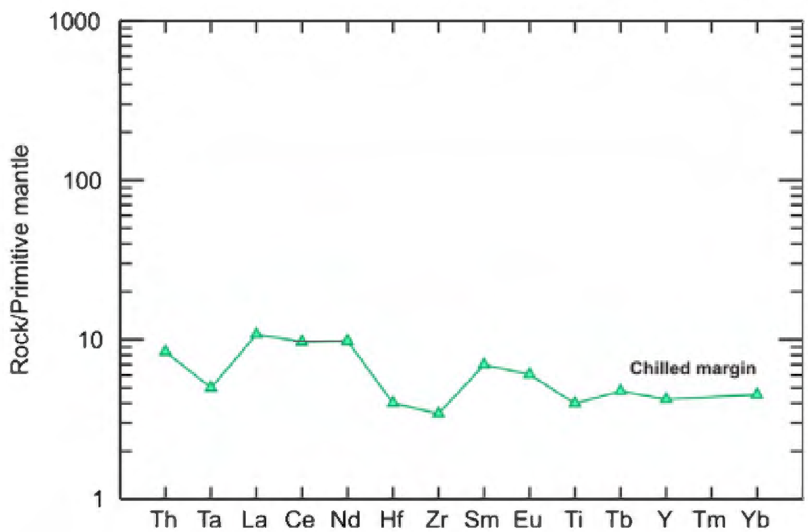

Figure 7. Multi-element diagram normalized to primitive mantle for the chilled margin of the Kéno intrusion. Primitive mantle values are from Palme and O'Neill (2004). The analytical methods are described in Sappin et al. (2005) and Constantin (2006).

Distance (in km)

0.0 Return to the trail. Turn left and walk 30 m to the NNE along the trail.
0.03 Turn right to the area named "La Mine."

STOP 4. Camp Kéno, "La Mine" (30 min)

This outcrop, discovered by Georges Perron in 1946, constitutes the Kéno mineralized zone. It measures approximately 40 m long by 10 m wide. Fine- to coarse-grained olivine-plagioclase orthopyroxenite is the main lithofacies (Fig. 8). The orthopyroxenite is coronitic and ophitic (orthopyroxene oikocrysts containing plagioclase). It contains decimeter- to meter-scale enclaves of fine- to coarse-grained gabbronorite, similar to the gabbronorite at Stop 2 (Fig. 9). The enclaves are composed of plagioclase interstitial to cumulus orthopyroxene and clinopyroxene. The contact between the orthopyroxenite and the gabbronorite is sharp, attesting to the solidification of the enclaves before the emplacement of the orthopyroxenite.

The orthopyroxenite and the gabbronorite contain traces of disseminated sulfides, principally pyrrhotite and rarely chalcopyrite. The sulfides are not particularly rich in metals compared with the sulfides associated with the well-mineralized rocks of the Lac Nadeau showing. Mineralized samples of the latter will be available for examination.

Figure 8. Sample of fine- to coarse-grained olivine-plagioclase orthopyroxenite.

Figure 9. Sample from an enclave of fine- to coarse-grained gabbronorite.

Distance (in km)

0.0	From the Camp Kéno parking lot, turn right onto the gravel road.
1.25	At the Y intersection, follow the sign "Retour" on your right.
12.3	End of the gravel road. Turn left onto route 367 north.
19.5	Turn left onto route 367 to Notre-Dame-de-Montauban and St-Ubalde.
38.3	At Notre-Dame-de-Montauban, turn right onto Rue du Pont, towards Lac-aux-Sables.
38.6	Turn right onto Route de la Traverse, towards Les Trois Mines.
39.2	Turn right onto Rue du Moulin.
43.2	Straight ahead, onto the gravel road.
46.4	Turn left onto the trail. Park here. Walk 400 m along the trail.

STOP 5. Southeast of Lac à la Vase (30 min)

This stop is situated in the southern part of the outer zone of the Lac à la Vase intrusion. The outer zone is composed mainly of olivine-free mafic rocks.

This outcrop is composed of leucocratic, medium- to coarse-grained metanorite. These rocks have an adcumulate texture, with cumulus plagioclase and a small amount of intercumulus orthopyroxene. The orthopyroxenes display coronas composed of hercynite–hornblende and hornblende. The metanorite is cut by a meter-thick diabase dike (Fig. 10) and by younger centimeter- to meter-scale aplite dikes (Fig. 11). All contacts are sharp and straight. The diabase dike has chilled margins at its contacts with the metanorite. The metanorite and the diabase dikes contain traces of sulfides (pentlandite).

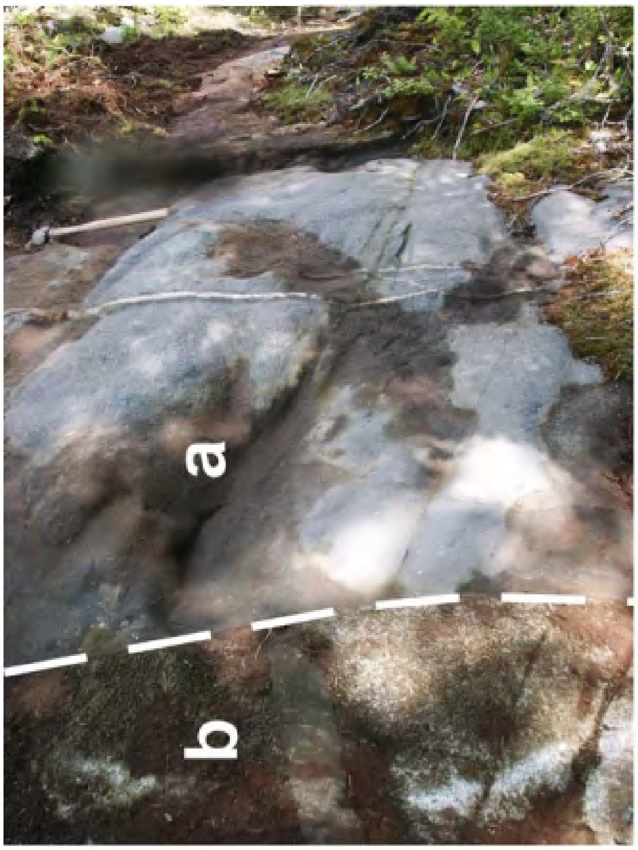

Figure 10. Diabase dike (a) intruding metanorite (b).

Figure 11. Thin aplite dikes intruding a diabase dike.

Distance (in km)
0.0 From the parking area of Stop 5, turn left onto the gravel road.
1.5 Stop near the trail located on the left side of the road. The trail is blocked by a gate. Park the car here. Walk 350 m along the trail.
1.85 Walk southeast 130 m into the woods.

STOP 6. East of Lac à la Vase (40 min)

This hill east of Lac à la Vase displays the contact between olivine-free mafic rocks and olivine-rich mafic and ultramafic rocks. The following layered section is from NW to SE (Fig. 12): (1) foliated metanorite (18 m wide), (2) olivine gabbronorite (11 m), (3) plagioclase lherzolite (5 m), and (4) lherzolite (20 m). Contacts between the units are transitional.

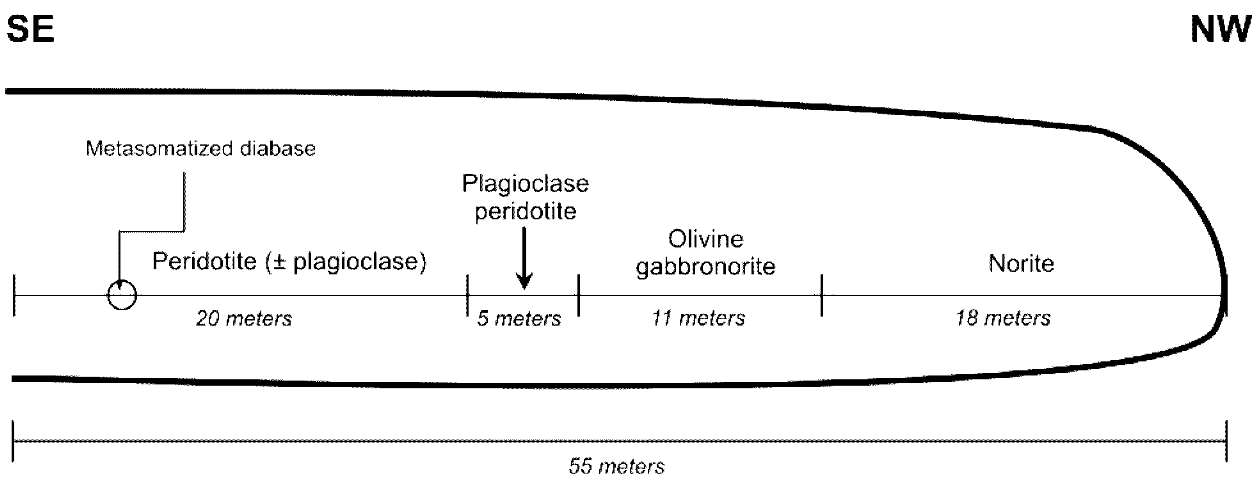

Figure 12. Sketch (plan view) of the outcrop at Stop 6.

The metanorite is mesocratic and medium to very coarse grained. Locally, the rock composition changes to plagioclase-bearing orthopyroxenite and orthopyroxenite. Orthopyroxene is cumulus and plagioclase is interstitial (Fig. 13). In places, we can see euhedral plagioclase crystals probably resulting from an early crystallization in another magma. The norite contains injections of fine-grained pyroxenite with irregular, curving contacts, suggesting magmatic interpenetration. The olivine gabbronorite is melanocratic, coronitic (Fig. 14), ophitic (with oikocrysts of plagioclase containing olivine, orthopyroxene, and clinopyroxene), and medium-grained. The plagioclase lherzolite and lherzolite are medium grained, ophitic, and ophitic, with oikocrysts of orthopyroxene and clinopyroxene containing olivine (Figs. 15a, 15b). The lherzolite (± plagioclase) contains several pockets of monomineralic cumulate (plagioclase or pyroxene). These pockets were extracted from a deeper magma chamber by the magma associated with the lherzolite. The lherzolite also contains a decimeter-scale enclave of metasomatized rock rich in calc-silicate minerals. This outcrop attests to the local presence of thick magmatic layering within the zoned Lac à la Vase intrusion and to the dynamic magmatic processes occurring in the magma chamber. The evidence also suggests multiple magma pulses and perhaps magma mingling. These observations are very important because, to obtain economic concentrations of Ni, Cu, and precious metals, it is necessary for the sulfides to react with a large amount of magma, preferably more primitive, after their formation to enhance their metal concentrations. Ni, Cu, and especially the PGE have partition coefficients (describing metal partitioning between sulfide liquid and silicate liquid) favoring their concentration in the sulfide liquid: $D_{Ni} = 1000$ (Arndt et al., 2005), $D_{Cu} = 1000$ (Naldrett et al., 1999), D_{PGE} ranges from 10^4 to 10^5 (Ballhaus et al., 1994; Peach et al., 1994; Fleet et al., 1996).

The metanorite contains traces of pyrrhotite and pyrite, and the olivine gabbronorite contains 1% of pyrrhotite, pentlandite, and chalcopyrite. The plagioclase lherzolite is also locally mineralized, with 1–2% of pyrrhotite, pentlandite, and minor chalcopyrite.

Distance (in km)

0.0 Return to the trail. Turn left and walk west 400 m along the trail.
0.4 Walk southeast 90 m into the woods.

STOP 7. Rousseau showing, north shore of Lac à la Vase (30 min)

The Lac à la Vase intrusion contains several showings. The Rousseau showing, located at the northern end of Lac à la Vase, is a good example of sulfide textures in olivine-free rocks.

This outcrop is composed of the same norite as in the marginal zone of the Lac à la Vase pluton. The norite here is mesocratic and medium grained. It has an adcumulate texture, with cumulus plagioclase and a small amount of

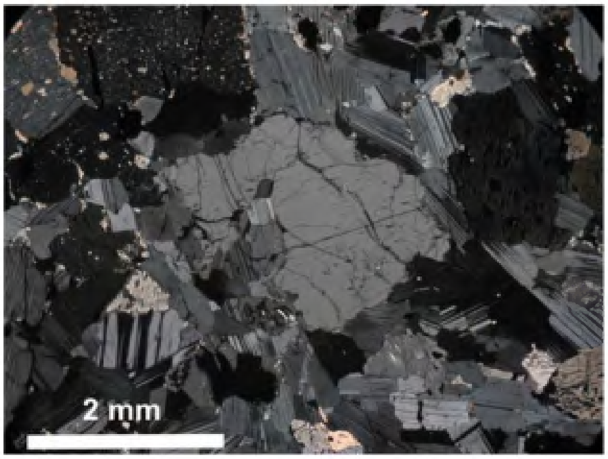

Figure 13. Photomicrograph (cross-polarized light) showing the texture of metanorite.

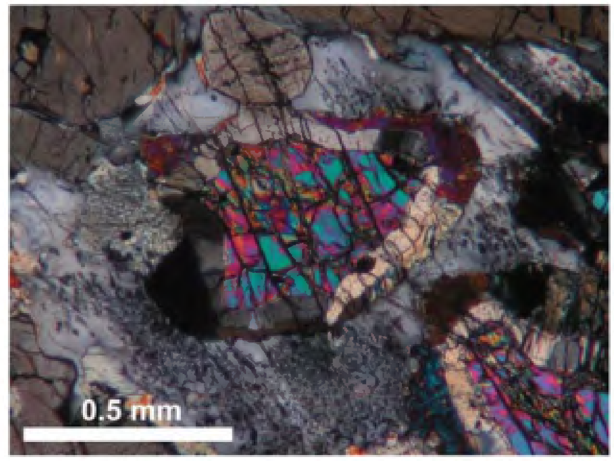

Figure 14. Photomicrograph (cross-polarized light) showing the coronitic texture of olivine gabbronorite. The olivine is surrounded by a corona of orthopyroxene–amphibole–symplectite of amphibole and spinel.

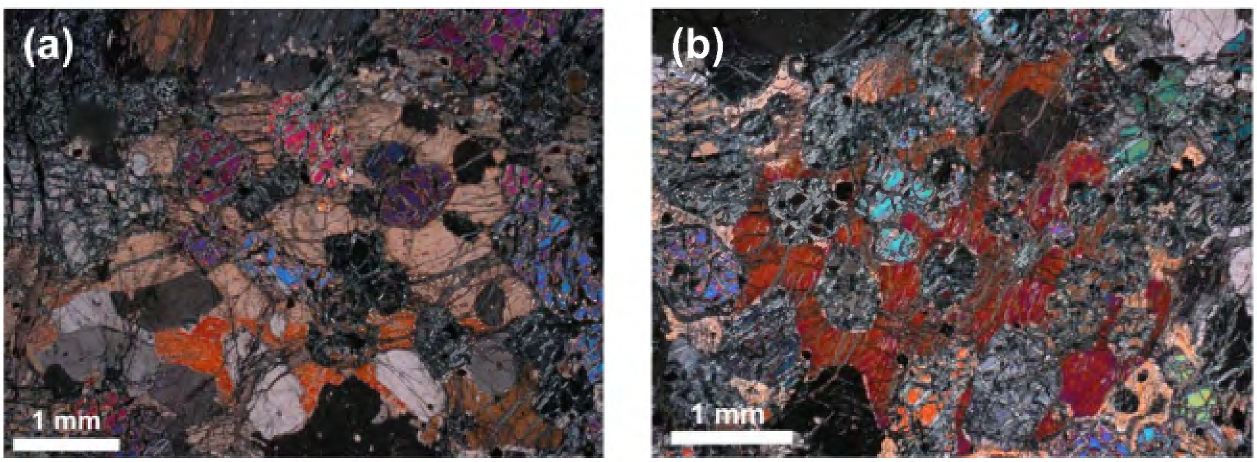

Figure 15. Photomicrograph (cross-polarized light) showing the ophitic texture of plagioclase lherzolite, with oikocrysts of orthopyroxene (a) and clinopyroxene (b) containing olivine.

intercumulus orthopyroxene. These rocks are cut by a 4 m wide and 20 m long (min.), mineralized dike of fine-grained, metamorphosed, plagioclase-bearing orthopyroxenite, locally with plagioclase oikocrysts containing orthopyroxene. The dike composition can vary to melanocratic norite. It is oriented ENE–WSW, with a northward dip. The mineralized dike contains 3% pentlandite, pyrite, and chalcopyrite. The sulfides are disseminated and locally net textured (Fig. 16). The metamorphic rock texture, the high amphibole abundance, the absence of pyrrhotite, and the unusual blebby texture of pentlandite attest to recrystallization of silicates and sulfides during regional metamorphism. During metamorphism, metal redistribution occurred between sulfide species and perhaps between sulfides and silicates.

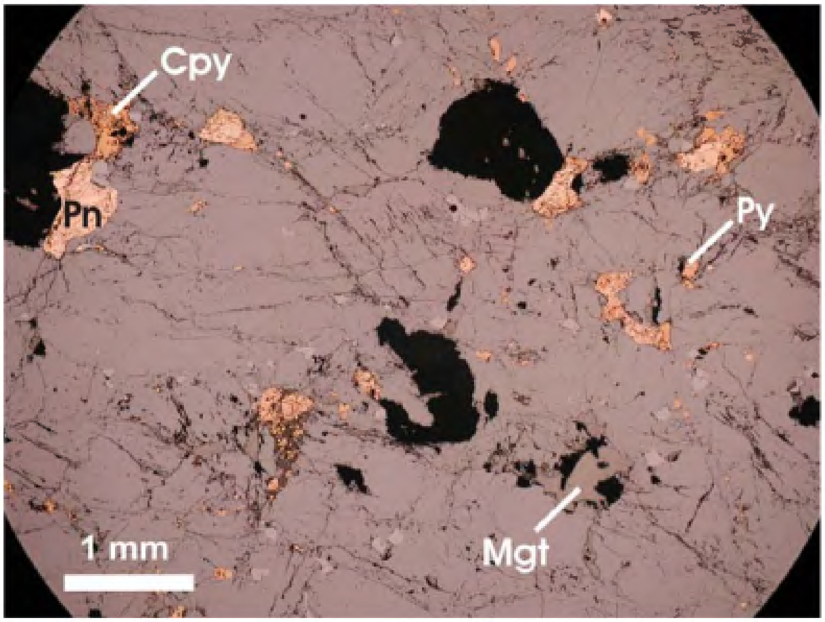

Figure 16. Photomicrograph (reflected light) of metamorphosed plagioclase-bearing orthopyroxenite containing disseminated blebs and locally net-textured pentlandite, pyrite, and chalcopyrite. (Cpy = chalcopyrite; Py = pyrite; Mgt = magnetite).

END OF FIELD TRIP. Return to Quebec City.

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A TOUR OF THE CHARLEVOIX IMPACT STRUCTURE

by

Léopold Nadeau and Pierre Brouillette
Geological Survey of Canada, 490, rue de la Couronne, Québec, QC G1K 9A9, Canada

Abstract

Located less than 125 km east of Quebec City, the Devonian-age (ca. 342 ± 15 Ma) Charlevoix impact structure is among the largest and the most accessible meteorite impact structures in eastern North America. The peripheral ring trough, 54 km in diameter, forms a prominent open valley that locally reaches an altitude of 250 m. The highest point in the valley is nearly 850 meters below the mean elevation, approximately 1100 m, of the external Laurentian plateau and 550 m below the central uplift, "Mont-des-Éboulements," which stands 780 m above sea level. Its overall morphology matches that of a complex impact crater. Shatter cones, mylolisthenite injections and shock-related planar deformation microstructures in quartz and feldspar are widespread, hence providing compelling evidence for the extent of shock metamorphism.

The field trip provides an opportunity to enjoy the panoramic view of the peripheral trough and ring structure from the central uplift, and to visit key outcrops showing shock-related features, including shatter cones, impact breccias, and related fault zones.

Résumé

Localisée à moins de 125 km à l'est de la ville de Québec, la structure d'impact de Charlevoix, d'âge dévonien (342 ± 15 Ma), est parmi les plus grandes et les plus accessibles structures de ce type de l'est de l'Amérique du nord. La dépression annulaire périphérique, d'un diamètre de 54 km, forme une vallée évasée dont l'altitude atteint localement 250 m. Cette dépression est en retrait de près de 850 m par rapport au niveau moyen du plateau laurentien dont l'altitude se situe autour de 1100 m, et de près de 550 m par rapport au soulèvement central, le mont des Éboulements, dont l'altitude atteint 780 m. Sa physiographie correspond à celle d'un cratère de type complexe. Les cônes d'impact, les injections de mylolisthénite et les microstructures de choc dans le quartz et le feldspath sont répandus, témoignant ainsi de l'importance du métamorphisme de choc.

Cette excursion offre l'occasion d'apprécier la vue panoramique de la dépression annulaire périphérique à partir du point le plus élevé du soulèvement central, le mont des Éboulements, et de visiter des affleurements clefs présentant des produits caractéristiques d'impact dont des cônes-de-choc, des mylolisthénites et des brèches de faille reliées à l'impact.

PROLOGUE

This field trip to the Charlevoix impact structure is, so to say, "un retour aux sources." I was introduced as a teenager, back in 1968, by Dr. Jehan Rondot to the geology of the Charlevoix region, shortly after his discovery of the impact structure. This also marked my initiation to field geology, as an insect and mineral collector, and my first encounter with a real geologist, with all the romantic imaginings that such a pioneer figure can trigger in a 14-year-old boy's eager mind.

My subsequent geological studies and professional work kept me away from pursuing study of the Charlevoix impact structure. Accordingly, I am at best an educated geologist enthusiastic to communicate his modest knowledge of this unusual geological feature. To this day, Drs. Rondot and Roy remain by far the experts on the Charlevoix impact structure and, as such and circumstances permitting, either one would be a much more knowledgeable leader for this field trip.

—Léopold Nadeau

INTRODUCTION

The Charlevoix region displays a rich geological heritage. It is located at the present-day erosional limit of three geological landmarks in central and eastern North America. A tapering fringe of Cambro-Ordovician sediments of the St. Lawrence Platform intervenes between the Mesoproterozoic crystalline rocks of the Grenville Province of southeastern Laurentia (to the northwest) and the thrust-accreted rocks of the Appalachian Mountain Belt (to the southeast). In other terms, the Charlevoix region lies along the late-Neoproterozoic to Cambrian St. Lawrence rift system, immediately inboard from the Appalachian front with thrust activity dating back to Upper Ordovician. Orogeny-driven faulting and fault reactivation likely occurred through the Paleozoic and Mesozoic. Hence, the Devonian-age meteorite impact event added on to an already compound geologic history, significantly weakening the crust and making it more prone to subsequent seismic activity.

Given the turbulent geological history of the Charlevoix region, crosscutting and overprinting structural and tectonic relationships in the area are in places difficult to decipher, and their full significant is somewhat debatable. While evidence for a major impact structure is conclusive, the role of Iapetus rifting and subsequent Appalachian telescoping in the development and reactivation of the fault network and in the preservation of the St. Lawrence Platform sediment fringe is likely more important than initially anticipated.

PREVIOUS WORK AND REFERENCES

Readers are referred to the landmark contributions of Rondot (1995, 2000), Lamontagne (1987, 1999), Lemieux et al. (2003), Roy (1979), Robertson (1975), and references therein, for a comprehensive review on the impact structure, regional geology and stratigraphy, structural evolution, and recent seismic activity.

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SUPPORTING FIGURES

The following set of figures provides an overall geological context and background information in support of the field trip. The field trip stops are shown on the location map (Figure 1).

The tectonic setting of the Charlevoix impact structure is depicted in Figure 2. The Charlevoix impact structure is opportunely sited on the St-Laurent fault and Logan's Line, reworking a fringe of Paleozoic St. Lawrence Platform sediments wedged between Precambrian Grenvillian basement and the Appalachian thrust belt.

Given its diameter of ~54 km, central uplift, and annular fault-bounded graben (peripheral ring trough), the Charlevoix impact structure is classified as a complex crater (Figure 3 and 4). Development of such a structure can be described as a three-stage process involving excavation, central uplift, and post-impact gravitational collapse. It occurs "in a flash" compared to the long geological history of the region.

The geometry and significance of minor fault plays is locally revealed through gaps and duplications in the Paleozoic St. Lawrence Platform sedimentary sequence (Figure 5). The fieldtrip allows for a close examination of the lower siliciclastic and overlying limestone intervals.

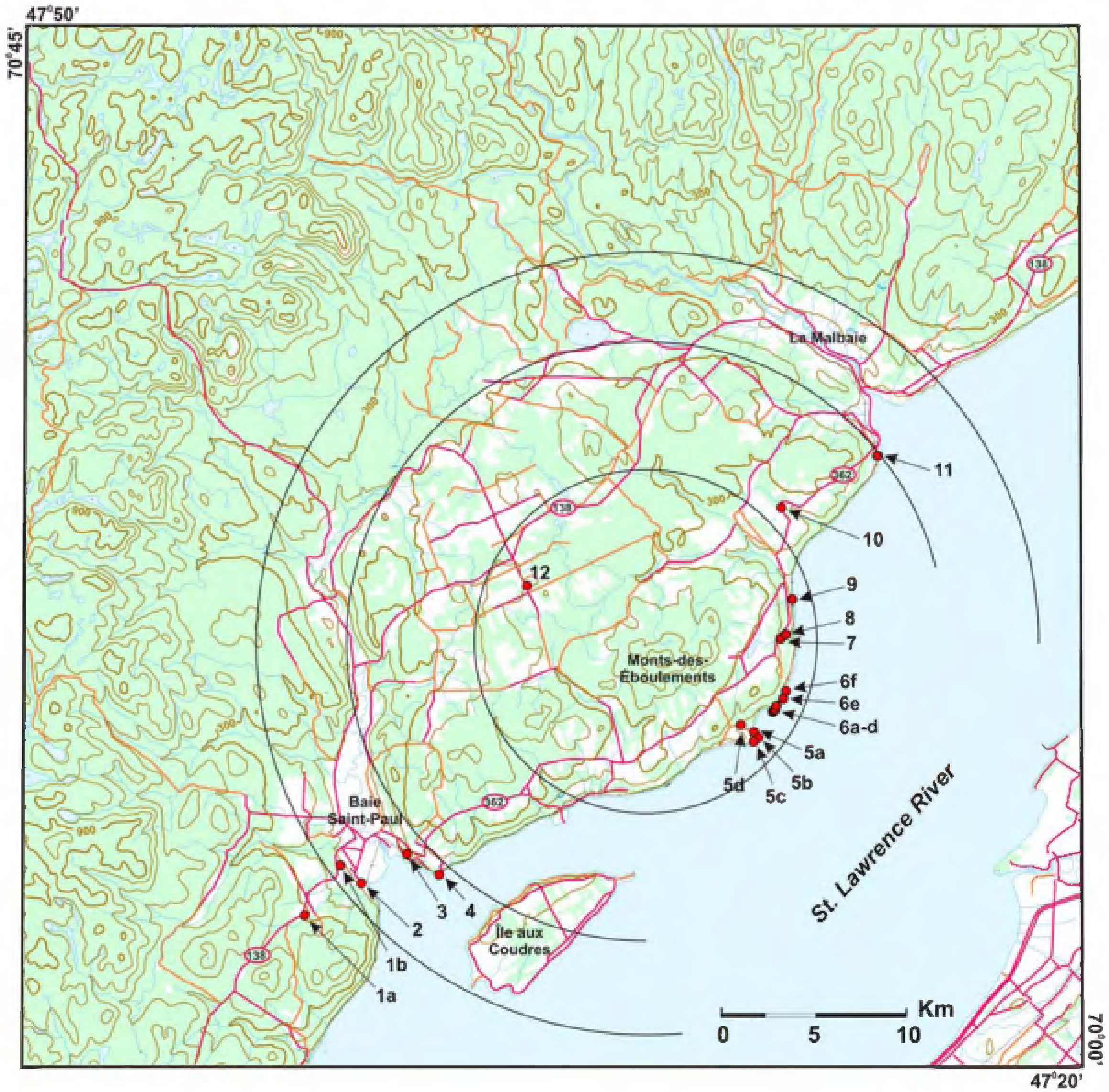

Figure 1. Field trip stop-location map (stops 1 to 12) and main road access.

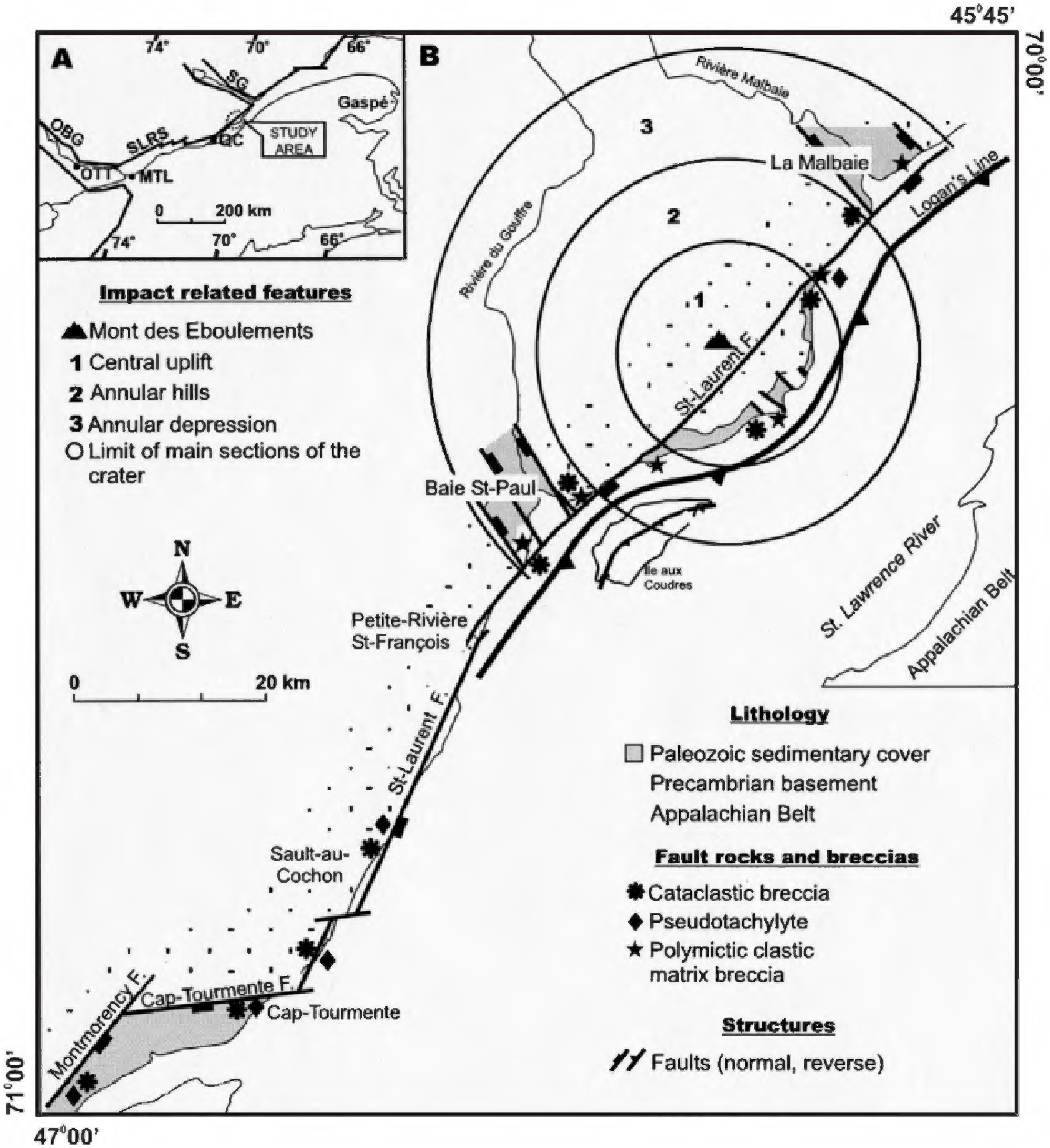

Figure 2. (A) Simplified map of the St. Lawrence rift system (SLRS) showing the location of the Ottawa-Bonnechère (OBG) and Saguenay River (SG) grabens. OTT, Ottawa; MTL, Montréal; QC, Québec. (B) Simplified geological map of the Charlevoix area. Numbers and circles represent different divisions of the impact crater morphology. Mont-des-Éboulements represents the highest point in Charlevoix and corresponds to the inferred point of impact. Map also shows the distribution of cataclasite breccia, and the polymictic clastic matrix breccia (Rondot's mylolisthenite). Note the restriction of the mylolisthenite to the crater's limit. F., fault. (Figure from Lemieux et al., 2003).

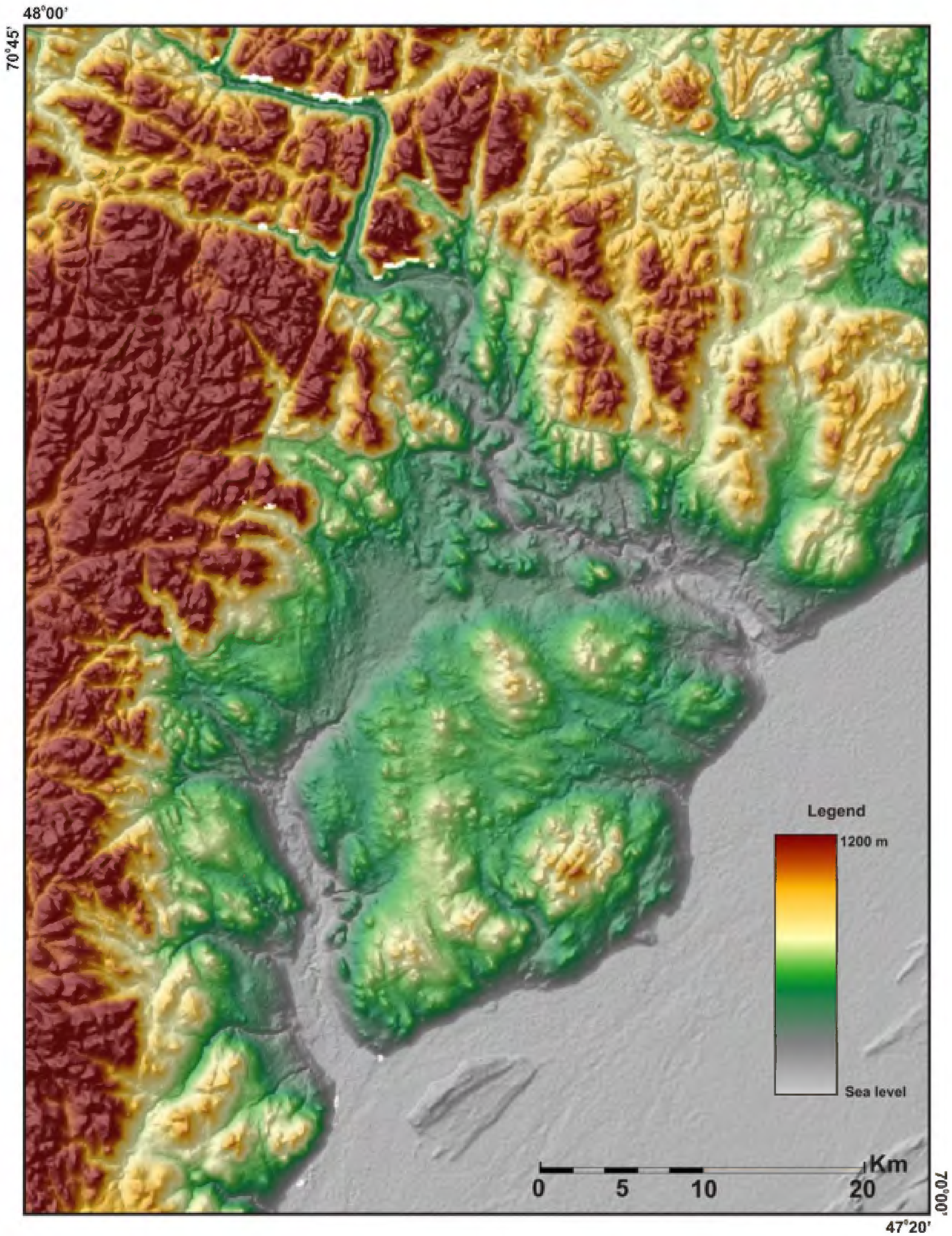

Figure 3. Digital elevation model staging the main topographic features defining the Charlevoix impact structure. The peripheral ring trough, 54 km in diameter, forms a prominent open valley that locally reaches an altitude of 250 m. The highest point in the valley is nearly 850 m below the mean elevation, approximately 1100 m, of the external Laurentian plateau and 550 m below the central uplift, "Mont-des-Éboulements," which stands at 780 m above sea level.

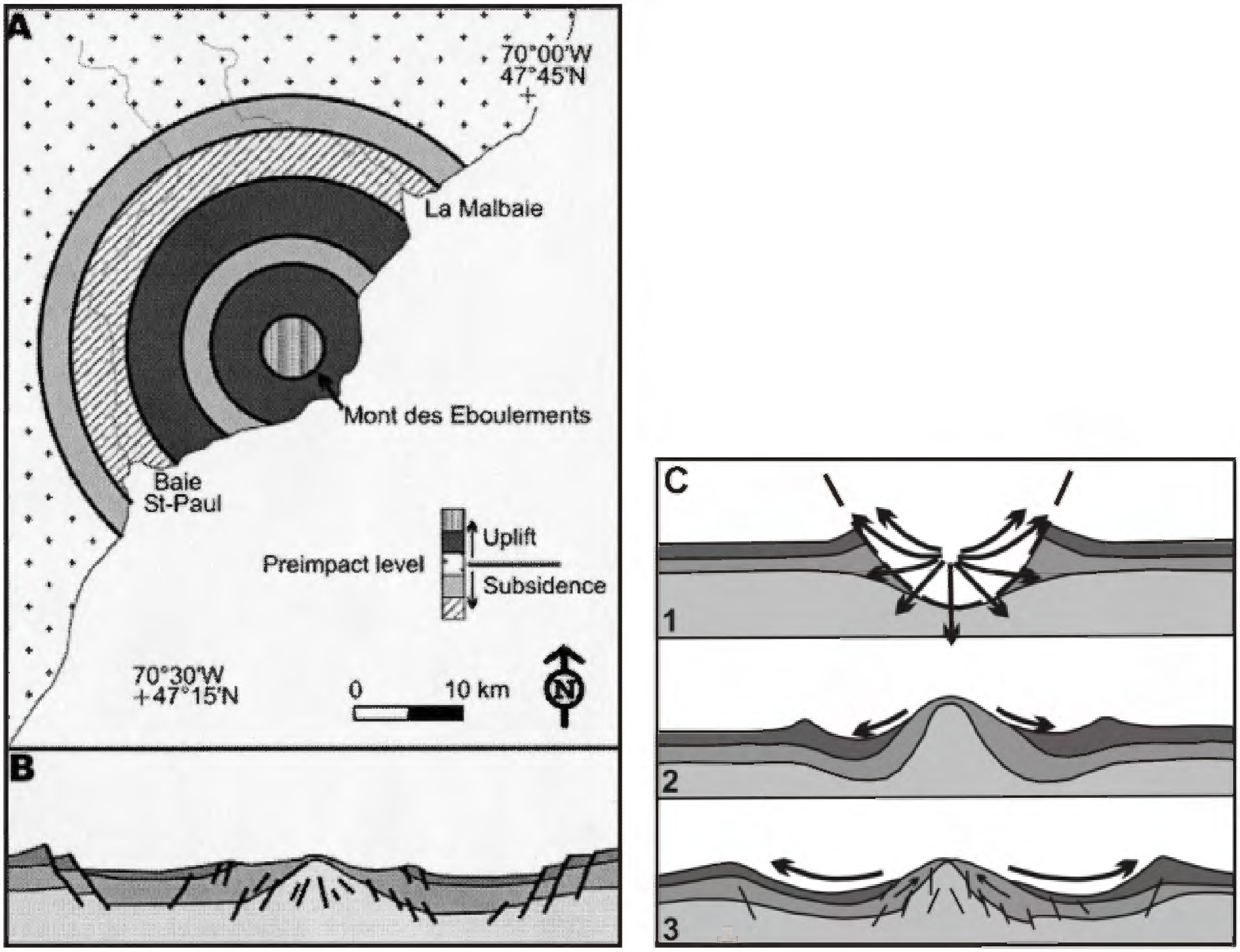

Figure 4. (A) Schematic topographic map showing the geomorphology of the Charlevoix impact structure. The plus-sign pattern represents the mean level of the Grenvillian basement and rocks of the St. Lawrence Platform before the impact. (B) Schematic cross-section of an idealized impact crater showing the orientation of normal faults surrounding the central uplift and bounding the outer limit of the impact crater. (C) Schematic model depicting the three phases of development of a complex impact crater: (1) excavation, (2) central uplift, and (3) gravitational collapse and crustal isostatic reequilibration.(Figure from Lemieux, 2001).

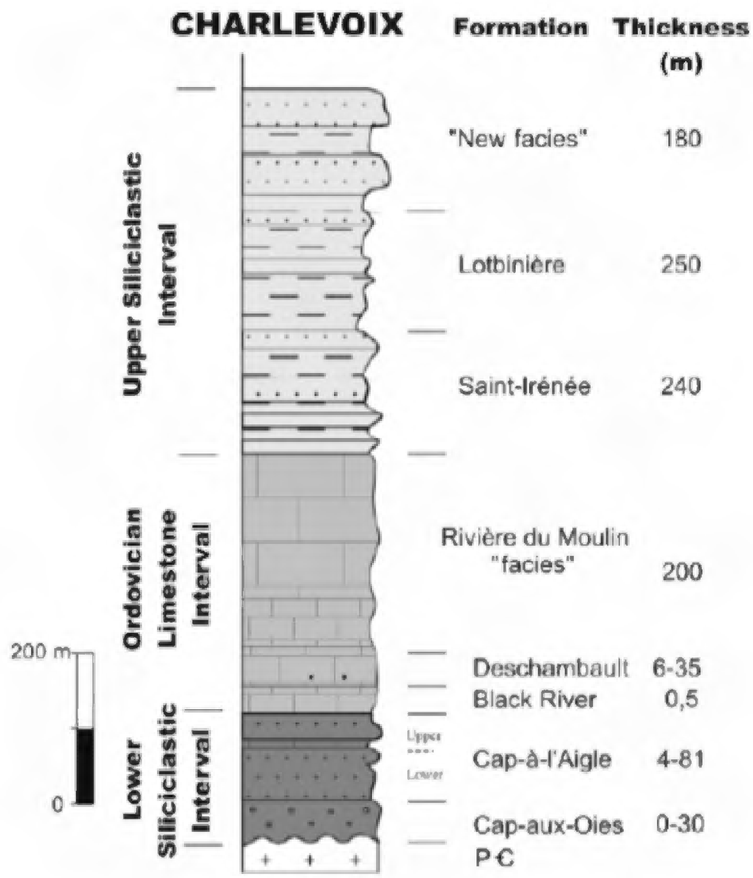

Figure 5. Stratigraphic column of the Charlevoix area with relative thickness of sedimentary units. Figure not to scale. (Figure from Lemieux et al., 2003).

FIELD TRIP LOG

Note: UTM coordinates given in the road log below refer to the NAD 83 map projection.

STOPS 1a and 1b. Panoramic view of the Charlevoix impact structure
Highway 138 – Stop 1a: 382993 E, 5251491 N; Stop 1b: 384970 E, 5254131 N

These lookouts are located on the outer rim of the Charlevoix impact structure. The panoramic views include the main regional-scale landmarks of the exhumed roots of the impact structure within Precambrian basement gneiss. The highland and nested hills in the far background correspond to the annular hills and central uplift centered on Mont-des-Éboulements, which stands 780 m above sea level. The lower Rivière-du-Gouffre valley farmland corresponds to the impact annular graben comprising a few scattered outcrops of the St. Lawrence Platform sediments. Logan's Line runs outboard from the St. Lawrence River shoreline, cutting across l'Île-aux-Coudres as part of the Appalachian Belt.

STOP 2. Normal faulting after post-impact isostatic reequilibration
Rivière-du-Moulin – 386077 E, 5253156 N

The waterfall at Rivière-du-Moulin exhumes a steep, northeasterly dipping normal fault that juxtaposes Precambrian footwall gneiss against Ordivician hangingwall limestone. Polymictic breccia occurs along the fault plane. Such faults, which occur as part of the annular graben, are interpreted as post-impact readjustment structures driven by isostatic reequilibration.

STOP 3. Annular graben fault zone
388542 E, 5254685 N

The road section exposes nearly upright tilting of Paleozoic sediments in the hanging wall of one of the normal faults bounding the annular graben. Note the abundance slickenside-ornamented fracture surfaces.

STOP 4. "Exotic" enclave of Ordovician limestone in faulted Precambrian basement
Cap-au-Corbeau – 390242 E; 5253338 N

This outcrop features spectacular mylolisthenite typical of the fault zones bounding the annular graben. The steep southeasterly dipping fault zone comprises highly fractured Precambrian charnockitic basement gneiss. Clasts are abundant and appear to be derived largely from the immediate wallrock.

Remarkable among the clasts is a metre-size "enclave" of Ordovician limestone. Emplacement of such an "exotic" enclave within the fault zone may be the result of up-and-down fault readjustment whereby a slice of overlying limestone is cut off, included, and moved within the fault zone. Alternately, such an enclave may have been forcefully pushed down within the basement fracture zone.

The occurrence of clasts of welded, brecciated rock within the mylolisthenite matrix suggests protracted cataclasis. Note the variability in clast size. The outcrop also features a sharply bounded, 20 cm wide breccia dike intruding basement gneiss.

STOP 5a. Shatter cones in Ordovician limestone
Cap-aux-Oies – 407220 E; 5260868 N

Striated fracture surfaces typical of shatter cones are recognizable in places at low tide on limestone bed surfaces. Note that they are preferentially developed in thick and more homogeneous beds. Cone axes generally trend towards and fan around the center of the impact structure.

STOP 5b. Mylolisthenite dike and sill-like injections in Ordovician limestone
Cap-aux-Oies – 407445 E; 5260572 N

Outcrops along the beach feature numerous thin and variably oriented mylolisthenite dikes and sill-like injections within Trenton limestone. Note the variability in clast content and size (up to 2 cm), and in matrix colour between injections. Intrusive boundaries are commonly irregular.

Light-grey mylolisthenite injections commonly feature more abundant and larger clasts and less regular intrusive contacts than the thinner and darker injections. The presence of blue quartz fragments, presumably derived from the crystalline basement, suggests the magnitude of breccia transport.

STOP 5c. Impact fracturing in Ordovician limestone
Cap-aux-Oies – 407179 E; 5260365 N

This outcrop displays a number of impact-related, closely spaced minor faults and fractures. The occurrence of mylolisthenite injections in such fracture zones confirms their origin.

STOP 5d. Duplication of the Ordovician sequence
Cap-aux-Oies – 406499 E, 5261276 N

Arkosic sandstone and limestone are duplicated after lateral telescoping due to the central uplift. Mylolisthenite injections occur along faults. Shatter cones with well-marked striations are developed in more-argillaceous limestone beds.

STOP 6. Map- and mesoscopic-scale impact structures
Cap-aux-Oies to l'Anse-au-Sac

This group of stops is located ~6.5 km from the centre of the impact structure at Mont des Éboulements, near the outer limit of shocked quartz metamorphism. Proceeding northerly along the beach from Cap-Corneille to Pointe-au-Père, the Ordovician sedimentary succession crops out in step-faulted contact with Precambrian orthogneiss. While a number of northeast-striking fault segments are viewed as reworked splays of the rift-related St. Lawrence fault zone, segments at high angles to the latter are attributed to the impact. In view of the widespread occurrence of mylolisthenite dikes and shatter cones, the origin of minor faults and folds remains somewhat contentious.

STOP 6a. Fault contact between Ordovician Trenton limestone and Precambrian basement
Cap Corneille – 408231 E, 5261944 N

The sedimentary succession is crosscut by variably oriented mylolisthenite dikes up to 15 cm thick. Mylolisthenite injections are more difficult to recognize in basement gneiss. Also note the local occurrence of vesicles in the dark-green-coloured breccia matrix and of a silicification fringe along the wallrock contact.

STOP 6b. Mylolisthenite dike in Ordovician limestone
408302 E, 5262033 N

This outcrop shows a mylolisthenite dike in Ordovician limestone near the contact with basement gneiss. The dike is pinched and strikes nearly at right angles to the fault segments bounding the Ordovician sediments. Note the presence of vesicles and the fluidal structure of the breccia.

STOP 6c. Shatter cones in limestone
408378 E, 5262014 N

Striated fracture surfaces in limestone are evidence for shatter cones. The latter tend to be preferentially developed in mechanically homogeneous and tenacious rock types. This is well illustrated by this occurrence, in a 20 cm thick limestone bed, of a truncated shatter cone defined by opposite and converging striated fracture surfaces.

STOP 6d. Fault bounded Cambrian quartzite
408573 E, 5262162 N

A fault-bounded, 30-meter bloc of contrasting Cambrian quartzite occurs encased in a fault play juxtaposing Trenton limestone and quartz pebble conglomerate of the Cap-aux-Oies Formation. Note also the occurrence of centimetre-size shatter cones.

STOP 6e. Brecciated basement gneiss within Ordovician sediments
Pointe au Père – 408810 E, 5262647 N

The outcrop is located at the edge of a kilometre-size fault-bounded wedge of Precambrian basement orthogneiss within Paleozoic sediments. The orthogneiss is brecciated and locally pulverized, forming a cataclastic breccia. The fine-grained matrix comprises fragmental crystals derived from the wallrocks.

STOP 6f. Brecciated basement gneiss and mylolisthenite dikes
Pointe-au-Père - 408950 E, 5263050 N

Mylolisthenite dikes carrying centimetre-size gneiss fragments also occur within flanking limestone. Among them, one dike appears to be aligned with the cataclastic breccia in basement gneiss, hence supporting the hypothesis of impact-driven brecciation and forceful emplacement. Note, however, that similar breccias also occur along the St. Lawrence fault zone away from and unrelated to the impact structure.

STOP 7. Impact-related fault contact between Precambrian basement and Paleozoic sediments
Ruisseau Jureux – 408721 E, 5265850 N

This stop is located in the northeast flank of the central uplift. Precambrian basement granitic orthogneiss occurs in close proximity to Ordovician clastic sediments and limestones of the Cap-à-l'Aigle and Cap-aux-Oies formations. The granitic orthogneiss features fractured surfaces with converging sheaf lineations defining decimetre-size shatter cones.

STOP 8. Reworked contact between Precambrian basement granite and Cambrian quartzite
409002 E, 5266060 N

Mylolisthenite intervenes along the contact between Precambrian basement granite and overlying Cambrian quartzite.

STOP 9. Appalachian deformation in Paleozoic platform sediments
Saint-Irénée – 409381 E, 5267941 N

Paleozoic sediments are fault bounded against Precambrian basement gneiss. Strata are moderately dipping towards the northeast. Calcareous sandstone locally forms olistostromes, and the schistosity matches that of the St. Lawrence fault.

STOP 10. Suevite-type dike
Gros Ruisseau – 408876 E , 5272811 N

This stop is located ~10 km from Mont-des-Éboulements. Basement gneiss is crosscut by a suevite-type breccia marked by glassy black matrix and vesicles. Prehnite is the chief mineral in the breccia. The gneiss contains a schistose cataclastic zone, 1 x 3 m in extent, with abundant chlorite and albitic plagioclase formed during retrograde metamorphism.

STOP 11. Appalachian thrust faulting in Paleozoic sediments
Pointe-au-Pic – 414069 E , 5275492 N

This outcrop of Paleozoic limestone is located in the impact-related annular graben, a short distance from the outermost foreland Appalachian thrust. While protected from erosion by their basal location in the annular graben, the rocks show a number of foreland-directed minor thrust faults, which are manifestations of Appalachian telescoping.

STOP 12. Shatter cones at the discovery outcrop
Saint-Hilarion – 395202E , 5268902 N

Shatter cones at this stop were discovered by Dr. Rondot in 1966, providing the first evidence for the Charlevoix impact structure. They occur in Precambrian basement charnockitic gneiss at ~8km from Mont-des-Éboulements. They lack a systematic preferred orientation due to post-impact isostatic fault readjustment along two sets of moderate- to steeply dipping fractures oriented N162°, 64°SW dip and N78°, 56°SE dip. Prehnite occurs as small, white-coloured mats within fractured gneiss. Note also the thin breccia injections.

END OF FIELD TRIP

QUATERNARY GEOLOGY AND GEOMORPHOLOGY OF THE QUÉBEC CITY – MONT SAINTE-ANNE REGION

by

Serge Occhietti, Université du Québec à Montréal, Montréal, QC H3C 3P8, Canada
Michel Parent, Geological Survey of Canada, 490 de la Couronne, Québec, QC G1K 9A9, Canada
Lise Lamarche, INRS-Eau, Terre et Environnement, 490 de la Couronne, Québec, QC G1K 9A9, Canada

INTRODUCTION

Although the Quaternary record of the Québec City region is of considerable importance for understanding that of the whole St. Lawrence Valley, it has remained somewhat understudied. Following pioneer observations by distinguished geologists such Lyell (1845), Dawson (1893) and Goldthwait (1933), LaSalle (e.g., LaSalle, 1978, 1984) and his colleagues (LaSalle et al., 1977a, 1977b; Chauvin et al., 1985) provided the first modern attempt at unravelling the Quaternary record of the region. More recently Bolduc and her colleagues (Bolduc, 2003; Bolduc et al., 2003) provided new surficial geology maps for the region; a simplified version of which is shown below (Fig. 1).

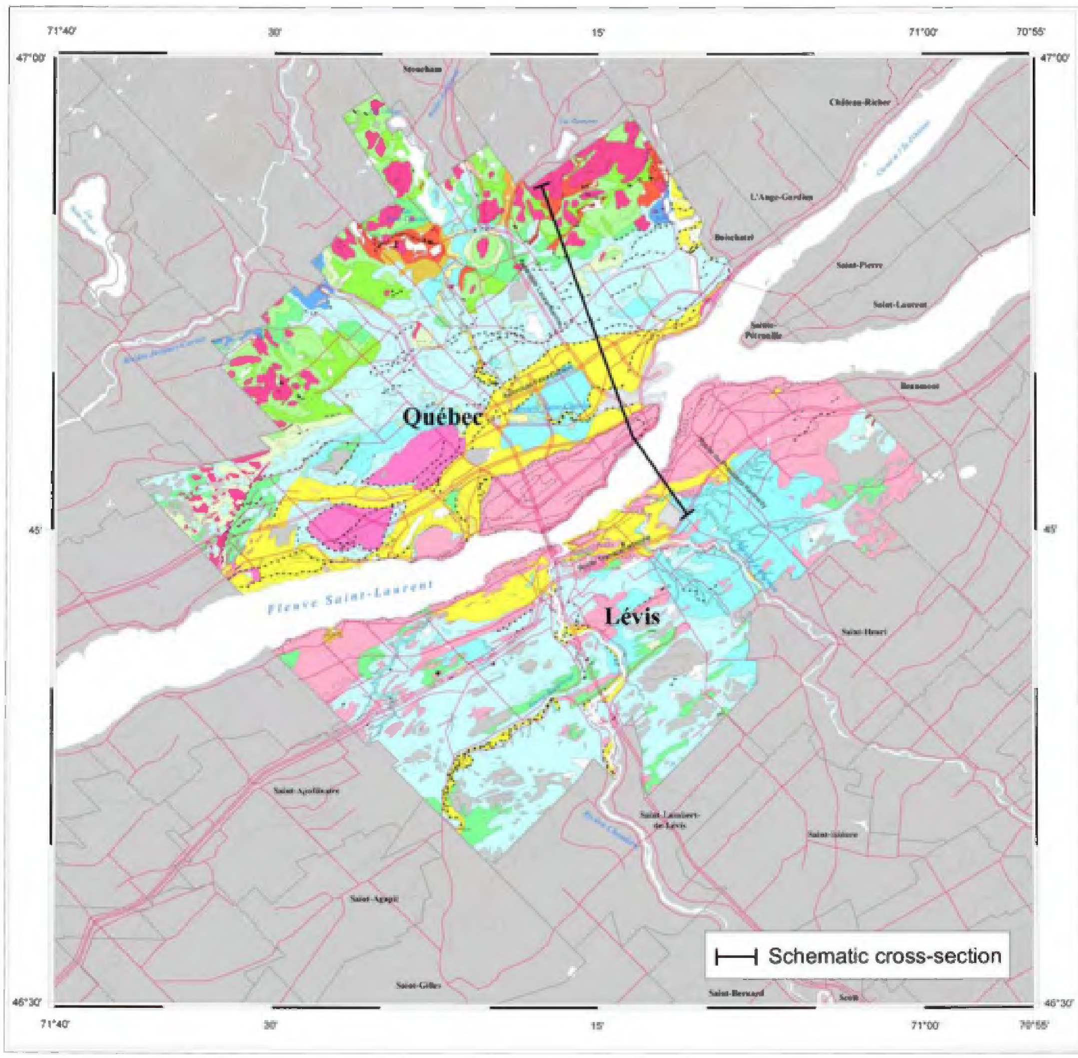

Figure 1. Simplified surficial geology of the Québec City region (after Bolduc, 2003, and Bolduc et al., 2003).

Near Québec City, the floor of the St. Lawrence Valley rises to elevations ranging from about 60 to 80m ASL, and this regional threshold exerted a major control on its Quaternary drainage history, particularly on the development of large glaciomarine and glaciolacustrine water bodies that episodically occupied the central St. Lawrence and that alternated with episodes of free drainage towards the Gulf of St. Lawrence. As the St. Lawrence River flows across this threshold, it is deeply entrenched in a narrow passage bordered by steep bedrock cliffs, a constriction that is commonly designated as the Québec City narrows (Fig. 2). The key role of this threshold at the end of the Champlain Sea episode has become increasingly obvious as we are currently trying to connect the sea level history of the St. Lawrence Estuary (Dionne, 1988, 1999, 2001) with that of river level history near Lake Saint-Pierre about 120km upstream (Lemelin, 2004; Lamarche, 2005) documented as a result of ongoing surveys.

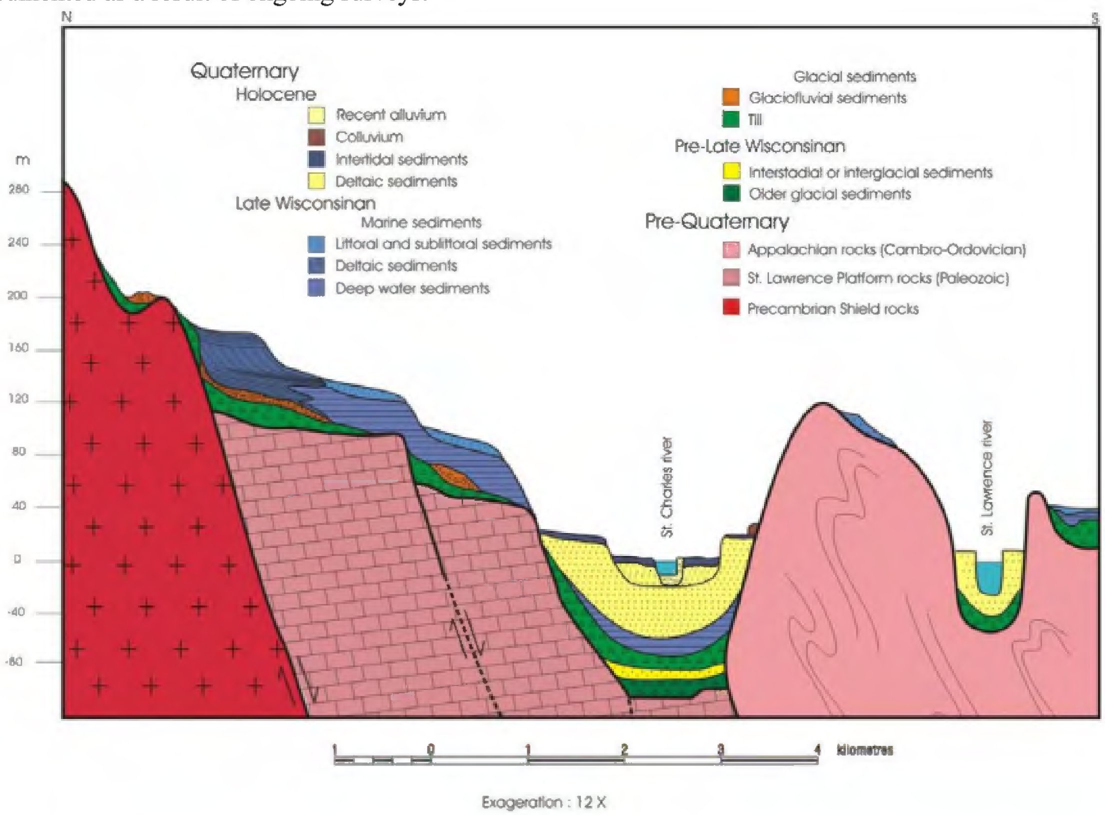

Figure 2. Schematic cross-section of Quaternary units in the Québec City region (modified from Lamarche, 2007).

In the course of a seismic microzonation project, the Geological Survey of Canada and its project partners (INRS-ETE, Laval University and Québec City) are producing a 3D model of the surficial geology of the Québec City region. Subsurface data from a variety of sources are being compiled and integrated into the 3D model as part of an ongoing Ph.D. thesis work (Lamarche, 2007). In the fall of 2006, a continuous Rotosonic drill core was recovered from the deepest part of the buried valley that lies below the floor of the Cap-Rouge/Limoilou depression, which is actually an abandoned channel formed by the early St. Lawrence River as it flowed north of the outermost Appalachian ridge, locally known as the Sainte-Foy island (Fig. 1), and into the receding Goldthwait Sea. A schematic section across the Québec City narrows (Fig. 2) shows what we presently know of the subsurface distribution Quaternary units. Most noticeable (and unexpected!) is a thick unit of marine deltaic sediments underlying most of the lower town, particularly on the north side of Rivière Saint-Charles. This deltaic unit had in fact remained unkown to earlier Quaternary geologists because it is seemingly continuously covered by 3 to 5m of mid-Holocene, organic-rich muds and thus lies below the reach of shallow excavations. However this geologic cross-section must be considered as preliminary as it is likely to undergo significant changes when new boreholes and analyses are carried out over the next few years. In particular, the presence and distribution of pre-Late Quaternary sediments need to be ascertained through paleoecological analyses and radiocarbon dating of sediments.

LATE GLACIAL EVENTS IN THE QUÉBEC CITY REGION

Recently observed glacial landforms and striae as well as lithological indicators, both upstream and downstream of Québec City, have confirmed the key role exerted by the St. Lawrence Ice Stream on regional deglacial events (Fig. 3; Parent and Occhietti, 1999; Occhietti et al., 2001), notably on late ice-flow reorientations in the valley (e.g., Bolduc and Paradis, 1999) as well as in the Appalachians (e.g., LaSalle et al., 1977; Chauvin et al., 1985; Lowell et al., 1985, 1990). Recent Quaternary surveys in the Montreal region has shown that during about the same time interval (Port Bruce to Port Huron), an ice stream formed in the Upper St. Lawrence valley causing widespread re-orientation of ice-flow in southwestern Québec and southeastern Ontario (Ross et al., 2006). These recent findings suggest that ice streams played a key role in the collapse of the Laurentide Ice Sheet in the St. Lawrence Valley prior to the Champlain Sea episode.

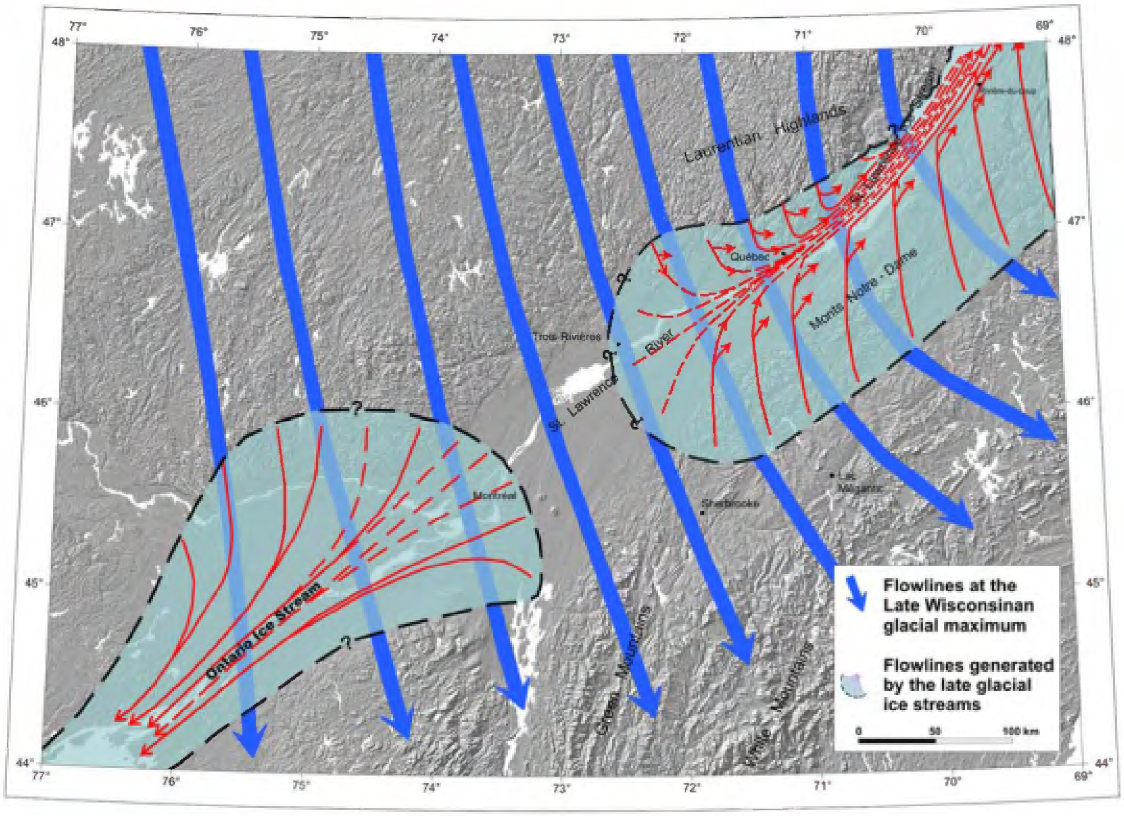

Figure 3. Late Wisconsinan ice streams and flow patterns in southern Québec and eastern Ontario.

In the ice stream model, the drawdown of the ice surface in the St. Lawrence valley is no longer caused by calving re-entrant in the Goldthwait Sea, thus allowing northward ice-marginal retreat in the southern St. Lawrence Valley (Lake Candona episode) to occur almost coevally with ice-flow reversal in the northern half of the Appalachians. The ice stream model also accommodates quite nicely the development of a successor outlet glacier in the St. Lawrence valley near Québec City, a feature that has now been well documented by ice-marginal features and ice-dammed lakes in the Mont Sainte-Anne region (stops 4 and 5) but has yet to be fully investigated throughout the Québec City region. Of course, the minor northeastward glacial readvance near Québec City (LaSalle and Shilts, 1993; Cummings and Occhietti, 2001) may constitute the latest record of this outlet glacier episode, but prior to the Younger Dryas cooling recorded by the Saint-Narcisse Moraine.

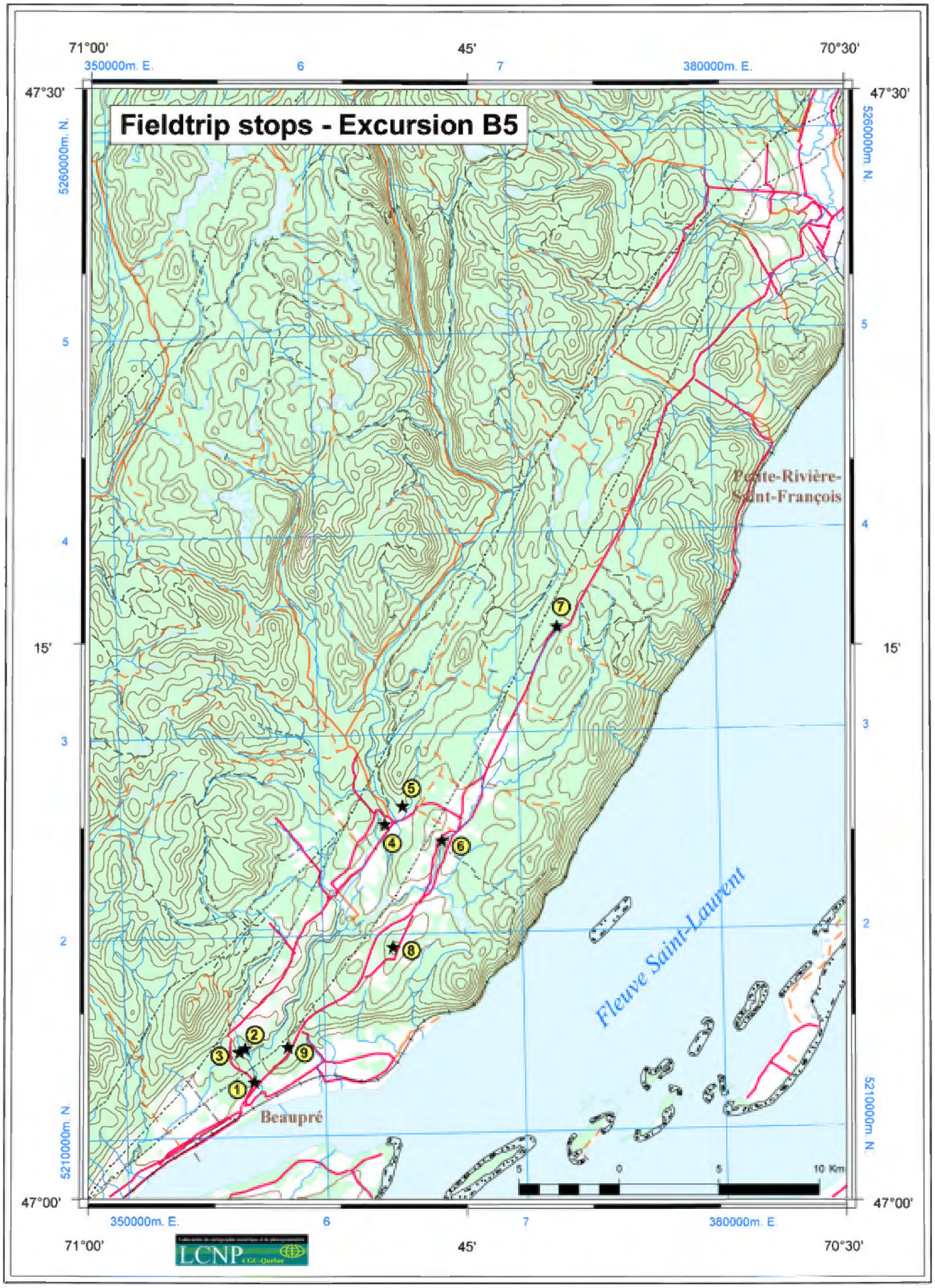

Figure 4. Location map of field trip stops in the Beaupré and Mont Sainte-Anne region.

LATE QUATERNARY STRATIGRAPHY AND EVENTS IN THE MONT SAINTE-ANNE REGION

Because of the outstanding Late Quaternary record as well as the excellent exposures of the Mont Sainte-Anne region, the fieldtrip will take us there, about 40km northeast of Québec City. The location of fieldtrip stops is shown in Figure 4. The main objectives are to present:

1) the general Pleistocene stratigraphy of the St. Lawrence Valley, with local complementary units,
2) the glacial style of a lateral local basin of the St. Lawrence Valley – the St-Tite basin close to the Mont Sainte-Anne – and the record of non glacial episodes during the Wisconsinan Stage,
3) the Wisconsinan ice dynamics in the Mont Sainte-Anne area, on the southern edge of the Laurentian Highlands, with emphasis on the St. Lawrence Ice Stream,
4) the ice retreat features prior to the Saint-Narcisse Moraine episode.

General Pleistocene stratigraphy of the St. Lawrence Valley in the Mont Sainte-Anne area

The classical units of the middle St. Lawrence Valley (Trois-Rivières area; see Table 1) can be observed in the lowlands of the Côte-de-Beaupré region. These local exposures correspond to the downstream limit of the extent of most of these units.

STOP 1. Beaupré site (Car window stop)

Due to urban development, the lower units of the Beaupré section are unfortunately no longer exposed. Within a thick unit of rhythmites (Beaupré varves), Lasalle et al. (1977b) had observed a bryophyte-bearing bed dated at > 39,000 years BP (GSC-1539). In spite of considerable efforts, this bed, which is probably discontinuous, could not be observed by Fournier (1998) or by the first author during his field work. A 3 m-deep excavation below the level of the bed reached a fine sand unit. The bed with organic matter is correlated with the Saint-Pierre Sediments, and the Beaupré varves with the Saint-Maurice Rhythmites. The lower sand unit may be a part of the Saint-Pierre Sediments or may represent an older unit.

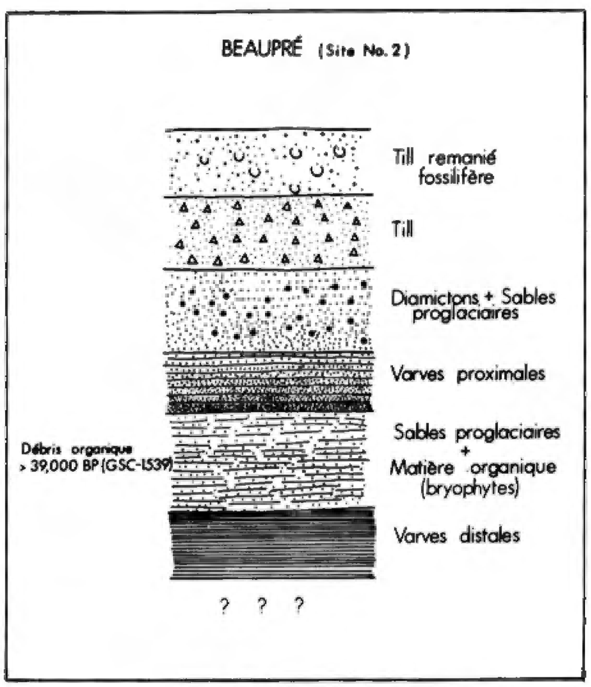

Figure 5. Sketch of the Beaupré section (from LaSalle et al., 1977b). Translation: *débris organique* = organic debris; *till remanié fossilifère* = fossiliferous reworked till; *sables proglaciaires* = proglacial sands; *varves proximales* = proximal varves; *matière organique* = organic matter; *varves distales* = distal varves.

Isotope stages		Lake Ontario	St. Lawrence Valley		Middle Estuary
	HOLOCENE		*Lake Lampsilis*		
	Dryas III		St. Narcisse Moraine		
1			*Champlain Sea*		*Goldthwait Sea*
		Lake Iroquois	*Lake Candona*		
		Port Huron Stade			
		Mackinaw Interstade			
2		Port Bruce Stade			
		Erie Interstade	Trois-Rivières		
	WISCONSINAN	Nissouri Stade			
			Stade		
		Plum Point Interstade		lake event?	marine event
3		Cherry Tree Stade	(3 glacial phases)		
		Port Talbot Interstade			local glacial lake
4		Guildwood Stade			
5a		(former St. Pierre Interstade)	Les Becquets Interstade	*Lake LaVerendrye*	
				Cartier Sea	
5b	SANGAMONIAN	*Lake Scarborough*	Nicolet Stade	*Lake Deschaillons*	glacial lake
5c			Grondines Interstade		
5d			*erosional surface*		
5e	climatic optimum	*Lake Coleman*			
					Guettard Sea
6	upper ILLINOIAN				
7					
8	ILLINOIAN s. l.				

Table 1: Main climatic events and environments since the Illinoian Stage, from the lower Great Lakes region to the middle Estuary of the St. Lawrence River (compiled from several authors).

STOP 2. Section on the left bank of Rivière Jean-Larose

This outstanding section was first reported by LaSalle et al. (1977). Clet and Occhietti (1996) studied in detail the rhythmites and sands below the till unit and the pollen content. Subsequent unpublished work was carried out separately by Occhietti, Beaudin and Bhiry. From Clet and Occhietti (1996), this part of the section exposes at least the complete non glacial succession from the Saint-Pierre Sediments to the Gentilly Till or its local equivalent (Quebec Till of LaSalle, 1984).

Due to recent erosion, the lowermost transitional units are currently exposed. The gelifract content of the units indicate local cold climatic conditions which followed the Becquets Interstadial (related to the Saint-Pierre Sediments; Lamothe, 1989) and preceded the glaciolacustrine invasion of Lake La Verendrye (related to the Saint-Maurice Rhythmites; Occhietti, 1990).

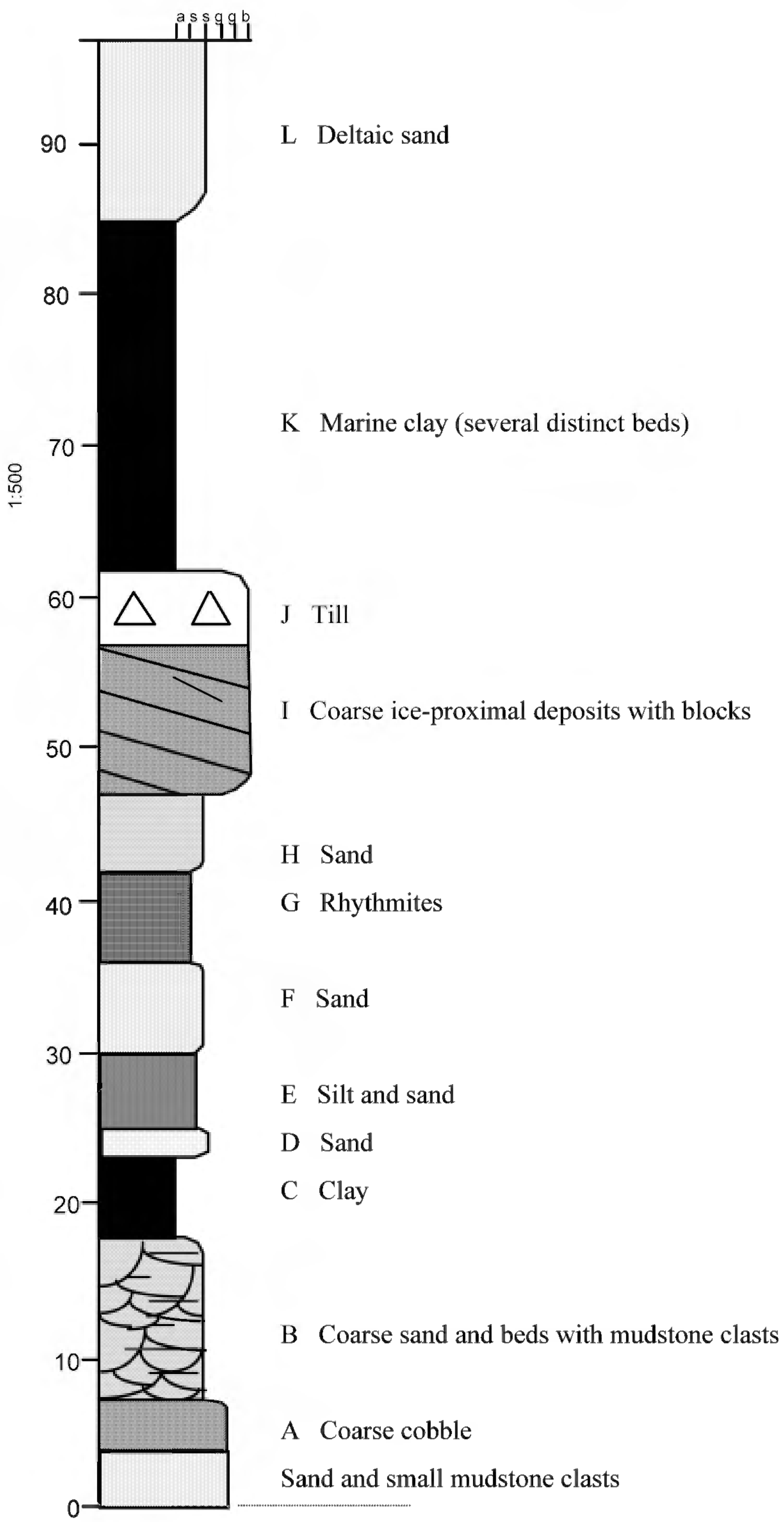

Figure 6. Simplified description of the Rivière Jean-Larose section (from Beaudin, 1996).

Below is a tentative correlation chart of the units exposed at Stops 2 and 3.

Riv. Jean-Larose	Facies	St. Lawrence Valley	
L	Deltaic sand		
K	Marine clay	Goldthwait Sea sediments	
J	Till	Till de Gentilly	
I	Coarse outwash	Upper beds of Vieilles-Forges Sands	
H	Deltaic sand	Lower beds of Vieilles-Forges Sands	Épisode Saint-Pierre
G	Glaciolacustrine rhythmites	Distinct lithozone	
F	Deltaic sand	of	
E	Prodeltaïc sediments	the	
D	Fluvial sand	Saint-Maurice	
C	Clay	Rhythmites	
B	Sand and clasts of local origin	Transitional lower beds : local	
A	Coarse cobble	or distal fluvial sediments	

Table 2. Origin and correlation of the units of the Rivière Jean-Larose sections with the classical units of the St. Lawrence Valley.

STOP 3. Lateral upper section, right bank of Rivière Jean-Larose

This section (Fig. 7) is accessible from the road. It exposes the complete regional facies succession, from deglaciation through marine invasion and regression, to exundation at the end of the Late Wisconsinan Stage. Shells in the lower beds of the Goldthwait Sea clay were dated at 11,890 ± 90 BP (TO-10929) ($\Delta\ ^{13}C = 0$ ‰) (Laliberté, 2005).

Glacial style of a local lateral basin of the St. Lawrence Valley – the St-Tite basin near Mont Sainte-Anne – and record of non glacial episodes during the Wisconsinan Stage

The Saint-Tite basin, which consists of the lower Rivière Sainte-Anne valley and the Rivière Lombrette Valley, contains a unique stratigraphic record of transitional glaciation–deglaciation phases in the region. During early phases of glaciation, as glacier ice expanded and filled the St. Lawrence Valley, small glaciolacustrine water bodies were impounded at relatively high elevations in lateral basins such as the Saint-Tite basin and this resulted in the deposition of fine-grained rhythmites. Such rhythmites are exposed in the Rivière Lombrette section (Fig. 8) and a few other sections in the Saint-Tite basin (Fournier, 1998).

A similar setting occurred during deglaciation, as a glacial lobe continued to occupy the estuary while the southern edge of the Laurentian Highlands was at least partly deglaciated.

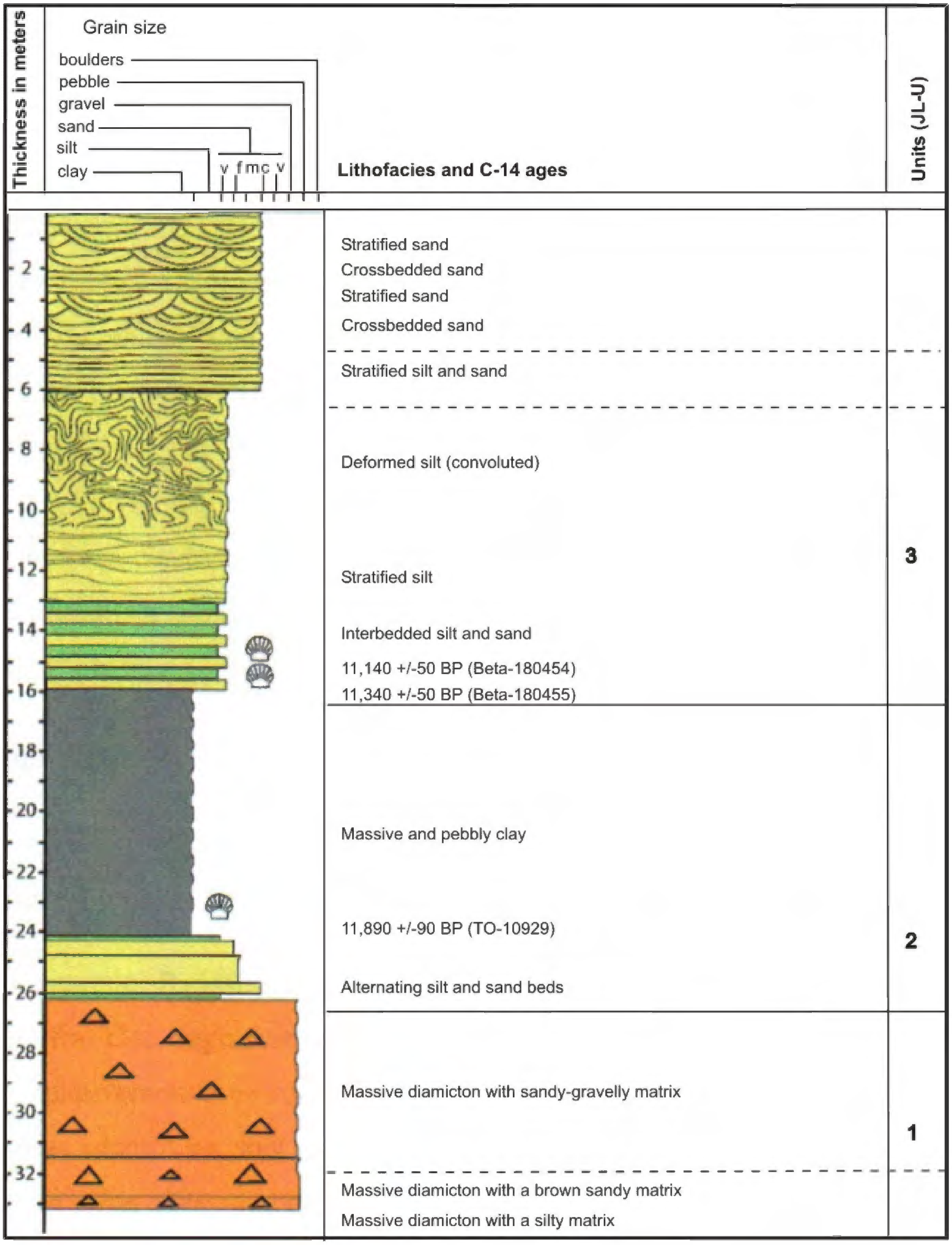

Figure 7. Late Wisconsinan glacial and glaciomarine units exposed on the right bank of Rivière Jean-Larose (Stop 3)

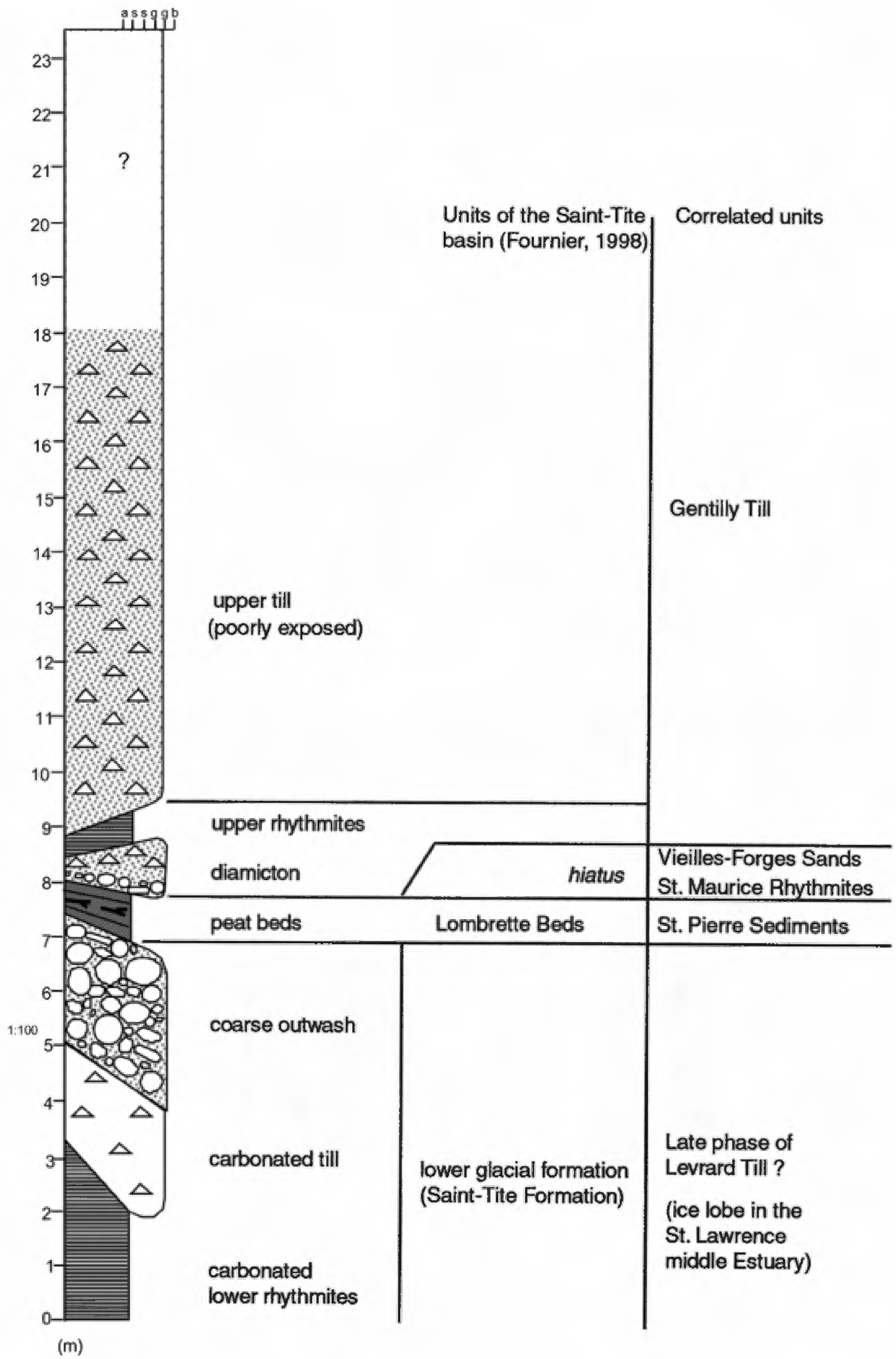

Figure 8. Quaternary units exposed in the Rivière Lombrette section (from Fournier, 1998).

STOP 6. The Rivière Lombrette section

This section, which was discovered by Fournier (1998), is located on the right bank of Rivière Lombrette. Due to difficult hiking conditions, the section will be observed from the left bank of Rivière Lombrette. The section is located at the margin of the Saint-Tite topographic basin, at an elevation between 370 and 350m ASL (1130-1060 feet), well above that of the post-glacial marine domain, and at the same elevation as the Saint-Léon Delta (stop 5).

The following units are exposed from the bottom to the top (Fig. 8):

1. Lower calcareous varves (1 to 8%), containing pollen.
2. Lower calcareous till (4 to 6%), with Paleozoic clasts (6%) in the lower part but apparently without Paleozoic clasts in the upper part. A till fabric (A and C axes) indicates ice-flow from WNW.
3. Coarse outwash deposits with no Paleozoic clasts.
4. Peat bed and wood debris (Picea, Larix) in stratified silty sand. The pollen content (M. Clet, unpublished report) indicates a boreal forest. Macrofossils of Larix laricina, Viola sp., four species of Carex, and a few leaves of Sphagnum suggest a peat bog environment (N. Bhiry, unpublished report).
5. The diamicton is mostly matrix supported and weathered. A till fabric in the intermediate zone indicates ice flow from the north-northwest.
6. Upper non calcareous rhythmites, 40 to 80cm thick. The rhythmites are coarser at the base. The pollen content indicates a Picea boreal forest. About 160 rhythmites were exposed.
7. Upper non calcareous till. The matrix-supported till is 9.6m thick; the matrix is silty in the lower part and sandy in the upper part

The basal calcareous rhythmites and till, and coarse ablation till indicate an early glacial episode in the St. Lawrence Valley. The glacier impounded a glacial lake in the basin and subsequently overrode the glaciolacustrine clays. Sediments with organic matter and rhythmites record non glacial phases during the classical Wisconsinan which could be the equivalent of non glacial phases recorded in the Trois-Rivières area (Occhietti, 1980) and in the Appalachian area of Québec (Shilts, 1981).

Wisconsinan ice movements along the southern edge of the Laurentian Highlands in the Mont Sainte-Anne area

The Mont Sainte-Anne area and the adjacent local basin of St-Tite-des-Caps are located north of the limit between the upper (fluvial) and middle (brackish) estuary of the St. Lawrence, and south and west of the higher Laurentian highlands of the Parc des Laurentides and Charlevoix regions. In this original geomorphic setting, glacial striations, till fabrics, and till provenance data (e.g., Paleozoic clasts over Shield terrain) provide evidence of complex ice dynamics through time. From older to younger, the ice originated from:

- the Laurentide Ice Sheet (N to S flow during the Last Glacial Maximum, and later NNW to SSE and W to E flows),
- the St. Lawrence Ice Stream (SW to NE flow),
- northward flow from ice in the St. Lawrence Valley, related either to the northern edge of the St. Lawrence Ice Stream, or to the Appalachian northward reversal.

Maps of the different groups of oriented glacial striations in the area and in a part of southern Québec are provided in a reprint (Occhietti et al., 2001) that will be handed out to fieldtrip participants.

The relative chronology of these ice movements will be discussed, with emphasis on the role of the St. Lawrence Ice Stream. Northward-trending striations will be observed at **stop 8**, close to the Saint-Tite-des-Caps TV relay station.

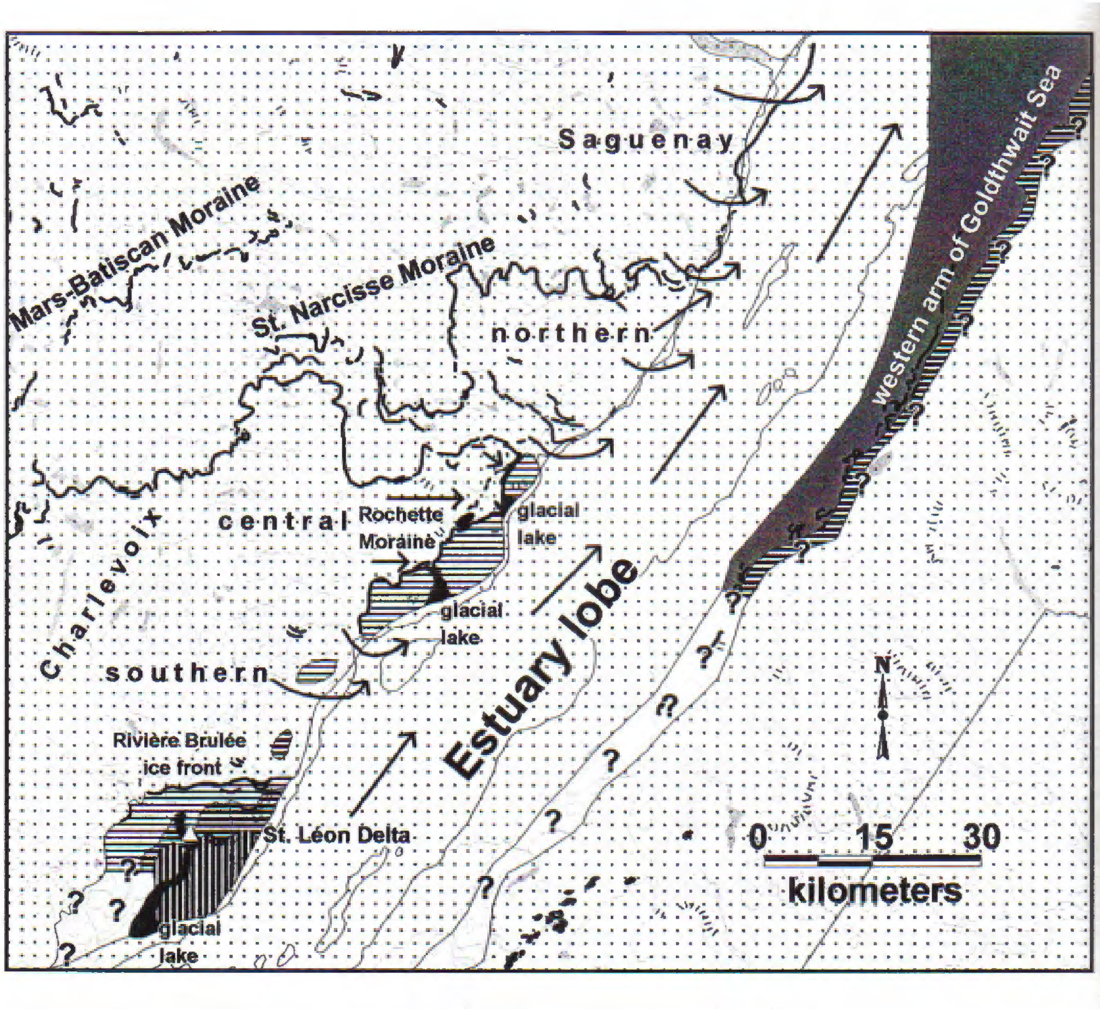

Figure 9. Map of the moraines in the Charlevoix region, north of the middle Estuary, with emphasis on the Brulée and Saint-Narcisse moraines (after Occhietti, 2001, and Govare, 1995).

Local ice retreat prior to the Saint-Narcisse Moraine episode

The main ice retreat features of the region can be observed in the Rivière Sainte-Anne valley. They comprise:

- an outwash fan which overhangs the lowermost reaches of the river (**stop 9** if we have time);
- a long valley train overlying thick glacial sediments and deeply incised by the river (the *Sept Chutes de la Sainte-Anne,* the Seven Falls);
- a morainic ridge, the Brûlée Moraine **(stop 7)**, which was emplaced transversally to the upper Sainte-Anne valley;
- the Saint-Léon delta kame (viewed from **stop 5** along the road) (Fournier, 1998) and a kame terrace **(stop 4)** that were deposited in a short-lived glacial lake; the top of the delta is at an elevation of 360 mASL (1180 feet). The meltwaters were impounded downstream by the margin of a glacial lobe in the St. Lawrence Valley.

Collectively these ice retreat features indicate early deglaciation of hilly terrain in the southern part of the region, followed by a stabilisation of the ice front at lower elevations along the edge of the Laurentian Highlands. This type of deglaciation pattern is unique on the north side of the St. Lawrence Valley. The St. Narcisse Moraine is located 45km northwest of the region. The Brulée Moraine is thought to have been deposited between 225 and 450 years prior to the main Saint-Narcisse episode. The inferred timing of deglacial events in the region is presented in Table 3.

Tentative correlation of events in the area of the St. Lawrence middle Estuary during Late Pleistocene and Early Holocene

Estimated age (^{14}C ka BP)	Charlevoix	Lower Saguenay and middle estuary	Québec City - Chaudière River area	Climatic phases
10 - 9.65		Laflamme Sea invasion	Stable relative marine level (St. Nicolas): eustatic rise	Early Holocene
10.1 - 9.9 10.6 10.7 10.8 10.9	Mars - Batiscan Moraine *slow ice front retreat* late phase / main episode / early phase — St Narcisse Moraine	 Saguenay Lobe Tadoussac proglacial delta ice readvance submarine fan	St. Nicolas surge or readvance	Younger Dryas
11.1 ± 0.1	*northward and westward retreat*	western arm of Goldthwait Sea	Champlain Sea Invasion western arm of Goldthwait Sea	Alleröd
?	Rochette Moraine, Brulée Moraine	post-St. Antonin Moraine surge or readvance and middle estuary lobe	(Beauce Event: ice readvance in the Chaudière/Etchemin area?)	Dryas II
? ?	early incomplete deglaciation? Les Eboulements (north shore)	early deglaciation: Rivière du Loup area (south shore)		Bölling

Table 3. Proposed correlation and timing of deglacial events in the Mont Sainte-Anne region.

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THE THETFORD-MINES OPHIOLITE

by

Jean H. Bédard, Geological Survey of Canada, 490 de la Couronne, Québec, QC G1K 9A9, Canada
Alain Tremblay, Département des Sciences de la Terre et de l'Atmosphère, Université du Québec à Montréal, Montréal, QC H3C 3P8, Canada

Abstract/Résumé

This field trip to the Ordovician Thetford-Mines ophiolitic Complex of southern Québec focuses on its stratigraphic, petrologic, and structural characteristics; with a particular emphasis on pre- to syn-obduction structures and associated lithological variations in the crust and mantle of the ophiolite, as well as its relationship to the overlying sedimentary cover of the Saint-Daniel Mélange. / *Cette excursion est axée sur la stratigraphie et la caractérisation pétrologique et structurale du Complexe ophiolitique ordovicien de Thetford-Mines dans le sud du Québec, avec un accent particulier sur les structures pré- et syn-obduction ainsi que les variations lithologiques associées des sections crustales et mantelliques de l'ophiolite, ainsi que les relations avec sa couverture sédimentaire du Mélange de Saint-Daniel.*

INTRODUCTION

This field trip will visit an Ordovician ophiolite from the oceanic domain (Dunnage Zone) of the southern Québec Appalachians: the Thetford-Mines ophiolite. A particular emphasis will be put on the characterization of pre- to syn-obduction structures and associated lihological variations in the crust and mantle sections. Relationships with the overlying sedimentary cover will also be examined, and serve as a template from which to understand ophiolitic and supra-ophiolitic rocks of the Southern Québec Appalachians on a regional scale.

Previous field trips to the Thetford-Mines and Asbestos ophiolites include Hébert and Laurent (1977, 1979), St-Julien and Hubert (1979), Laliberté et al. (1979), Laurent and Baldwin (1987), Hébert and Bédard (1998) and Tremblay and Bédard (2006). The stratigraphical and structural analysis of the Thetford-Mines ophiolite presented in this fieldguide results from detailed geological mapping and petrological work since 1991, with extensive work in 2000-2004 by graduate students under the supervision of both leaders (Schroetter, 2004; Bécu, 2005; Daoust, 2006; Pagé, 2006; DeSouza, 2007). Comparison and correlation of structures from the Thetford-Mines ophiolite with regionally extensive fabrics developed in rocks of the adjacent Laurentian continental margin (Tremblay and Castonguay, 2002) allow ophiolitic structures to be subdivided into pre-, syn- and post-obduction phases. The framework established for the Thetford-Mines ophiolite has been applied to the rest of the Southern Québec ophiolitic belt, allowing along-strike, regional-scale lithological and structural correlations (Schroetter et al., 2003, 2005, 2006).

Our understanding of the ophiolite has benefited from numerous discussions with scientists involved in the geology of southern Québec. The authors wish particularly to express their gratitude to Réjean Hébert, Roger Laurent and the late Pierre St-Julien for introducing us to the area and sharing their knowledge during earlier field seasons, to Bertrand Brassard (former director of the exploration department at Ressources Allican) for his inspired contribution to the initiation of Thetford-Mines ophiolite project in 1999-2000, to Pierre Cousineau and the late lamented Gifford Kessler for volcanological and sedimentological insights, and to the Thetford-Mines (Jean-Michel Schroetter, Philippe Pagé, Valérie Bécu) and Lac-Brompton (Caroline Daoust and Stéphane DeSouza) teams of graduate students for their passion for field geology, and their interest in ophiolites. It must also be remembered that this document represents our own vision of the Southern Québec ophiolitic Belt, and that other interpretations exist. We hope that this field trip will be a forum for discussion of ophiolite genesis, and about how they can serve as analogues to modern and ancient oceanic lithosphere.

THE SOUTHERN QUÉBEC APPALACHIANS

The southern Québec Appalachians comprise three lithotectonic assemblages (Fig. 1): 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 boundary between the Humber and Dunnage Zones corresponds (on the surface) to a zone of dismembered ophiolites and serpentinite slices defined as the Baie Verte-Brompton line (BBL; Williams and St-Julien, 1982). The Dunnage zone is locally unconformably overlain by Upper Silurian and Devonian rocks of the Gaspé Belt.

The Humber Zone is subdivided into External and Internal zones (Tremblay and Castonguay, 2002). The External Humber Zone consists of very low-grade sedimentary and volcanic rocks (e.g., the Caldwell Group: Bédard and Stevenson, 1999) deformed into a series of northwest-directed thrust nappes (Fig. 1). The Internal Humber Zone is made of greenschist to amphibolite facies metamorphic rocks (the Sutton-Bennett Schists on Fig. 1) that represent distal facies of the External Humber Zone units. The highest-grade metamorphic rocks occur in the cores of doubly-plunging dome structures (i.e., the Sutton Mountains and Notre-Dame Mountains anticlinoria; Fig. 1). Regional deformation phases include a S_{1-2} schistosity and syn-metamorphic folds and faults that were overprinted by a penetrative crenulation cleavage (S_3 of Tremblay and Pinet, 1994). The latter is 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 and Castonguay, 2002; Fig. 1).

Amphibole and mica $^{40}Ar/^{39}Ar$ ages from the internal Humber Zone vary between 431 and 410 Ma (Fig. 2). Ordovician high-temperature step ages (462-460 Ma; Fig. 2) suggest that the geochronologic imprint of typical Taconian metamorphism is only locally preserved (Castonguay et al., 2001; Tremblay and 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 hangingwall (Fig. 1). 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 Dunnage Zone occurs in the hangingwall 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 packages (Fig. 1): (1) the Southern Quebec ophiolites, with four main 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).

THE SOUTHERN QUÉBEC DUNNAGE ZONE

The ophiolites of the Thetford-Mines and Asbestos areas are characterized by well-preserved mantle and crustal sections, whereas only the mantle and a thin veneer of lavas 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 (Fig. 2; Dunning et al., 1986; Whitehead et al., 2000). These three ophiolitic massifs are dominated by magmatic rocks with boninitic affinities (with subordinate tholeiites), a feature which has been attributed to their genesis either in a forearc environment (Laurent and Hébert, 1989; Hébert and Bédard, 2000; DeSouza et al., 2006), and/or in a backarc setting (Oshin and Crocket, 1986; Olive et al., 1997). In contrast, only the crust is preserved in the Mont-Orford ophiolite, which contains a greater diversity of magma types, interpreted as an arc-backarc (Harnois and Morency, 1989; Hébert and Laurent, 1989; Laurent and Hébert, 1989) or arc-forearc to backarc (Huot et al., 2002). The Mont-Orford ophiolite has a maximum age of 504 +/- 3 Ma (David and Marquis, 1994).

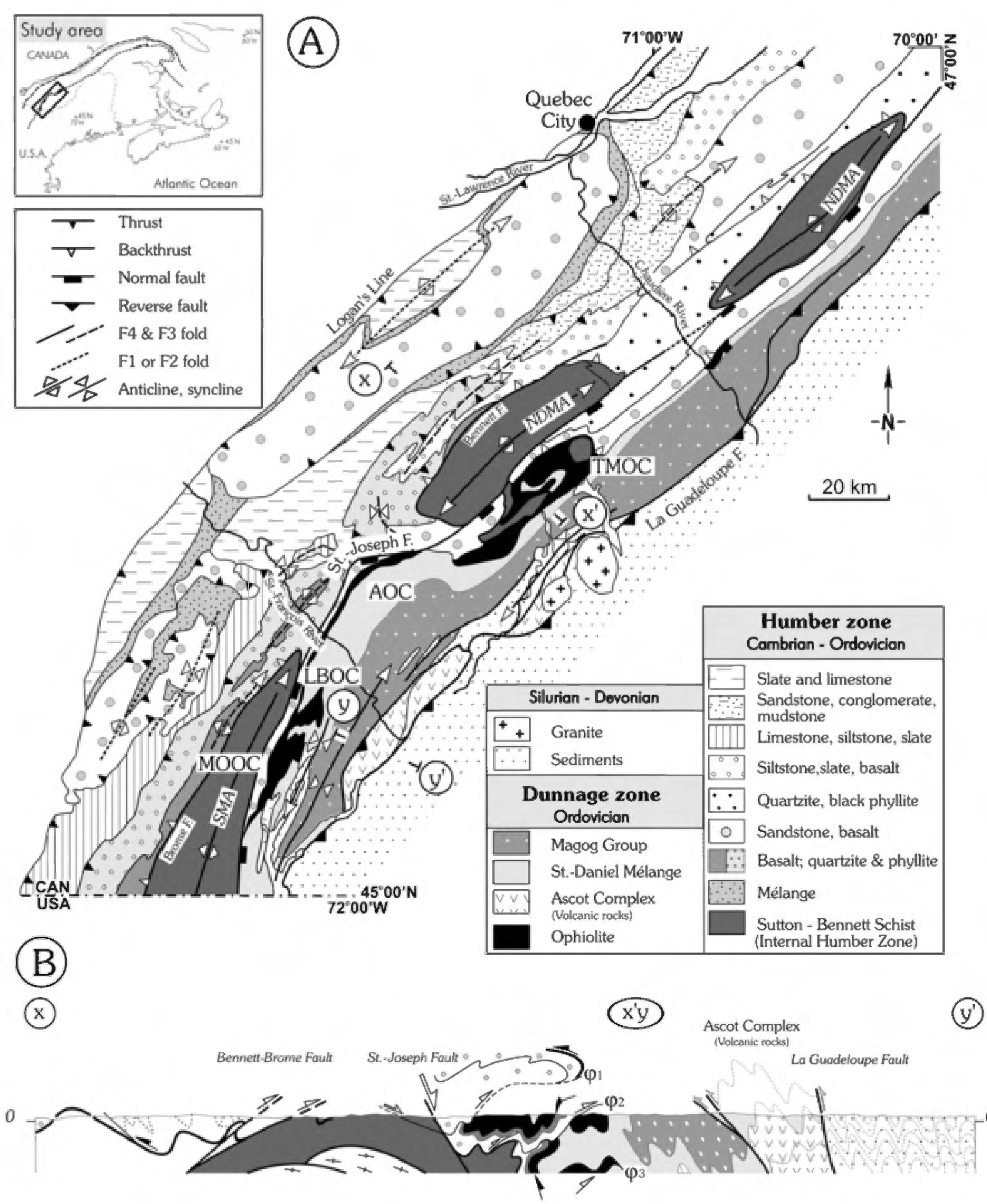

Figure 1. Geological map of the southern Québec Appalachians. TMOC, Thetford-Mines ophiolitic Complex; AOC, Asbestos ophiolitic Complex; LBOC, Lac-Brompton ophiolitic Complex; MOOC, Mont-Orford ophiolitic Complex. Adapted from Schroetter et al. (2006). / *Carte géologique des Appalaches du sud du Québec. TMOC, Complexe ophiolitique de Thetford-Mines; AOC, Complexe ophiolitique d'Asbestos; LBOC, Complexe ophiolitique du Lac-Brompton. Tiré de Schroetter et al. (2006).*

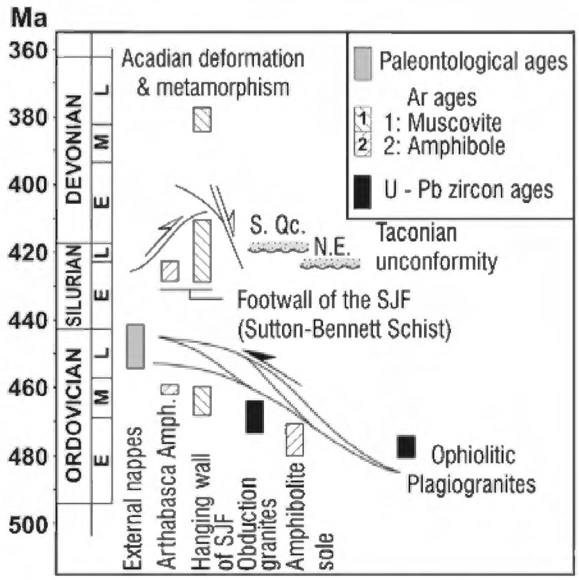

Figure 2. Diagram summarizing age constraints for the deformation and metamorphic events in the southern Quebec Appalachians. / *Figure 2. Sommaire des contraintes d'âges pour la déformation et le métamorphisme dans les Appalaches du sud du Québec.*

Amphibolites from the dynamothermal sole of the Thetford-Mines ophiolite and adjacent continental micaschists yield $^{40}Ar/^{39}Ar$ ages of 477±5 Ma (Whitehead et al., 1995) and 469-461 Ma (Fig. 2; Castonguay et al., 2001), respectively, suggesting that intra-oceanic detachment of the ophiolite (ca. 477 Ma) occurred immediately after oceanic crust formation (ca. 480 Ma). Peraluminous intra-mantle granites with high $^{87}Sr/^{86}Sr$ initial ratios yielded 469+/-4 to 470+/-5 Ma crystallization ages (zircon U/Pb, Whitehead et al., 2000), and were probably derived by the partial fusion of continental margin sediments during emplacement of the still-hot ophiolite (Clague et al., 1985; Whitehead et al., 2000).

The Saint-Daniel Mélange (Fig. 1) is a Llanvirn 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 is an erosional unconformity marking the base of the forearc basin. The processes that formed the chaotic breccias of the mélange were the successive uplift, erosion, and burial by debris flows of different parts of the ophiolite and of the underlying metamorphic rocks during the emplacement of the ophiolite. A 467 Ma $^{40}Ar/^{39}Ar$ muscovite age yielded by metamorphic fragments of basal debris flows of the Saint-Daniel mélange (Schroetter et al., 2006, Fig.10) is within the age range of regional metamorphism in rock units structurally below the ophiolite, and implies that exhumation and erosion occurred during or shortly after the emplacement of the ophiolite onto the continental margin.

The Magog Group (Fig. 1; Cousineau and St-Julien, 1994) overlies the Saint-Daniel Mélange. 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*, in the Beauceville and Saint-Victor formations are Late Llandeilian to Early Caradocian (Middle Ordovician).

The Ascot Complex (Fig. 1) has been interpreted as the remnant of a 460 ± 3 Ma volcanic arc sequence (Tremblay et al., 1989, 2000). It is made up of metavolcanic rocks, in fault contact with laminated and pebbly phyllites that have been correlated with the Saint-Daniel Mélange (Tremblay and St-Julien, 1990).

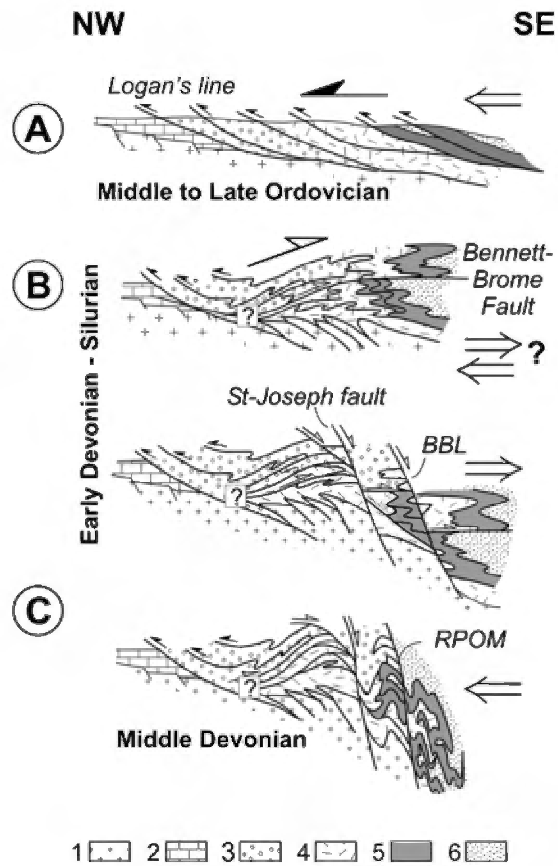

Figure 3. Schematic model for structural evolution of Laurentian margin in southern Quebec. 1- Grenvillian rocks, 2- St. Lawrence Lowlands platform, 3- External Humber zone, 4- Internal Humber zone, 5-6- ophiolites and sedimentary rocks of Dunnage zone, respectively. / *Figure 3. Modèle schématique de l'évolution structurale de la marge Laurentienne dans le sud du Québec. 1- Grenville, 2- plate-forme des Basses-Terres du St-Laurent, 3- zone de Humber externe, 4- zone de Humber interne, 5-6- ophiolites et roches sédimentaires de la zone de Dunnage, respectivement.*

Structure and metamorphism

In the Southern Québec Dunnage Zone, regional deformation and metamorphism are mostly related to the Middle Devonian Acadian orogeny (Tremblay, 1992; Cousineau and Tremblay, 1993). Evidence for intense Ordovician (Taconian) metamorphism and deformation is nearly absent. Peak Acadian 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 (Fig. 1). $^{40}Ar/^{39}Ar$ dating of greenschist-grade metamorphic rocks of the Ascot Complex yielded 380-375 Ma (Fig. 2; Tremblay et al., 2000). The Magog Group is characterized by tight regional folds, generally overturned to the NW, and plunging gently or moderately to the SW or the NE.

Schroetter et al. (2005) showed that the Humber zone, the southern Quebec ophiolites and the overlying Saint-Daniel mélange have a common structural evolution. Detailed mapping in the Thetford-Mines ophiolite discriminates pre-, syn- and post-obduction structures. Syn-obduction (Taconian) structures are shear zones and ductile fabrics developed in the ophiolitic metamorphic sole and in the immediately overlying mantle and underlying continental margin rocks. Two generations of post-obduction structures are recognized: (i) SE-verging backthrusts and backfolds correlated with the Late Silurian-Early Devonian deformational episode recorded in the Humber Zone (Fig. 2); and (ii) NW-verging folds and reverse faults attributed to the Acadian Orogeny (Tremblay and Castonguay, 2002). However, as a result of normal faulting along the Saint-Joseph-BBL fault system (see Fig. 1b), the backthrust deformation in the ophiolites is of lower metamorphic grade than backthrust deformation in the margin.

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 (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., 1998).

On the basis of age data for arc volcanism and ophiolite genesis in southern Québec, as well as similar lithological and structural settings of ophiolites from 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 and Castonguay (2002). The Taconian stage (ca. 480 to 445 Ma) involves stacking of northwest-directed thrust nappes (Fig. 3a). D_{1-2} deformation 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 by this event except for minor tectonic slicing. Underplating of the overridden margin, and westward (foreland) translation of metamorphic rocks because of frontal accretion, led to exhumation of deeper crustal levels of the orogen (preserving Ordovician isotopic ages). These deeper crustal rocks are 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; Fig. 3b). $^{40}Ar/^{39}Ar$ age data suggest that D_3 began as ductile shear zones (i.e., the Bennett-Brome fault) defining a major upper plate-lower plate (UP-LP) boundary, and culminated with normal faulting along the St-Joseph fault and the Baie Verte-Brompton line (Fig. 3b). 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 faults were probably activated in Late Silurian-Early Devonian time (Figs. 2 and 3b) and crosscut the UP-LP boundary, which leads 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 sytem, the D_3 event 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 and 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 (Fig. 3c). Tectonic inversion of normal faults also probably occurred.

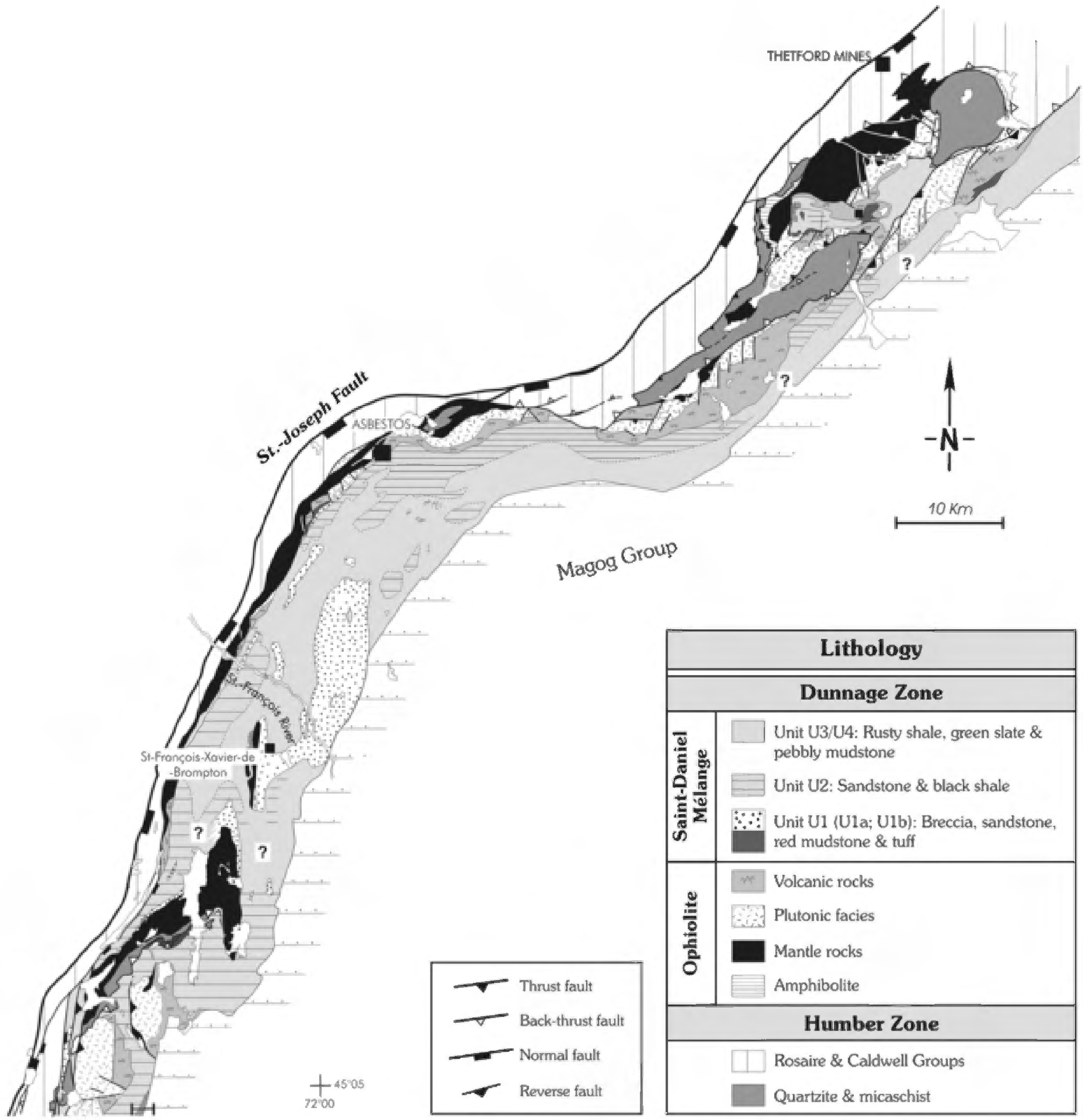

Figure 4. Geological map showing the major ophiolites and distribution of the various facies of the Saint-Daniel Mélange in the southern Québec Appalachians. Compiled from Cooke (1938, 1950), Brassard and Tremblay (1999), St-Julien and Slivitsky (1985) and Schroetter (2004). / *Figure 4. Carte géologique montrant les principales ophiolites et la distribution des faciès du Mélange de Saint-Daniel dans les Appalaches du sud du Québec. Compilé de Cooke (1938, 1950), Brassard et Tremblay (1999), St-Julien et Slivitsky (1985), et Schroetter (2004).*

THE SOUTHERN QUÉBEC OPHIOLITE BELT

The ophiolites of southern Québec have been historically considered as km-scale, fault-bounded blocks within the Saint-Daniel Mélange, which was interpreted as a subduction-accretionary complex (Cousineau and St-Julien, 1992; Tremblay et al., 1995) in fault contact both with the ophiolites and the Magog Group. However, mapping in key areas (Schroetter et al., 2003, 2005, 2006) indicates that the Saint-Daniel Mélange is a sedimentary sequence that stratigraphically overlies the ophiolites and is, in turn, depositionally overlain by the Magog Group (Fig. 4). As such, the Saint-Daniel Mélange forms the lowermost part of a piggyback basin that records the infilling of a forearc oceanic crust with an inherited topography (Fig. 5a). Schroetter et al. (2005) suggested that the southern Québec ophiolites were accreted to the margin as a single, large slab of supra-subduction oceanic lithosphere. Therefore, these ophiolites should not be considered as genetically unrelated tectonic slices incorporated into a subduction complex (i.e., the Saint-Daniel Mélange), but as a coherent segment of oceanic lithosphere (although structurally complex and partially dismembered) which extends laterally for over a hundred kilometres of strike, and that has experienced at least two episodes of regional deformation after obduction (Fig. 5b).

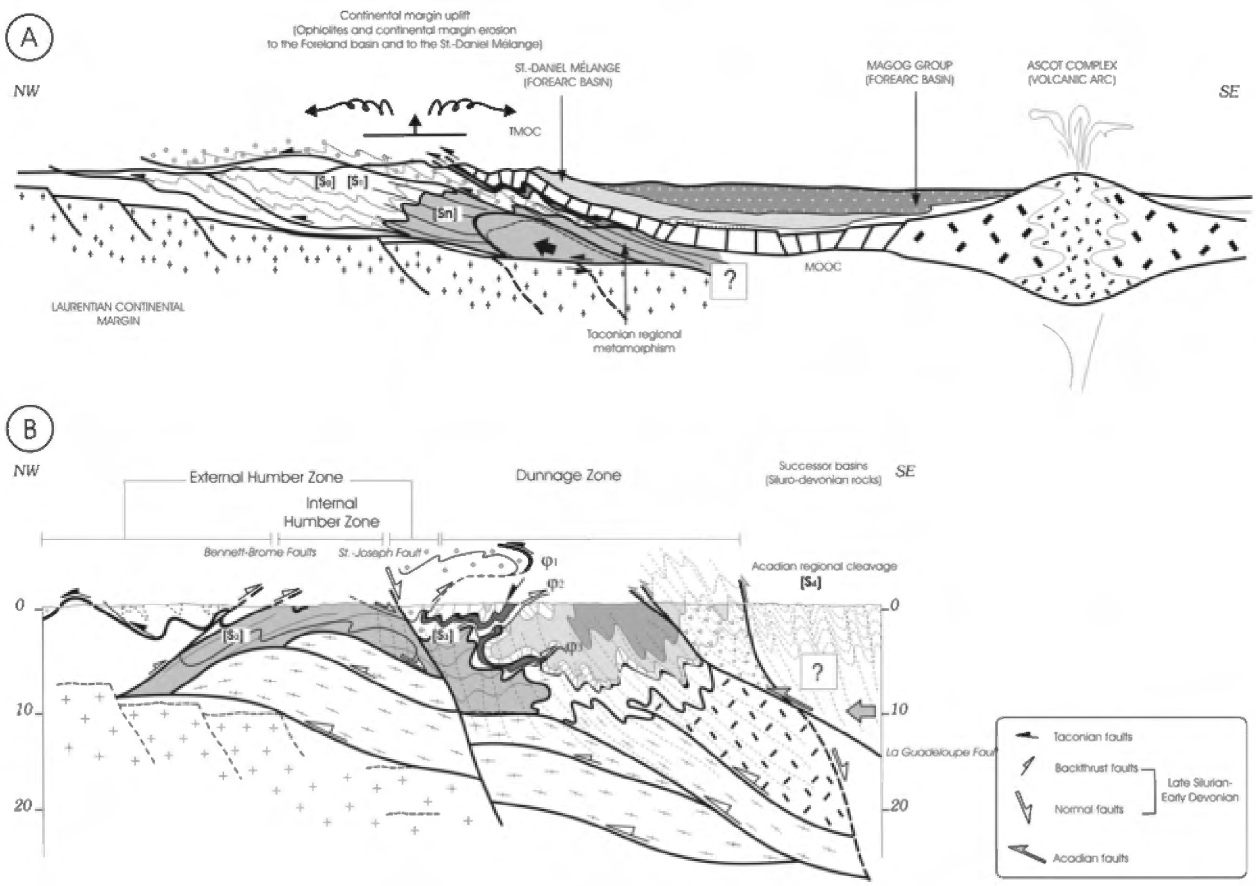

Figure 5. Schematic composite structural profile across the Laurentian margin and the adjacent oceanic domain from Schroetter et al. (2005), showing the regional tectonic setting of the Southern Québec Appalachians during the Taconian orogeny, and the sedimentary and tectonic evolution of the Saint-Daniel Mélange and the Magog Group. / *Figure 5. Profil structural composite de la marge laurentienne et le domaine océanique tiré de Schroetter et al. (2005), montrant le contexte tectonique pour les Appalaches du sud du Québec pendant l'orogénie taconienne, et illustrant l'évolution sédimentaire et tectonique du Mélange de Saint-Daniel et du Groupe de Magog.*

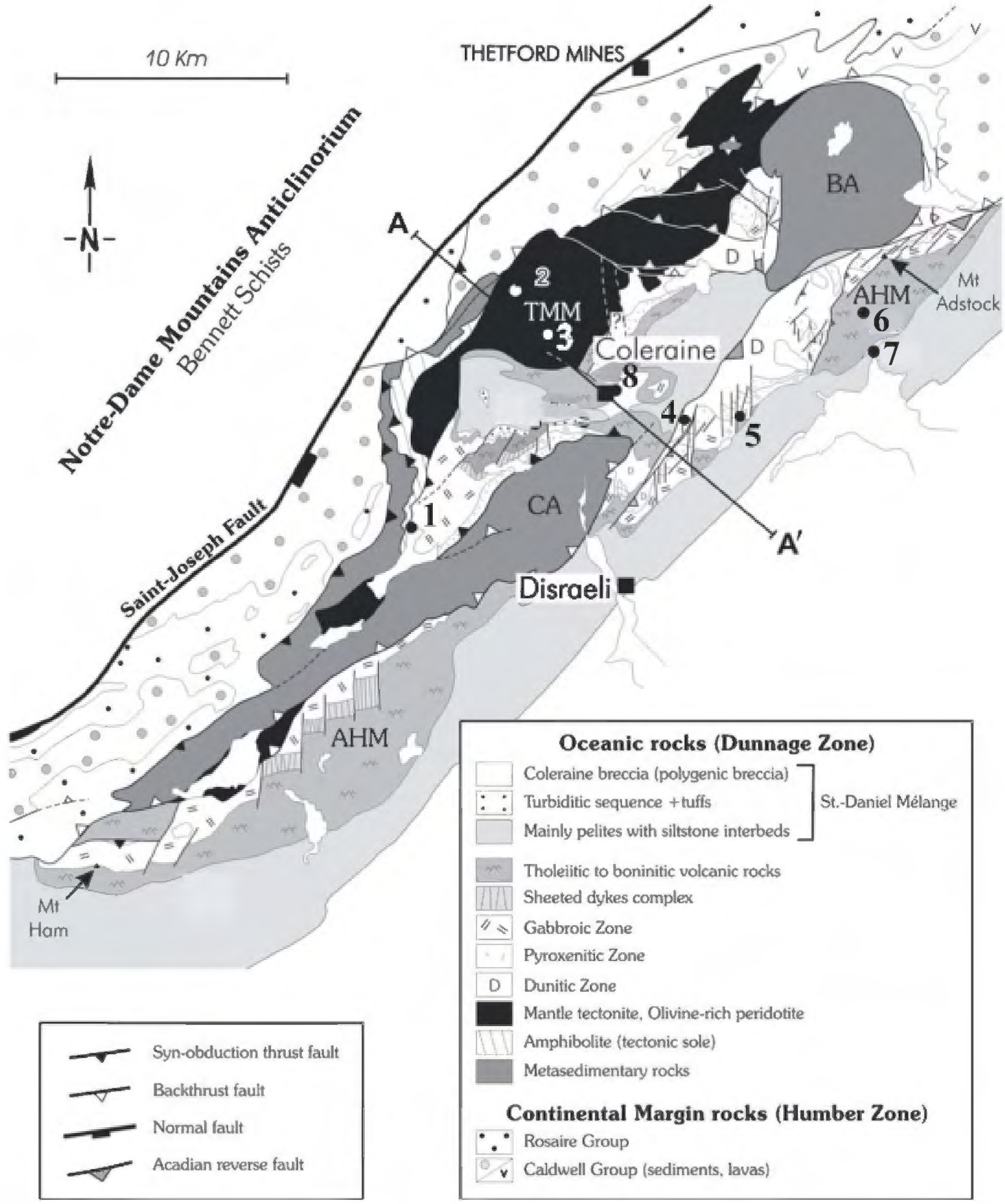

Figure 6. Geological map of the Thetford-Mines ophiolitic Complex and location of stops. Adapted from Schroetter et al. (2005). / *Figure 6. Carte géologique du Complexe ophiolitique de Thetford-Mines et localisation des arrêts. Tiré de Schroetter et al. (2005).*

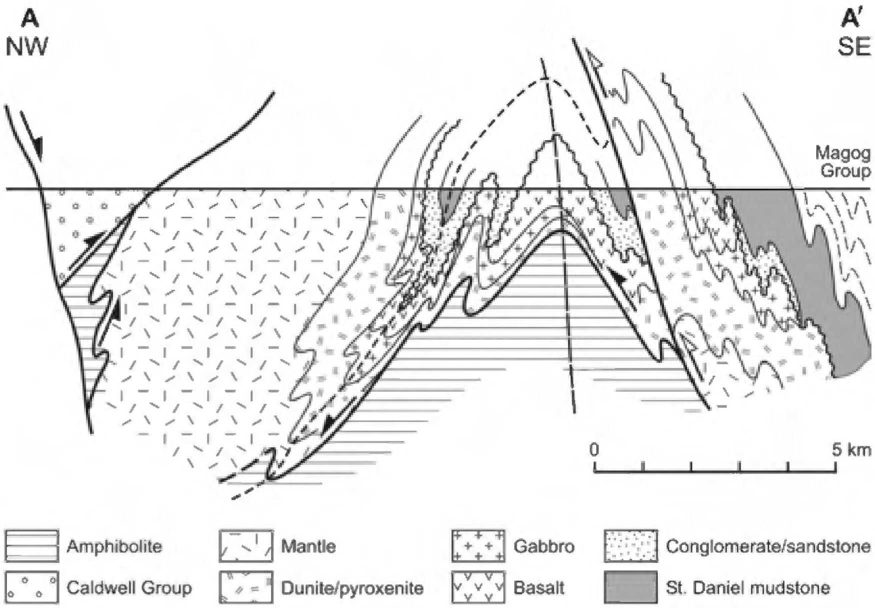

Figure 7. Structural profile A-A' of the Thetford-Mines ophiolite. See Fig. 6 for location. / *Figure 7. Profile structural A-A' de l'ophiolite de Thetford-Mines. Voir la Fig. 6 pour la localisation.*

The Thetford-Mines Ophiolite

The Thetford-Mines ophiolite outcrops as a NE-trending belt 40 km long and 10-15 km wide (Fig. 4). It is divided into the Thetford-Mines (TM) massif to the northwest and the Adstock-Ham Mountains (AHM) massif to the southeast (Figs. 6 and 7). The TM massif has a ca. 5 km thick mantle section (Laurent et al., 1979; Pagé et al., 2003, 2007) and a 0.5 to 1.5 km-thick crustal section (Schroetter et al., 2005). The oceanic mantle is not preserved in the AHM massif. Mineral-chemical and geochemical (Hébert, 1985; Hébert and Laurent, 1989; Pagé, 2006; Pagé et al., 2007) signatures imply that the mantle is residual from 20-25% melting, with involvement of small amounts of a dominantly sediment-derived 'arc' component. The mantle records both Moho-perpendicular asthenospheric fabrics, and overprinting Moho-parallel lithospheric fabrics in the Duck Lake Block (Pagé et al., 2007). Both of these fabrics helped guide movement of melt. In the Caribou Mountain Block, these older fabrics are overprinted by penetrative, lower-temperature ductile deformation that is interpreted to record exhumation of the lower crust and mantle along a normal fault dipping 45° (Pagé et al., 2007). Exhumation of an oceanic core complex would explain the problematic outcrop pattern where basalts directly overlie mantle rocks, and implies that the ridge-related extensional faults in the crust may root in the mantle.

The crustal section in both massifs consists of basal dunite-dominated (±chromitite) cumulates, that grade up through a thin harzburgite/lherzolite cumulate zone, into orthopyroxenite/websterite cumulates, and then into a variety of gabbroic rocks (gabbronorite, gabbro, ferrogabbro, amphibole gabbro). The Gabbroic Zone is up to 1200 m thick. Cumulates are cut by mafic to ultramafic dikes (all of boninitic affinity), which locally grade up into a sheeted dike complex (Bédard et al., 2001; Schroetter et al., 2003). The liquid-line-of-descent of these cumulates suggests a boninitic lineage. Inversion models (Bédard et al., 2007: Fig. 8) also imply that most cumulate rocks crystallized from melts of boninitic affinity.

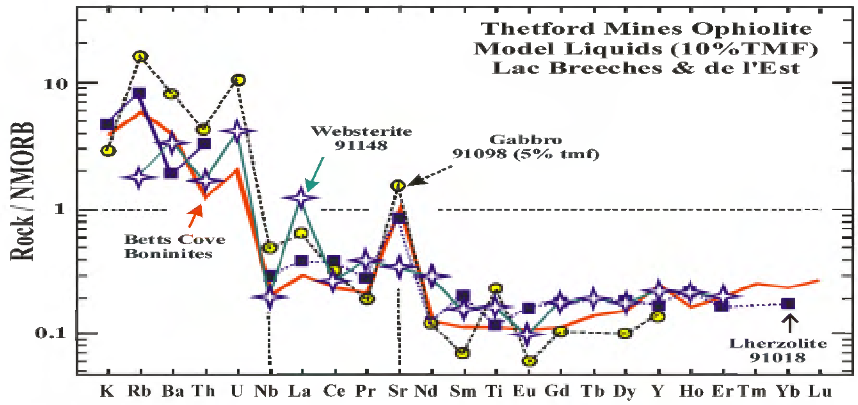

Figure 8. Trace element inversions using the procedure and partition coefficient datasets of Bédard (1994, 2001). Modes estimated from thin sections and norms. Trapped melt fractions vary from 5-10%. Average Betts Cove boninite lava from Bédard (1999). NMORB from Sun and McDonough (1989). / *Figure 8. Inversions géochimiques selon les procédures et coéfficients de partage de Bédard (1994, 2001). Modes estimées des lames minces et calculs normatifs. Les % de liquide piégés varient de 5 à 10%. La boninite moyenne de Betts Cove est de Bédard (1999). NMORB de Sun et McDonough (1989).*

Gabbros locally grade up into an extremely complex apical suite characterized by trondjhemitic breccia complexes, into which the sheeted dykes are rooted. Two types of hypabyssal facies rocks occur: dyke swarms and breccias. The dykes (30 cm to ~ 1 m thick) are mafic to ultramafic, show microgabbroic, porphyritic or aphanitic textures, and are commonly oriented N-S. In some sectors, the dykes constitute 40-100% of the outcrop over 100s of meters, and are mapped as a sheeted dyke complex (Fig. 13). Exposures of sheeted dykes are not common, however, and this facies was not previously recognized, mainly because the sheeted dyke complex was either excised by normal faulting, eroded, brecciated by subvolcanic explosions, or rotated by normal block-faults into parallelism with the overall stratigraphy and interpreted as sills. The breccia facies reaches a maximum of 150 m in thickness and separates plutonic and volcanic sequences. Where it has been studied in detail (Schroetter et al., 2003), the breccia facies caps the gabbroic sequence and is overlain by boninitic lavas and volcaniclastic deposits.

The extrusive sequence is composite and extremely variable (Fig. 9); with marked lateral changes in thickness and facies (Figs. 6 and 13), although boninitic lava flows and felsic pyroclastic rocks generally dominate. Vesicular pillow lavas are intercalated with massive flows, hyaloclastite breccias, and submarine talus breccias. The base of these lavas and flow deposits erodes down into the dunite zone in places (Fig. 9). The volcaniclastic rocks are blocky pyroclastic flow breccias containing rounded pillow-lava or cumulate fragments in a volcaniclastic matrix. Intercalated fine-grained dacitic tufs and argillites are locally present. A tholeiitic sequence is locally preserved in graben keels and is capped by a 1-2-m thick red argillite at Lac de l'Est (Hébert, 1983; Hébert and Bédard, 2000). The tholeiitic sequence seems to thicken towards the south, and is better developed in the Asbestos ophiolite.

Detailed mapping in the Thetford-Mines ophiolite has shown the presence of sub-vertically dipping, N-S-striking faults, spaced ~1 km apart on average (Figs. 6 and 13; Schroetter et al., 2003). In the lower crust, the faults are manifested as sheared dunites and syn-magmatic breccias (Fig. 14), and correspond to breaks in lithology. Kinematic analysis suggests that these structures are normal faults separating a series of tilted blocks. In the upper crust, N-S-striking fault blocks contain N-S-striking dykes that locally constitute a sheeted complex. The faults correspond to marked changes in the thickness and facies assemblages of supracrustal rocks (Fig. 9), are locally marked by prominent subvolcanic breccias, and have upwardly decreasing throws suggesting that they are growth faults.

The ophiolitic extrusive sequence is overlain by discontinuous debris flows, known as the Coleraine Group of Riordon (1954), or the Coleraine breccia of Hébert (1981). These thick-bedded debris flows have cm- to m-scale angular fragments. They wedge out laterally into fine-grained siliciclastic rocks, and grade up into turbidites, argillites, siltstones and the archetypal pebbly mudstones of the Saint-Daniel Mélange (Schroetter et al., 2006). Clasts in the debris flows are dominantly of ophiolitic provenance at the base of the Coleraine breccia unit, but continent-derived material becomes more abundant and becomes dominant up-section. A micaschist clast yielded a muscovite $^{40}Ar/^{39}Ar$ age (467±2.6 Ma, Fig. 10) similar to metamorphic ages from Laurentian margin rocks.

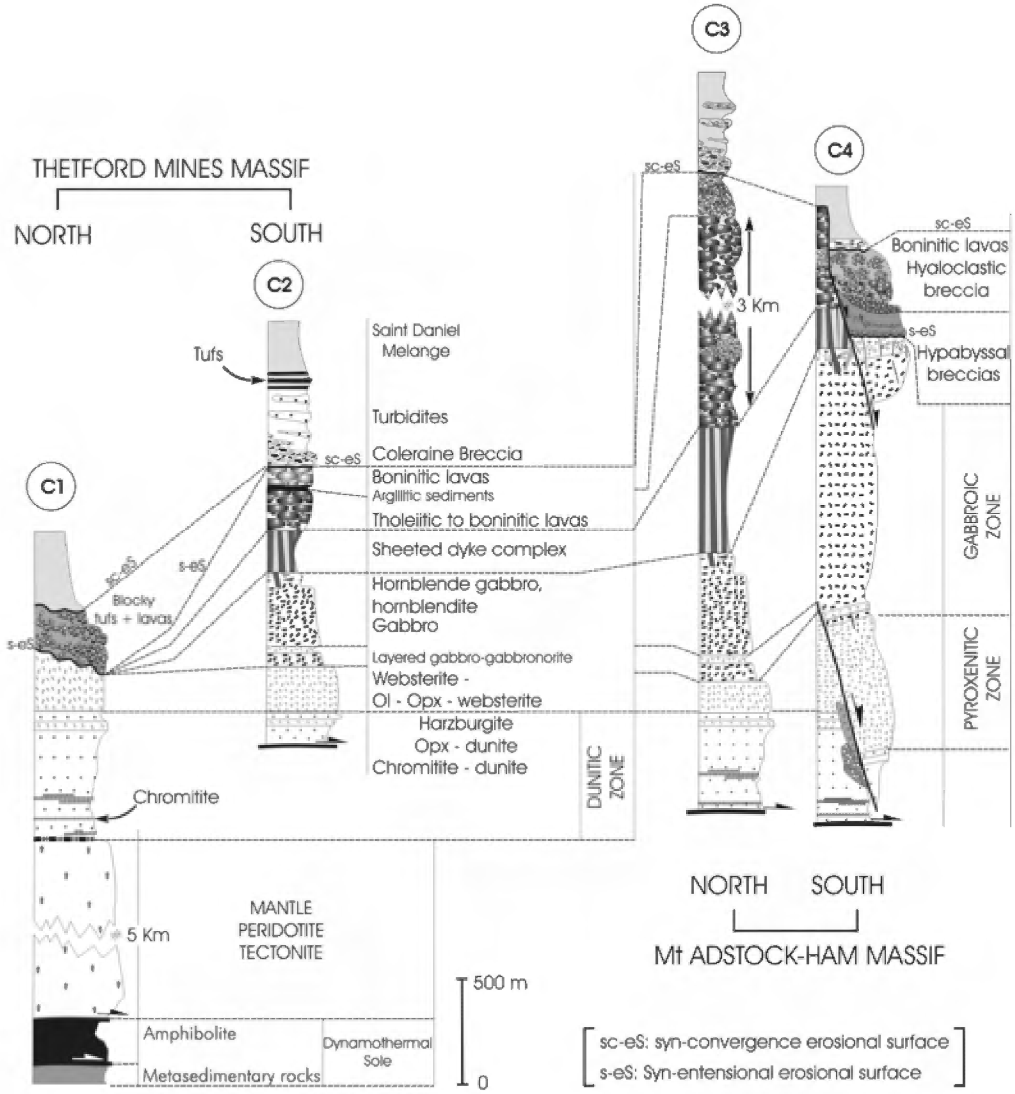

Figure 9. Stratigraphic columns for different locations of the Thetford-Mines ophiolitic Complex. Adapted from Schroetter et al. (2003). / *Figure 9. Colonnes stratigraphiques de différentes localités du Complexe ophiolitique de Thetford-Mines. Tiré de Schroetter et al. (2003).*

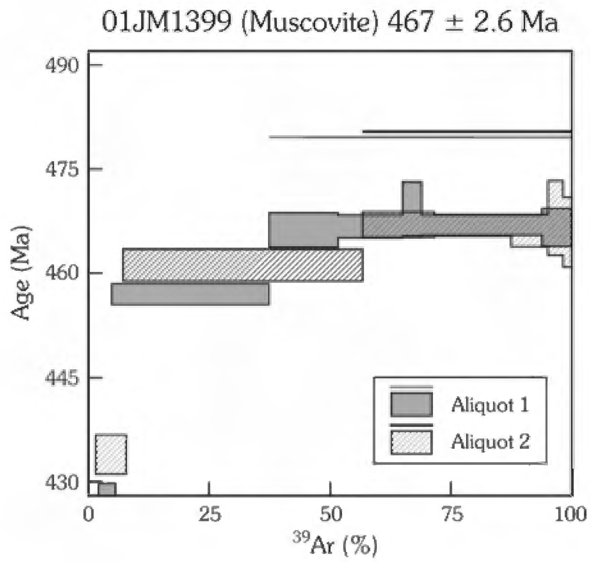

Figure 10. $^{40}Ar/^{39}Ar$ age spectra for two muscovite samples from a metamorphic clast of supra-ophiolitic debris flows. From Schroetter et al. (2006). / *Figure 10. Spectre d'âge $^{40}Ar/^{39}Ar$ de deux échantillons de muscovite provenant d'un fragment de micaschiste des coulées de débris supra-ophiolitiques. Tiré de Schroetter et al. (2006).*

The Asbestos Ophiolite

The coeval Asbestos ophiolite is located approximately 20 km to the southwest of the southernmost extremity of the Thetford-Mines ophiolite (Fig. 4). It preserves a thinner (2000-2500m) but very similar ophiolitic sequence, consisting of harzburgitic mantle, overlain by ultramafic-to-mafic cumulates (dunite, pyroxenite and gabbro), and capped by diabasic and volcanic rocks (Hébert, 1980). The ophiolitic lavas are overlain by fine-grained volcaniclastic rocks and flow breccias, and then by the Saint-Daniel Mélange (Lavoie, 1989).

The Lac-Brompton Ophiolite

Ophiolitic plutonic rocks occurring in the vicinity (south) of the Saint-François River (Fig. 4), consist of dunitic peridotite, gabbro, lava and volcaniclastic rocks, and can be correlated with rocks of the Asbestos ophiolite (Schroetter et al., 2005). This sequence of ophiolitic rocks extends almost continuously southwards until it merges into the Lac Montjoie ophiolitic mélange (Lamothe, 1978), previously described as a serpentinite diapir. Recent fieldwork suggests that Lac Montjoie is part of an ophiolitic sequence (mantle and lower crustal peridotites) forming the Lac-Brompton ophiolite (Daoust et al., 2005; Daoust, 2006). The ultramafic rocks are overlain by Asbestos-type boninitic lavas and tuffs, and by the Saint-Daniel Mélange, with the whole sequence defining a northward-plunging anticline. The continuity of lithologies and exposures suggests that ophiolitic rocks crop out discontinuously between Asbestos and Lac-Brompton. Given the resemblance between the Thetford-Mines, Asbestos and Lac-Brompton ophiolites, this implies that the ophiolitic rocks of this large area (over 100 km of strike length) were obducted as a single panel of oceanic lithosphere (Schroetter et al., 2005; DeSouza et al., 2006; DeSouza, 2007).

The Mont-Orford Ophiolite

The Mont-Orford ophiolite (Fig. 4) occurs as two main masses, the Mont Chauve and the Mont Orford-Chagnon massifs, which are dominated by gabbro, and overlain by basalt and various types of volcaniclastic rocks (Rodrigue, 1979; Laurent and Hébert, 1989; Huot et al., 2002). The tectonostratigraphic link between the Asbestos and Mont-Orford ophiolites can be inferred from structural relationships shown by the ophiolitic rocks in the Lac-Brompton area (Fig. 4) where the southern extremity of the Lac-Brompton ophiolite is separated from the Mont-Orford ophiolite by an extensive metamorphic unit of micaschists and albite-chlorite laminated greenschist (Schroetter et al., 2005; Daoust et al., 2006). According to Schroetter et al. (2005), the Mont-Orford ophiolite and overlying Saint-Daniel Mélange are structurally overlain by the metamorphic rock unit mentioned above, and by the

Lac-Brompton ophiolite; the structural juxtaposition occurring along a northwest-dipping fault zone (the φ_3 fault of Fig. 5b) which is folded by a north-plunging Acadian antiform (Fig. 5b).

FIELD TRIP LOG – THE THETFORD-MINES OPHIOLITE

The field trip focuses on features of the Thetford-Mines ophiolite that illustrate how peri-continental fore-arc oceanic crust is constructed and obducted. Stop locations are shown on Figs. 6, 11 and 13. Figures 7 and 9 present a NW-SE trending section, and stratigraphic columns established from different sites of the ophiolite, respectively.

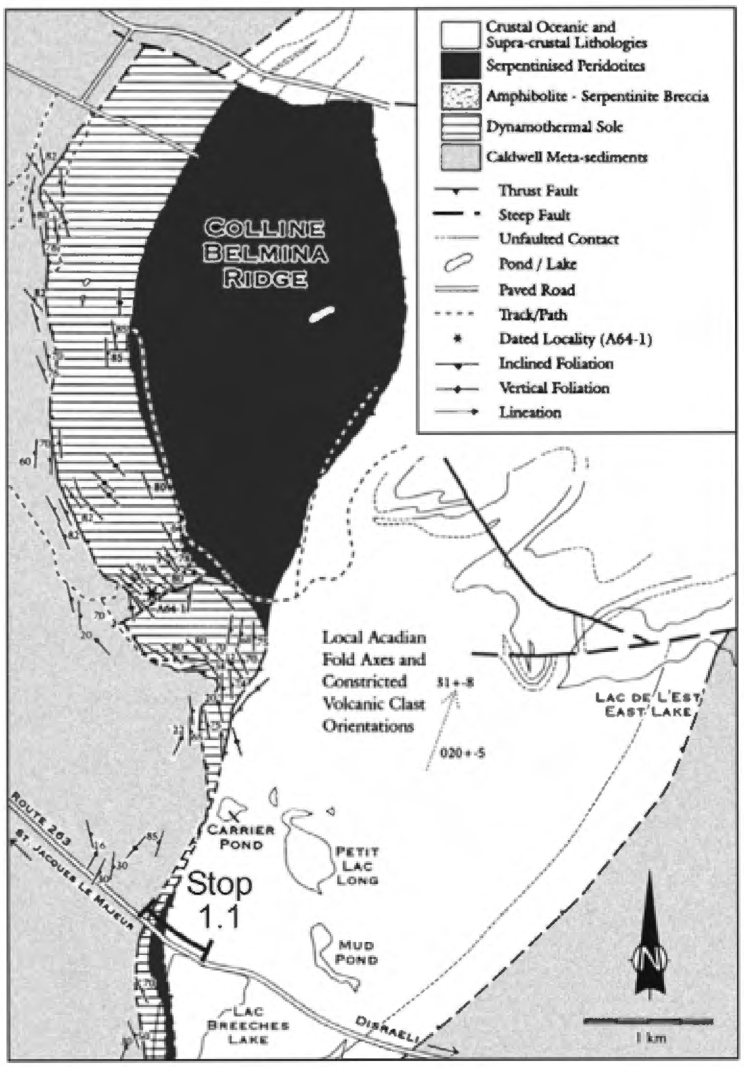

Figure 11. Geologic map of the Belmina Ridge area (from Whitehead et al., 1995) and location of stop 1. / *Figure 11. Carte géologique de la région de Belmina Ridge (tirée de Whitehead et al., 1995) et localisation de l'arrêt 1.*

STOP 1. The metamorphic sole and the gabbroic sequence of the Thetford-Mines ophiolite at Lake Breeches

Location. From Québec drive south to Thetford Mines and then take route 112 west to Disraeli. Turn right at the flashing light and cross the bridge. Just after the bridge, turn right on road 263 North, and drive until Lake Breeches (approx. 8 km). The dynamothermal sole outcrop is a roadcut located 1.3 km west of the rest area on the lake, whereas the ophiolitic gabbro crops out just in front of the lake (Fig. 11).

Field description.

The dynamothermal sole. From east to west, the outcrop exposes (Fig. 12), (1) serpentinized ultramafic rocks, (2) approximately 20 m of amphibolite with a strong foliation (S_1) defined by the preferred orientation of sodic hornblende and epidote crystals (also rutile and albite), garnet is absent in amphibolites in this outcrop, and (3) garnet-bearing micaschists belonging to the Laurentian margin sequence. The contact between (2) and (3) is sharp, strikes N340° and dips 65°E. Microprobe mineral compositions determined on clinopyroxene-garnet-amphibole and garnet-amphibole assemblages suggest that near its upper contact, the amphibolite reached equilibrium temperatures of 780-850°C, and that temperatures decreased to 380-500°C away from the contact. Inferred pressures vary between 5 and 7 kbars. The data indicate an inverse thermal gradient of 40°C/Km (Feininger, 1981).

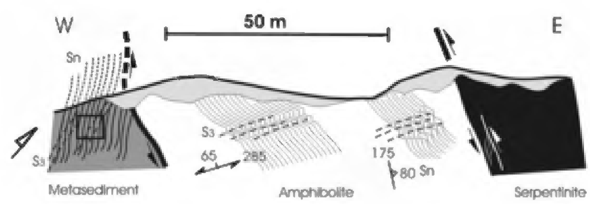

Figure 12. Field sketch of the contact ophiolite-margin at the Belmina Ridge amphibolitic sole (stop 1). / *Figure 12. Schéma de terrain du contact ophiolite-marge sur le site de l'amphibolite de Belmina Ridge (arrêt 1).*

The gabbroic sequence. These outcrops expose complexly-deformed and hydrothermally metamorphosed layered gabbro, pyroxenite, and boninitic dykes. Layered gabbro is locally transformed to high-temperature amphibolite + trondhjemite in a 1st syn-ridge event. Igneous rocks are dissected into 10 x 2 m phacoidal slivers by tightly-spaced brittle-ductile greenschist facies shear zones. Epidozite veins abound in these shear zones, with older epidote veins being folded and then cut by younger epidote veins. Prominent chloritic haloes surround this generation of veins. The volume of epidozite suggests a focussed hydrothermal discharge, with fluid volumes most consistent with a ridge-related system. A younger generation of breccia-veins filled with quartz-prehnite-calcite crosscuts all older structures. The age and origin of this youngest event is not known.

STOP 2. The upper mantle at Vimy Ridge and Mt Caribou

Location. Drive back to Disraeli and follow road 112 West until the town of St-Joseph-de-Coleraine. In town, turn left on Vimy road and drive for 7 km until the Vimy settlement. If weather is good, we will park behind the large community center and ascend the trail to the summit of Mt. Caribou (20 minute ascent time). If weather is poor, we will park in front of the house on the North side and visit the outcrop behind that house (accessible via the driveway).

Field description. The smaller Vimy Ridge outcrop exposes harzburgitic mantle peridotite with subordinate dunitic pods. There are numerous orthopyroxenite dykes, and abundant Asbestos veins (stockwerk). The summital outcrop shows spectacular fold closures, in addition to the various dyke types. These outcrops are part of the Caribou Mountain Block of Pagé et al. (2007). Mineral chemical and whole-rock geochemical data imply that the harzburgite is residual from extensive partial fusion (Pagé et al., 2007). Porphyroclastic textures are typical, with a strong, locally mylonitic foliation striking roughly N-S, parallel to the regional orientation of seafloor-spreading related paleo-normal faults in the crust. The nature of fabrics and textures suggests a lithospheric deformation, possibly related to tectonic denudation (oceanic core complex; Tremblay et al., 2006; Pagé et al., 2007). This would explain problematic lava/mantle contacts in the area (Fig. 6).

STOP 3. Scenic view of mine Lac d'Amiante at Black Lake and syn-obduction two-mica granites

Location. Return to Coleraine and turn towards Thetford Mines on route 112. Drive for ca. 4 km and park at the Belvedere. If time permits, we will drive down the hill to the 1st intersection and park on the right. Walk back 30 m to a small stream and descend the slope. The 2-mica syn-obduction granites are well exposed there.

Field description. From the Belvedere, we can see the open pit mine in the upper mantle sequence of the Thetford-Mines ophiolite. A closer examination of the open pit reveals the presence of light-coloured intrusions that are foliated to unfoliated, and partly rodingitized granodiorites and granites (Laurent and Baldwin, 1987). These two-mica granitoids are peraluminous, have high $^{87}Sr/^{86}Sr$ initial ratios and igneous zircons with low $^{208}Pb/^{206}Pb$ ratios, and have yielded 469+/-4 to 470+/-5 Ma crystallization ages (Fig. 2; U/Pb on zircon, Whitehead et al., 2000) that are similar to the age from the sole amphibolites, suggesting that the 2-mica granites were derived by the partial fusion of continental margin sediments during emplacement of the still-hot ophiolite (Clague et al., 1985; Whitehead et al., 2000).

STOP 4. Syn-oceanic deformational and intrusive features of the lower crust at Mamelon Nadeau

Location. Drive back to Coleraine. At the entrance of town, turn left (just after the local arena) onto Bisby Lake road. Stay on the main gravel road for 4 km and park just in front of a cleared area on your left. The next outcrop is a 500 metres walk. It is located on top of the smaller and nearest hill to the north, called Mamelon Nadeau.

Field description. The location of this outcrop is shown on Fig. 13 (marked as 1.5). This map area has been extensively described by Schroetter et al. (2003), and corresponding to their sector 1. Mamelon Nadeau is entirely contained within the Dunitic Cumulate Zone (Fig. 13). From West to East, massive blue dunite with disseminated chromite gives way (over 0.5 m) to a thick (100s of metres) reddish breccia composed of angular, 1-10 cm, clasts of dunite, locally with chromitite beds within them, in an orthopyroxenitic stockwork (Fig. 14). The orthopyroxenite-dominated veins can be understood in terms of conventional phase relationships, where melts segregating out of an olivine-dominated cumulate rapidly cross the olivine/orthopyroxene peritectic and will only crystallize orthopyroxene. As the (poorly exposed) main fault plane is approached, sheared serpentinites appear in the dunite, culminating in 2-3-m-wide serpentinite mylonites that mark the core of faults. These breccias and mylonites are cross-cut by undeformed, tabular websterite and lherzolite intrusions (30-50-m-wide), that are oriented N-S, parallel to the main series of faults. At the top of the Mamelon Nadeau, the rhythmically-layered dunite-chromitites are cut by shallowly-dipping, E-W striking websterite dykes that lack chilled margins against their dunitic hosts, suggesting that these rocks were still quite hot at the time of dyke emplacement. A series of faults associated with serpentinite veins are parallel to dyke contacts and offset chromitite beds to the East. On the same outcrop, these same websterite dykes are chopped up into cm-scale horst-and-graben structures by a series of conjugate, steeply-dipping, N-S-striking normal faults. 50 metres further north, another exposure shows these same dykes being sheared and boudinaged due to the occurrence of another fault with a peridotite intrusion in its hanginwall (Fig. 14).

From this series of exposures, the history of syn-magmatic deformation can be divided into three increments (E1 to E3; Schroetter et al., 2003). The early event (E1) corresponds to the localized development of a high-temperature layering-parallel fabric (chromitite schlieren and isoclinal folds). Restoration to the horizontal of the chromitite beds gives the websterite dykes and parallel faults of increment E2 a sub-vertical orientation. E2 faults are thus interpreted as having originally been steeply-dipping, normal faults. The last increment of deformation (E3) defines a horst-and-graben system marking a continuation of extension.

STOP 5. Upper gabbros and the brecciated hypabyssal sequence at the Boulettes section

Location. From stop 4, continue onto Bisby Lake road until the next road intersection. Turn left and park after 1.8 km (i.e. at the right-angle bend of the road). Follow the trail going NW from that point and keep going for ca. 100–150 m in the same direction.

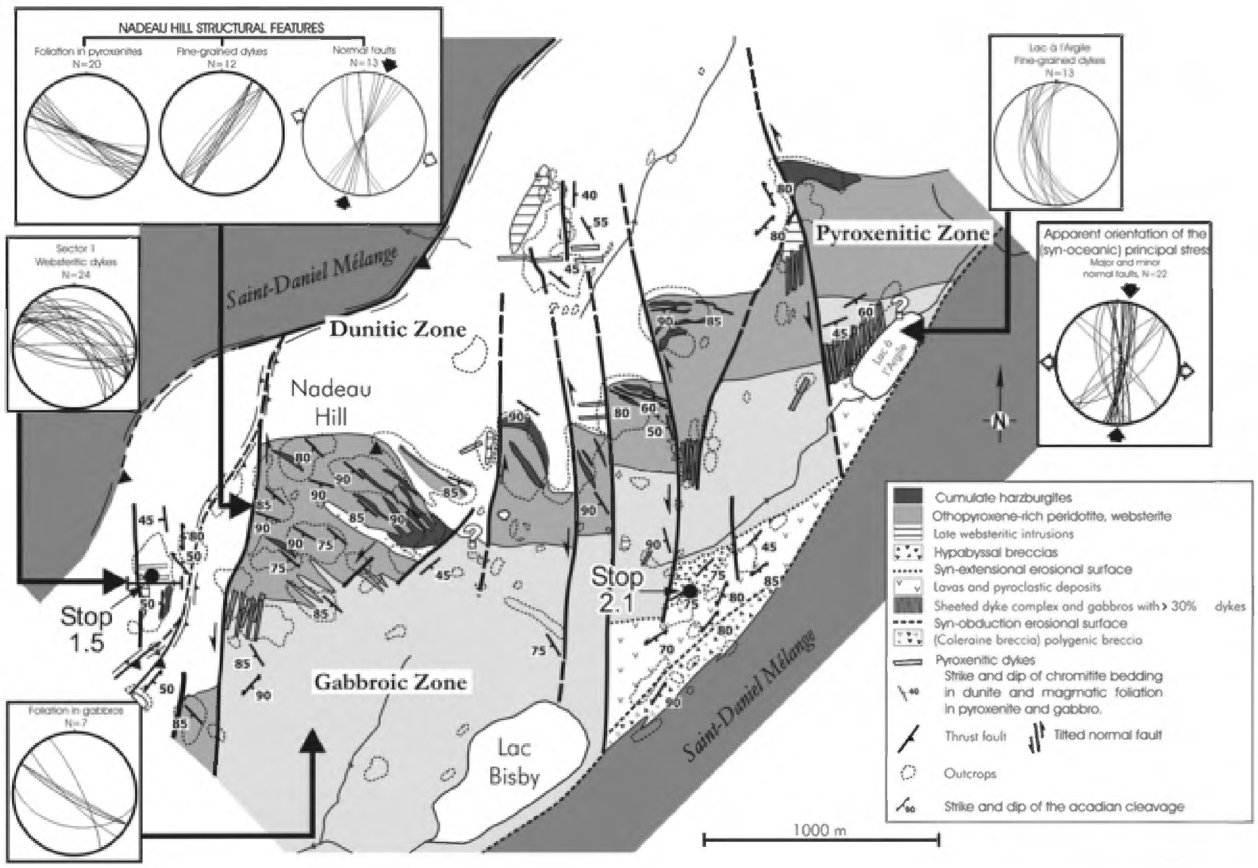

Figure 13. Geological map of part of the Adstock-Ham Massif showing the location of normal(?) faults interpreted as syn-magmatic structures. Stratigraphic up is to the South-East (bottom right). Adapted from Schroetter et al. (2003). STOPS 4 and 5 are marked on the map as stops 1.5 and 2.1, respectively. / *Figure 13. Carte géologique d'une partie du Massif d'Adstock-Ham montrant la localisation de failles normales(?) interprétées comme des structures syn-magmatiques. Le haut stratigraphique est vers le sud-est (en bas à droite). Tiré de Schroetter et al. (2003). Les arrêts 4 et 5 sont localisées sur cette carte comme les arrêts 1.5 et 2.1, respectivement.*

Field description. This series of outcrops (Fig. 13) exposes the faulted and brecciated transition between supracrustal rocks (lavas and flow deposits) and underlying hypabyssal breccias. The breccia matrix is generally igneous, and the jigsaw-puzzle morphology of the rocks seems compatible with some type of magmatic hydro-fracture mechanism, perhaps accentuated by phreato-magmatic explosions caused by ascent of hot volatile-rich magma into rocks impregnated with seawater (Fig. 15; Schroetter et al., 2003). Amygdaloidal intrusions are injected into the microgabbroic breccia, and then are stretched and offset by faults (Fig. 13), suggesting that faulting and magmatism were coeval. Field observations suggest that syn-magmatic faulting must have played a role in brecciation, because some breccias have a cataclastic matrix, and field mapping shows that the brecciated hypabyssal facies is preferentially developed along the extension of the major N-S normal faults described in the area (Fig. 13).

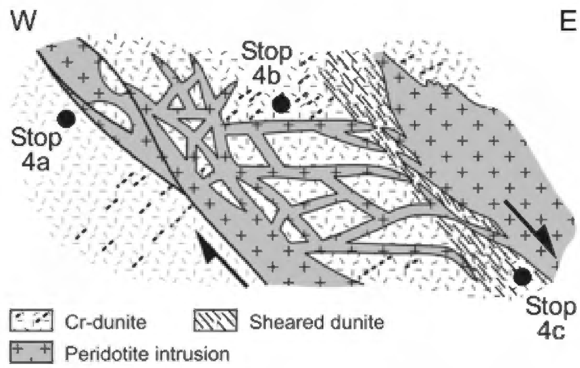

Figure 14. Field sketch (stop 4) illustrating the inferred syn-magmatic faults preserved at the base of the ophiolitic crust. / *Figure 14. Schéma de l'arrêt 4 illustrant les failles syn-magmatiques présumées préservées dans la section crustale de l'ophiolite.*

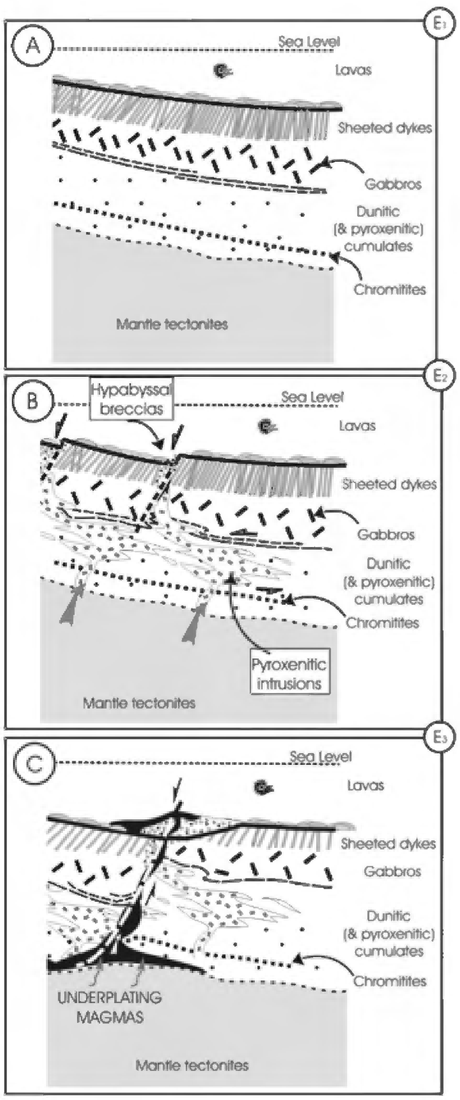

Figure 15. Schematic illustration of a possible evolutionary scenario for the main crust-forming event of the Thetford-Mines ophiolite. From Schroetter et al. (2003). / *Figure 15. Illustration schématique d'un scénario d'évolution possible pour la formation de la croûte de l'ophiolite de Thetford-Mines. Tiré de Schroetter et al. (2003).*

STOP 8. The Coleraine Breccia at the type-locality

Location. Drive back to Coleraine, on road 112. Turn left on the second street to your left. The outcrop is located immediately beyond the cemetery.

Field description. This outcrop and other exposures in the surrounding area (Fig. 6) constitute the type-locality for the Coleraine breccia (Riordon, 1954; Hébert, 1981). This is a polygenic debris flow breccia characterized by cm-to-m-sized fragments in a fine- to medium-grained matrix of greywacke. Fragments include basaltic lava, fine-grained sedimentary rocks (argillite and siltstone), gabbro, peridotite, hornblende diorite, and rare metasedimentary rocks. Large fragments (up to 1 metre) of red mudstone showing soft- sediment deformation structures are present within the breccia and are interpreted as large rafts or rip-up clasts. The occurrence of such argillitic fragments also indicates that part of the marine sedimentary sequence of the oceanic crust was reworked by debris flows formed during its emplacement onto the continental margin. Such breccias are overlain by, and interbedded with, a sequence of metre-thick beds of wackes and greywackes of the same composition as the breccia matrix.

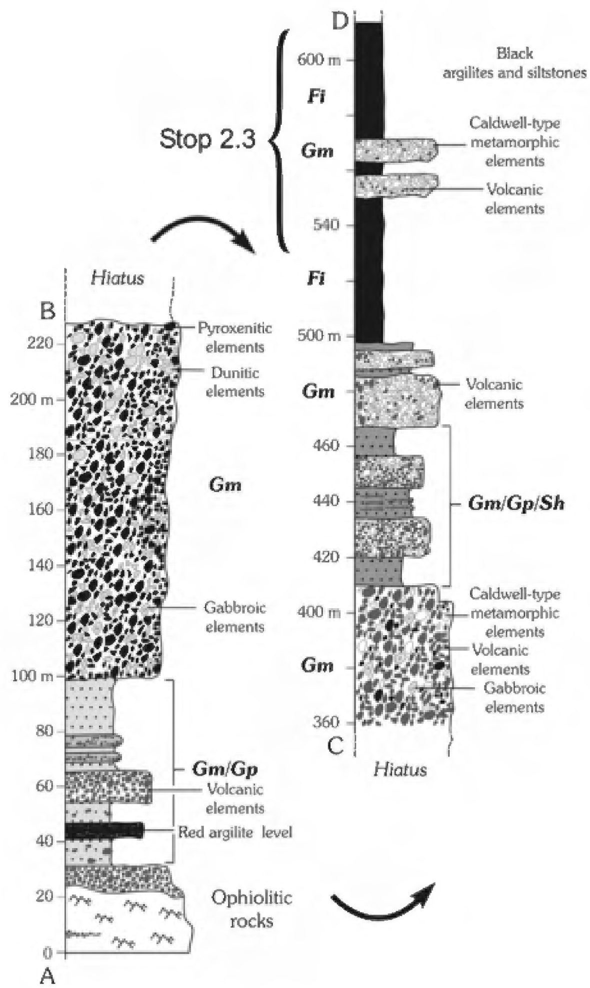

Figure 16. Stratigraphic section of the Saint-Daniel Mélange as exposed in the Rivière de l'Or (stop 7). Adapted from Schroetter et al. (2006). / *Figure 16. Section stratigraphique du Mélange de Saint-Daniel tel qu'exposée dans la Rivière de l'Or (arrêt 7). Adapté de Schroetter et al. (2006).*

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THE MONTAUBAN GROUP AND THE LA BOSTONNAIS COMPLEX: KEY ELEMENTS IN THE ACCRETIONARY HISTORY OF THE SOUTH-CENTRAL GRENVILLE PROVINCE

by

Léopold Nadeau and Pierre Brouillette, Commission géologique du Canada / Geological Survey of Canada,
490, rue de la Couronne, Québec, QC G1K 9A9, Canada
Claude Hébert, Ministère des Ressources naturelles et de la Faune du Québec,
880, chemin Sainte-Foy, Québec, QC G1S 4X4, Canada

GEOLOGICAL OVERVIEW

The Portneuf–Mauricie region, south-central Grenville Province, is located at the juncture between the geologically and tectonically contrasting northeast and southwest segments of the Grenville Province (Fig. 1). Major rock units include the Montauban group, the La Bostonnais Complex, the Grenville Supergroup, granulites of the Mékinac-Taureau domain, and a variety of crosscutting plutons ranging from gabbro to porphyritic granite and monzonite (Figs. 2 and 3).

The region comprises four contrasting lithotectonic domains (Fig. 1; Nadeau and Corrigan, 1991; Nadeau et al. 1992a). On the northwest, the structurally lowest Mékinac-Taureau domain makes up a broad crustal-scale dome composed mainly of transposed and granoblastic, intermediate and felsic granulitic orthogneisses. One of the orthogneiss bodies has yielded a U-Pb zircon crystallization age of 1.37 Ga. This dome is structurally overlain on its south and east flanks by the allochthonous monocyclic Morin Terrane, and to the east, by the allochthonous polycyclic Portneuf-Mauricie domain. These domains were intruded by a number of small gabbronorite intrusions at 1.07 Ga and by large masses of porphyritic granite and monzonite at ca. 1.06 Ga; the latter also underlie most of the Parc des Laurentides domain farther east.

These domains exhibit contrasting geophysical signatures, reflecting the physical properties of the rocks, their lithological makeup, metamorphic grade, and tectonic fabric. The Portneuf-Mauricie domain is singled out by a strong, northerly elongated, positive anomaly on the Bouguer gravity map (Fig. 4). This anomaly comprises three high points corresponding to gabbronorite intrusions, including the Lapeyrère Gabbronorite. The Mékinac-Taureau domain exhibits a low and uniform magnetic relief, which differs from the uniformly high magnetic relief of the Morin Terrane (Fig. 5). In contrast, the magnetic signatures of the Portneuf-Mauricie and Parc des Laurentides domains are marked by pronounced oval-shaped magnetic high corresponding to granitic intrusions.

The Morin terrane comprises the anorthosite-mangerite-charnockite-granite suite (AMCG) of the Morin Complex, emplaced at ca. 1.16 Ga, and stands out by an abundance of supracrustal rocks of the Grenville Supergroup, presumably deposited ca. 1.25 Ga. In addition, it may also comprise a younger metasedimentary sequence possibly deposited after ca. 1.18 Ga (Corrigan and van Breemen, 1997).

The ca. 1.45 Ga volcano-sedimentary paragneiss sequence of the Montauban group and the ca. 1.41–1.38 Ga calc-alkalic metaplutonic rocks of the La Bostonnais Complex constitute the distinctive lithological assemblages of the Portneuf-Mauricie domain (Figs. 2 and 3; Nadeau et al. 1992b). The Montauban area, long known for its Au, Pb, and Zn volcanogenic massive sulphide mineralizations, corresponds to a regional metamorphic low. This area is underlain by middle to upper amphibolite facies paragneiss in which primary structures are locally preserved. The planar fabric of the Portneuf-Mauricie domain generally dips gently or moderately to the southeast or east. Mineral and stretching lineations define two suborthogonal poles plunging gently SE and NNE. The southeast pole corresponds to early lineations associated with northwest-directed thrusting and peak metamorphism. Conversely, NNE-trending lineations locally mark late-Grenvillian extensional, oblique-senestral ductile shear zones. These are possibly a consequence of the exhumation of the Mékinac-Taureau domain dome, responsible for the preservation of the Montauban metamorphic low.

The origin of large tracts of medium- to high-grade quartzofeldspathic gneisses in much of the Grenville Province remains obscure, thus hindering lithostratigraphic and tectonic reconstruction. Quartzofeldspathic gneisses of the Montauban region are no exception. These gneisses and associated subordinate amphibolite, locally containing preserved pillow structure, are included in the Montauban group, named and defined by Rondot (1978). In the absence of distinctive geochemical fingerprinting, the recognition of relict primary features provides essential clues for the proper interpretation of these rocks. Until recently, the metabasaltic pillow lava at Mont Tétreault constituted the only known locality of volcanic rock in the region. Recently, however, a number of additional occurrences of relict volcanic features, including felsic lapilli tuff, have been found, hence shedding new light on the origin of some of the quartzofeldspathic gneiss of the Montauban group (Nadeau et al., 1999). Igneous zircon from a lapilli tuff have yielded an age of extrusion of ca. 1.45 Ga for the volcanic rocks of the Montauban group (Nadeau and van Breemen, 1994).

The La Bostonnais Complex is a typical arc-related calc-alkalic suite dominated by rocks ranging in composition from two pyroxene-hornblende diorite to hornblende-biotite granodiorite, and includes subordinate monzogranite and minor ultramafic rock and gabbro. This plutonic suite intruded the Montauban group within a few tens of millions of years after its deposition. Four samples from regionally extensive plutonic bodies ranging in composition from diorite to granodiorite yielded U-Pb zircon igneous crystallization ages of 1380–1410 Ma (Nadeau and van Breemen, 1994). The Lac Nadeau intrusion is a zoned, Ni-Cu-PGE-mineralized mafic-ultramafic body dated at 1.40 Ga (Sappin et al., 2004, and this volume). Rock textures and structures in the La Bostonnais Complex range from massive, with relict plutonic textures and mineralogy, to well foliated and in part gneissic and migmatitic. The trace element geochemical signature of the complex differs from that typical of an Andean-type magmatic arc but shares many similarities with evolved intra-oceanic plutonic arcs (Gautier, 1993). The La Bostonnais Complex plutonic suite may perhaps correspond to the deeper and more-evolved product of a more-mature island arc, signalled by the Montauban group volcanics.

This field trip provides an opportunity to examine key outcrops of the Montauban group and the La Bostonnais Complex, and to assess the structural and tectonic setting of these units within the broader context of the Grenville Province. Readers are also referred to the work of Dr. D. Corrigan, which provides a wealth of geochronological data and a provisional tectonic model for the region (Corrigan, 1995; Corrigan and van Breemen, 1997). The Ni-Cu-PGE deposits and their host mafic-ultramafic intrusions in the Lac Nadeau area are the subject of another NEIGC-FOG-AQUEST field trip (see Sappin et al., this volume).

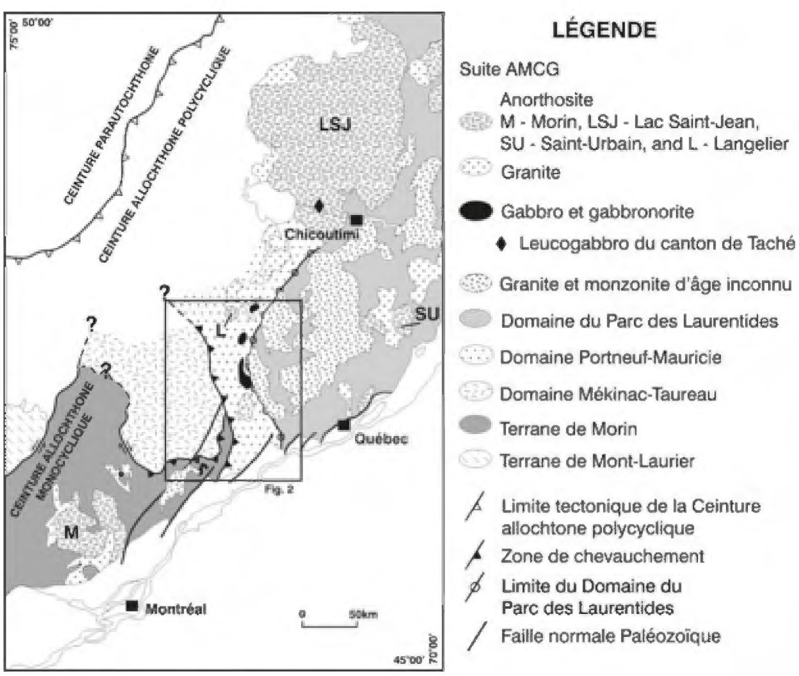
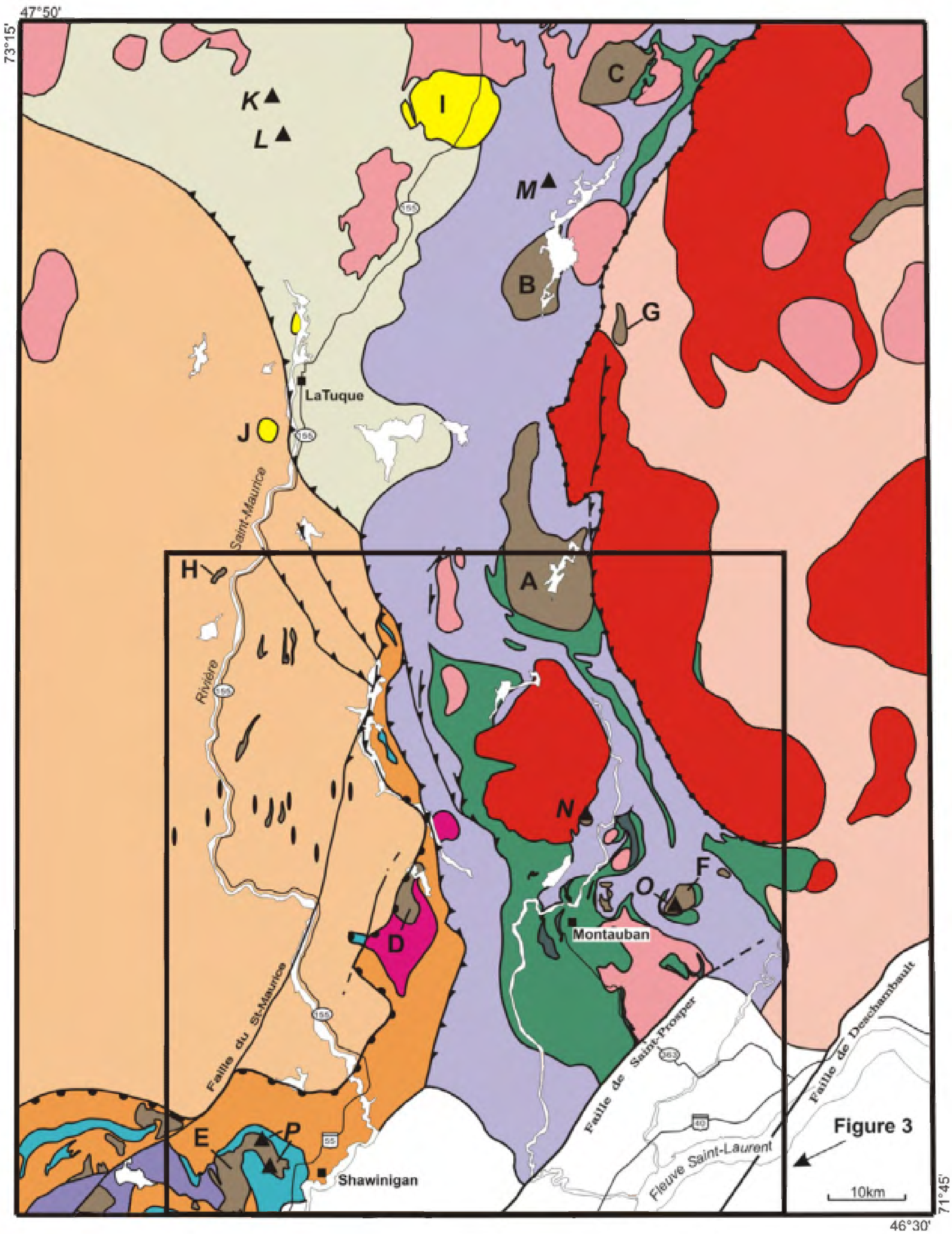


Figure 1. Location sketch map of the Portneuf-Mauricie region and tectonic subdivisions of the south-central Grenville Province (after Nadeau and van Breemen, 2001).



(legend overleaf)

Figure 2. Geological sketch map of the Portneuf-Mauricie region, Grenville Province (after Nadeau and Brouillette, 1994, 1995).

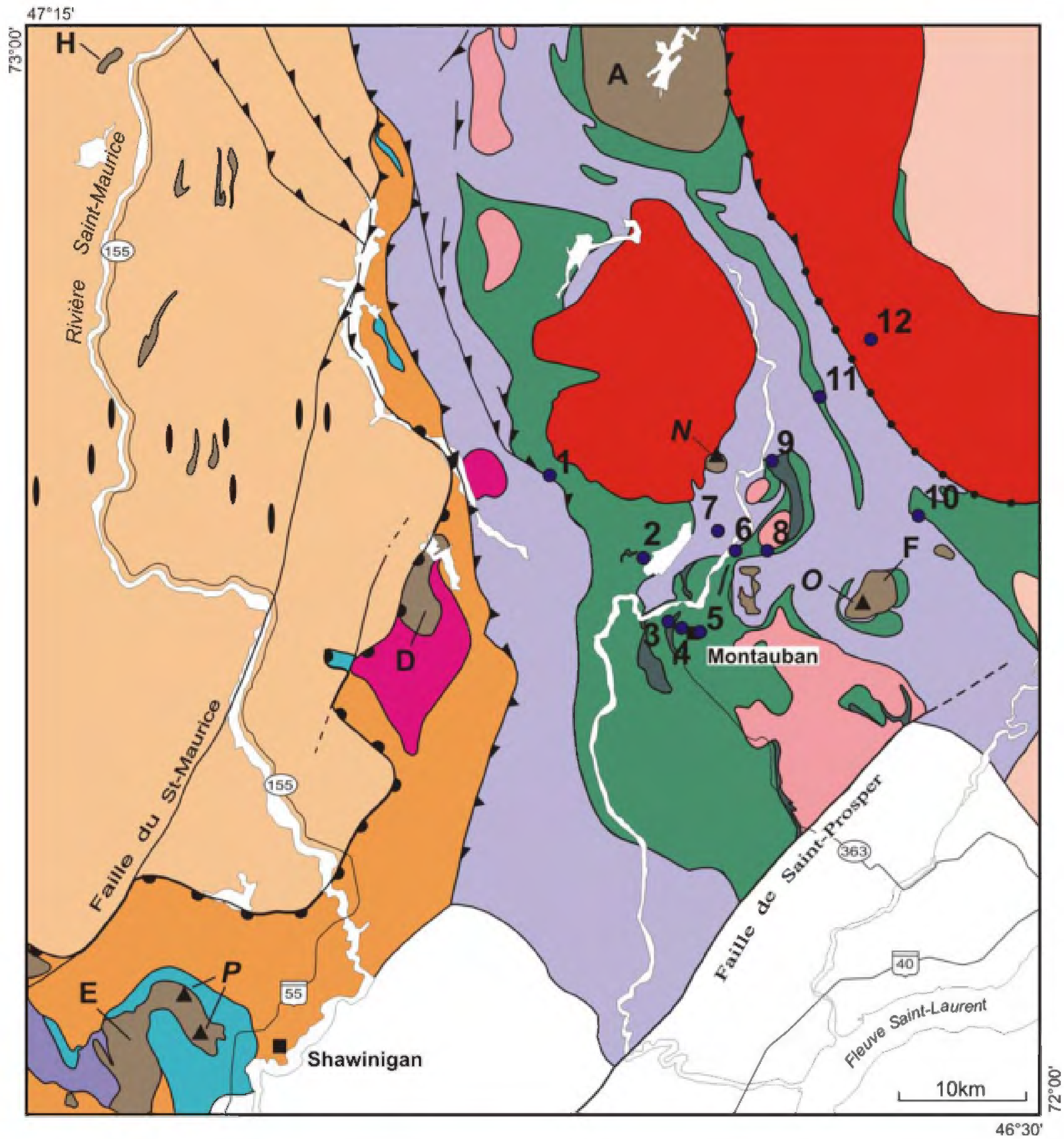


Figure 3. Geological sketch map of the field trip region, with stop locations. See Figure 2 for legend.

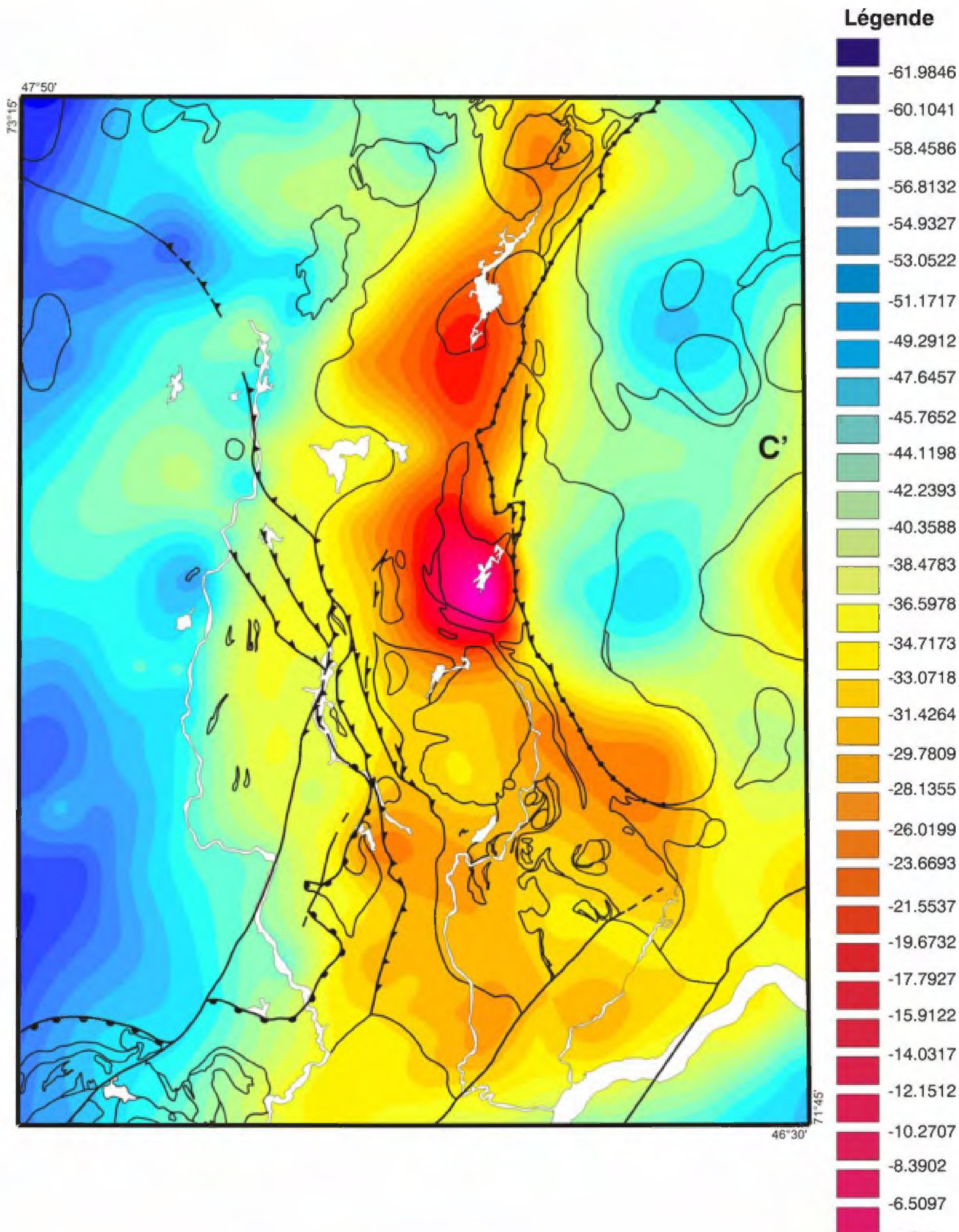


Figure 4. Bouguer gravity anomaly map of the Portneuf-Mauricie region

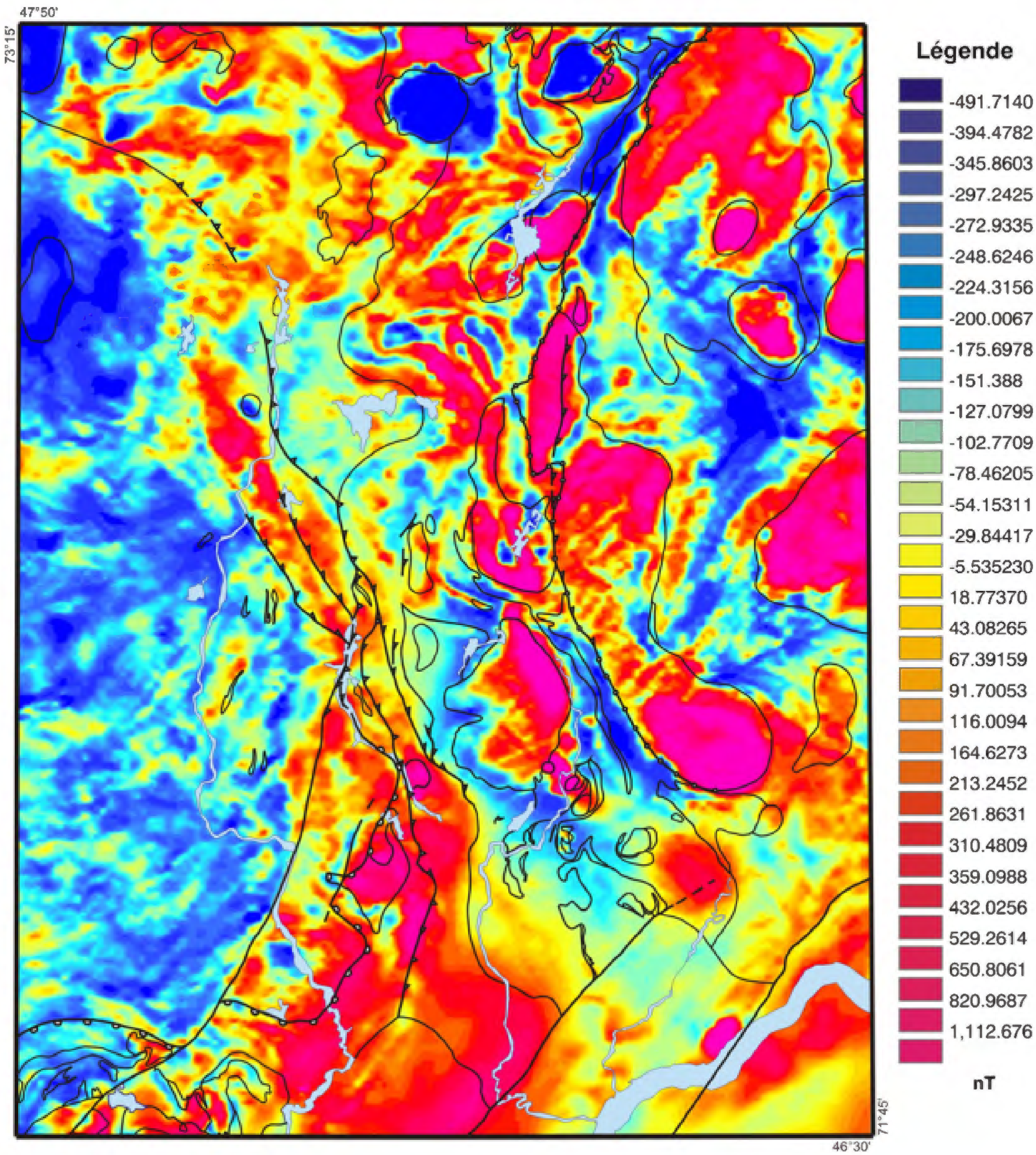


Figure 5. Magnetic anomaly map of the Portneuf-Mauricie region.

EPILOGUE

Regional studies in the Grenville Province during the last two decades have highlighted the orogenic role of ductile thrust, extensional, and strike-slip shear zones (e.g. Davidson, 1984; Hanmer, 1988; Rivers et al., 1989; Nadeau and Hanmer, 1992; Martignole and Pouget, 1994; Corrigan, 1995; Corrigan et van Breemen, 1997). The Taureau and Morin shear zones, as well as the thick shear zone that marks the imbrication of the Morin Terrane between the Mékinac-Taureau domain and the Portneuf-Mauricie domain, are among those recently recognized and currently under study. There may remain a number of important structures whose recognition will be essential to a full understanding of the nature and the structural position of the geological entities composing the regional mosaic.

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FIELD TRIP ROAD LOG

The field trip stops are shown on Figures 3 and 6. The UTM coordinates in the field trip log refer to the NAD 83 map projection.

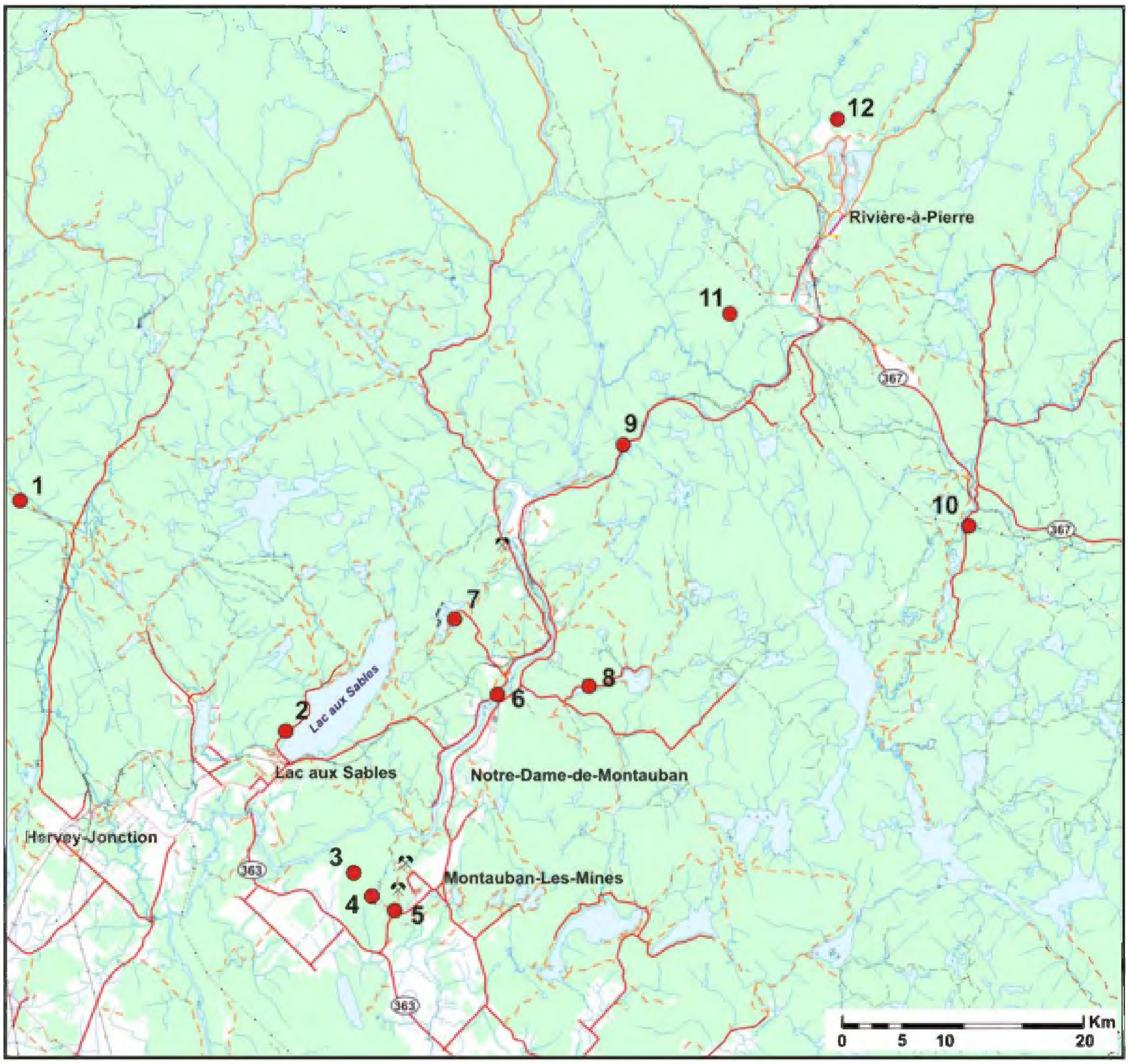


Figure 6. Field trip stop location map (Stops 1 to 12) and main road access.

STOP 1. Tawachiche River extensional shear zone
691250 E; 5201075 N

This outcrop contains porphyroclastic mylonite and ultramylonite produced in a late-Grenvillian, shallow-dipping ductile shear zone of oblique-extensional type. The shear zone juxtaposes mixed granodioritic-monzodioritic-dioritic orthogneisses of the La Bostonnais Complex footwall against structurally overlying volcano-sedimentary paragneisses of the Montauban group. The shear zone serves as channelway for pegmatite emplacement.

STOP 2. Typical biotite-hornblende granodiorite of the La Bostonnais Complex
699010 E; 5194335 N

This outcrop is located near the structural base of the Portneuf-Mauricie domain. It features biotite-hornblende metagranodiorite dikes typical of La Bostonnais Complex intruding paragneiss of the Montauban group. This granodiorite contrasts markedly with the gneisses of the structurally underlying Jésuite Complex of the Morin terrane.

STOP 3. Pillowed metabasalts of the Montauban group
701000 E; 5190175 N

Outcrops of pillowed metabasalt at Mont Tétreault feature the first definite metavolcanic structures recognized in the central Grenville Province (Pyke, 1966). Pillows are recognized by their flattened bulbous shapes and their well-defined, 1–2 cm thick, fine-grained selvages. They are a few decimetres in diameter and display ellipsoidal shapes in oblique section looking down the stretching direction. Contacts between pillows are smoothly undulating, sharp, and thin, with weathered, recessed, irregular interstices filled with calcite and calc-silicate minerals. Locally, calcite-filled vesicles up to 5 mm in diameter are preserved, testifying to shallow subaqueous extrusion. The major and trace element signatures of over 20 representative samples match those of juvenile oceanic arc and back-arc basalts. Note the marked stretching lineation and the middle amphibolite facies metamorphic paragenesis.

STOP 4. Volcaniclastic paragneiss and lapilli tuff of the Montauban group
701525 E; 5189500 N

The granoblastic, fine-grained, and well-bedded quartzofeldspathic gneisses exposed in this section are interpreted as derived from subaqueous pyroclastic and/or epiclastic sediments. The structurally upper part of the section comprises lapilli tuff, which has yielded a U-Pb zircon crystallization age of ca. 1450 Ma.

STOP 5. The "Montauban-les-Mines" ore zones
702200 E; 5189050 N

The occurrence of gold- and silver-bearing, polymetallic lead-zinc sulfide deposits in calc-silicate rocks and associated quartzofeldspathic gneisses at Montauban has been known since 1910. The ore and associated alteration zones are typical of high-sulfidation, volcanogenic massive sulfide deposits.

Intermittent mining took place from 1914 to 1989. Through 1965, estimated total production was 2.7 million metric tonnes of massive sulfide ore grading 6.8% Zn, 2.3% Pb, 1.3 g/t Au, and 131 g/t Ag. In addition, 2571 kg of gold and 8068 kg of silver were extracted between 1983 and 1989 from 0.9 million tonnes of disseminated sulfide ore grading 3.6 g/t Au and 17.7 g/t Ag.

Up the structural section, the lithologic sequence hosting the southern massive sulphide zone includes rusty sillimanite-muscovite-biotite paragneiss likely derived from altered lapilli tuff, calc-silicate rocks containing sulphide in the ore zone, and overlying biotite-hornblende gneiss. In addition, the north gold zone rock sequence includes cordierite-anthophyllite and sulphide-bearing garnet-gahnite quartzitic gneiss.

Minerals present at Montauban include garnet, sillimanite, diopside, tremolite, anorthite, scapolite, wilsonite (lilac pink), serpentine, talc, brucite, tourmaline, calcite, dolomite, breunnerite (= calcite), sphalerite, galena, chalcopyrite, pyrrhotite, molybdenite, and arsenopyrite, as well as the sulfates jarosite (yellow), rozenite (white), gypsum (fibrous white), and brochantite (green emerald).

Stop 6. Mylonitic, tourmaline-bearing leucogranite, schist, and quartzite
705200 E; 5195425 N

Schist and quartzite are less abundant than quartzofeldspathic gneiss and amphibolite in the Montauban group. They are associated here with a leucocratic, tourmaline-bearing monzogranite intrusion, possibly associated with a small subvolcanic porphyry intrusion.

STOP 7. Tectonic sliver of Montauban group
703950 E; 5197625 N

This set of outcrops comprises a screen of Montauban group metasedimentary gneiss a few tens of metres thick in mylonitic granodiorite of the La Bostonnais Complex. Note the transposition structures in the sheared granodiorite and the structural cutoff in paragneiss.

STOP 8. Sheared and cutoff section of Montauban group metavolcanics and associated paragneiss
707900 E; 5195650 N

This outcrop of upper amphibolite facies intermediate and mafic gneiss comprises relict mafic tuff, possibly thin massive flows, and associated volcano-sedimentary paragneiss. Note the alteration pattern in the amphibolite. What is the origin of the thinly layered mafic gneiss?

STOP 9. Stretched pillowed metabasalt of the Montauban group
708875 E; 5202675 N

Upper amphibolite facies amphibolite (metabasalt) shows relict pillow structures recognizable only in the section perpendicular to the stretching direction.

STOP 10. Massive to gneissic granodiorite of the La Bostonnais Complex
719000 E; 5200350 N

This set of outcrops features one of the most common facies of the La Bostonnais Complex. Four samples from regionally extensive plutonic bodies ranging in composition from diorite to granodiorite yielded U-Pb zircon igneous crystallization ages of 1380-1410 Ma. Note the occurrence of a number of distinct magmatic phases, of several dioritic enclaves, and of a few paragneiss xenoliths.

STOP 11. Northern extension of the Montauban group
712000 E; 5206500 N

Amphibolite (metabasalt?) occurs as metre-thick layers in paragneiss. Note the disappearance of primary structures, the development of high-grade metamorphic textures and structures, and the occurrence of a number of thin subhorizontal sinistral shear zones.

STOP 12. Rivière-à-Pierre Suite, Parc des Laurentides domain
715150 E; 5212250 N

In the quarry, K-feldspar-porphyritic hornblende monzonite and monzogranite, typical of late-tectonic intrusions of the Parc des Laurentides domain, are quarried. A sample from this body yielded a U-Pb zircon crystallization age of 1058 +/- 2 Ma.

END OF FIELD TRIP

STRUCTURAL GEOLOGY AND FLUID FLOW IN THE SAINT-DOMINIQUE CARBONATE SLICE, QUÉBEC APPALACHIANS STRUCTURAL FRONT

by

Stephan Séjourné, Gastem, 1155, Rue University, Bureau 805, Montréal, QC H3B 3A7, Canada
Michel Malo, INRS-ETE, Université du Québec, 490, rue de la Couronne, Québec, QC G1K 9A9, Canada
Martine M. Savard, Geological Survey of Canada, GSC-Québec, 490, rue de la Couronne, Québec, QC G1K 9A9, Canada

INTRODUCTION

The final architecture of the Appalachian frontal zone in southern Québec is mainly the result of a single orogenic event, the Middle to Late Ordovician Taconian Orogeny (St-Julien and Hubert, 1975; Tremblay and Pinet, 1994). The evolution of the structural front in this area is less complex than in western Newfoundland and New England (Fig. 1), where the effect of a second orogenic event is superimposed, the Middle to Late Devonian Acadian Orogeny (Stockmal et al., 1998). In southern Québec, the Appalachian structural front comprises thrust imbricated shelf carbonate slices (about fifty of them have been documented from seismic data; Béland and Morin, 2000) and synorogenic flysch units along Logan's Line and Aston Fault (Fig. 1). The front is poorly exposed as a long (hundreds of kilometers) but narrow (ten kilometers or less) strip separating far travelled thrust sheets and gently folded, unfaulted flysch and molasse units. Most of this zone is currently buried below the thrust sheets, so that our understanding of the orogenic front in southern Québec is largely attributed to subsurface investigations (Laroche, 1983; St-Julien et al., 1983; Ando et al., 1984; Béland and Morin, 2000; Malo et al., 2001a, 2001b; Bertrand et al., 2003; Castonguay et al., 2003, 2006; Séjourné et al., 2003). These studies provide accurate data on the regional scale but, did not revealed the local, small-scale structures and crosscutting relationships critical for establishing the structural evolution of this orogenic front. In that regard, the Saint-Dominique slice exposed at surface (Fig. 2) can provide further insight into the structural style of carbonate slices at a mesoscopic scale.

This field trip presents the results of a surface structural geological investigation of the Saint-Dominique slice. Geochemical data (fluid inclusions, $\delta^{18}O_{VPDB}$, $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ ratios) from host rock and structural cements (quartz and carbonate cements that seal faults and veins) are used to investigate the diagenetic evolution and the nature of the fluid flow prevailing during the deformation of the slice. Some observations on a correlative carbonate slice further south in Vermont (Fig. 2), the Highgate Springs slice (Kay, 1958), are also briefly presented.

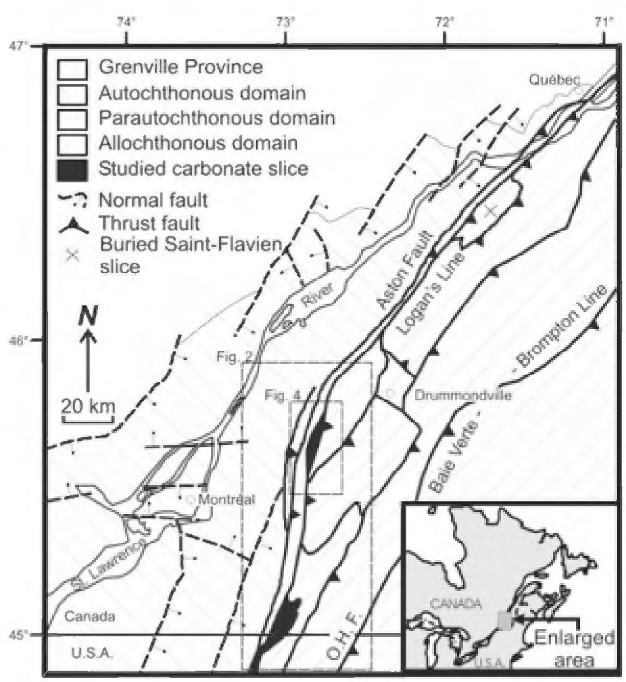


Figure 1. General location of the study area.

REGIONAL TECTONOSTRATIGRAPHIC SETTING

Four tectonostratigraphic zones are distinguished in southern Québec (Figs. 1, 2, 3), from NW to SE: the Grenville Province, the St. Lawrence platform and Appalachian foreland basin (autochthonous domain), a fault imbricated zone (parautochthonous domain), and the Appalachian thrust sheets (allochthonous domain).

The autochthonous platformal (Potsdam and Beekmantown groups) and foreland basin strata (Chazy to Queenston groups) of the St. Lawrence Lowlands have been unconformably deposited upon the eastern margin of

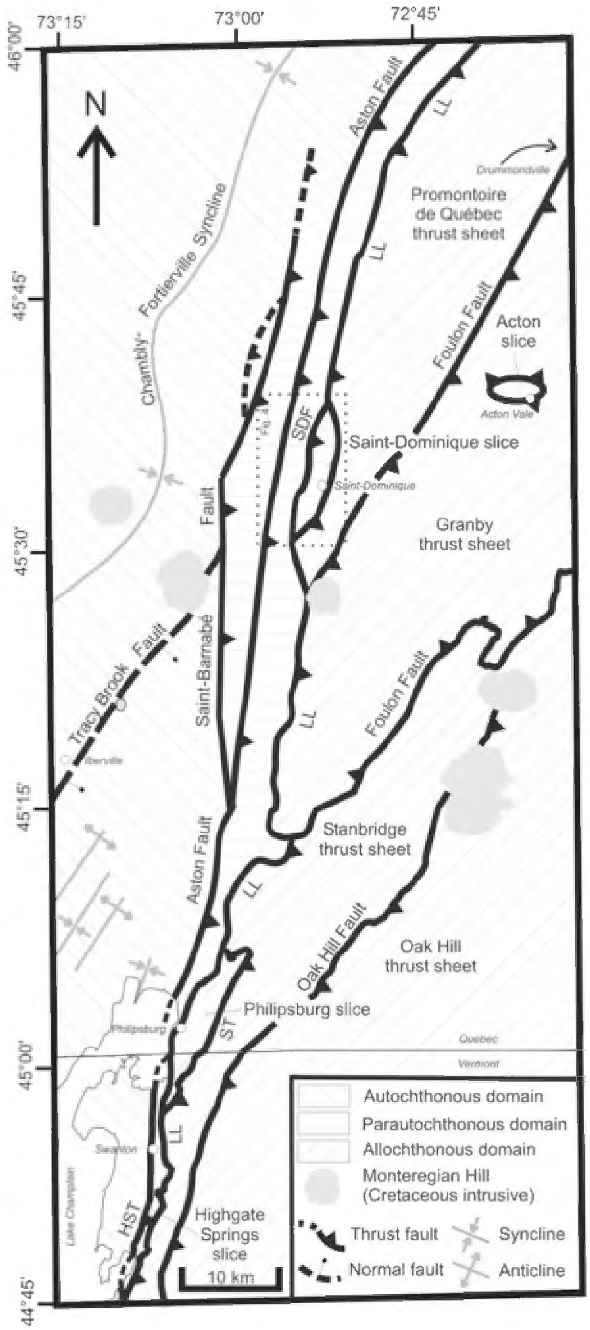


Figure 2. Map of main tectonostratigraphic units of southern Québec and location of the studied carbonate slices, modified from Clark (1964a, 1964b), Globensky (1987), Haschke (1994), and Doll et al. (1961). LL: Logan's Line, SDF: Saint-Dominique Fault, HST: Highgate Springs Thrust, ST: Stanbridge Thrust.

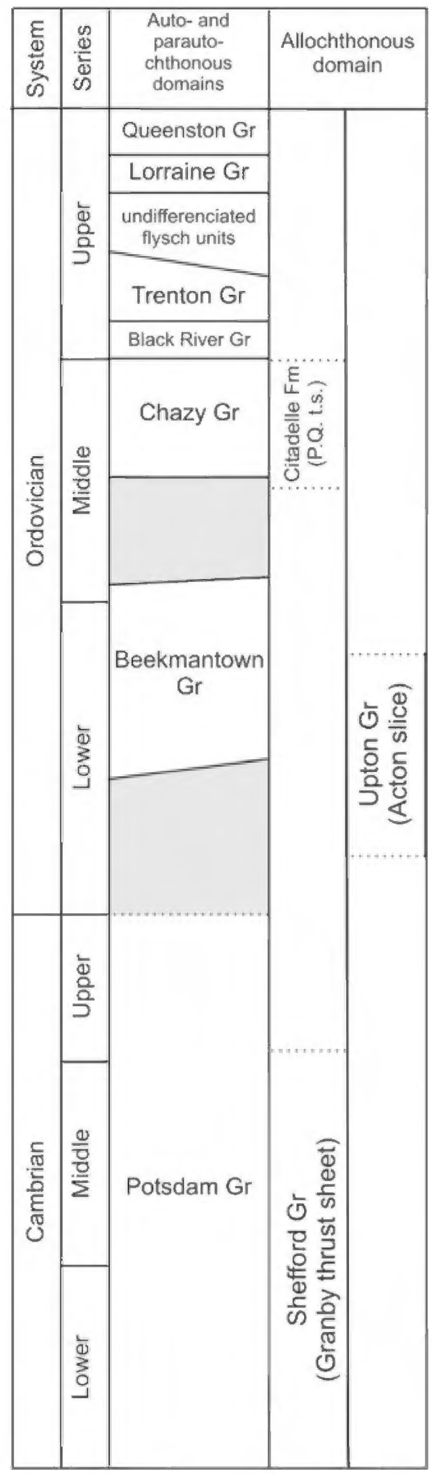


Figure 3. Schematic stratigraphic column of the autochthonous, parautochthonous and allochthonous domains in the study area. Gr: Group, Fm: Formation.

Laurentia (the Grenvillian basement) and represent a major trangressive-regressive cycle between Late Neoproterozoic to Early Cambrian opening and Middle Ordovician to Early Silurian closure of the Iapetus Ocean (Globensky, 1987).

Rocks of the parautochthonous domain are comprised of the platform and foreland basin units as in the previous domain (St-Julien and Hubert, 1975). The Saint-Dominique slice is the only carbonate slice cropping out in the parautochthonous domain of Québec (Beaupré, 1975). Immediately south of the border, the Highgate Springs slice lies in the same structural position and is comprised of the same stratigraphic units as the Saint-Dominique slice.

Lithostratigraphic units of the allochthonous domain belonging to the Humber zone of the Canadian Appalachians (Williams, 1979) are stratigraphically distinct from those in the autochthonous and parautochthonous domains (Slivitzky and St-Julien, 1987). In the study area, the allochthonous domain is made up of Lower Cambrian to Middle Ordovician basinal slope and rise rocks (Citadelle Formation, Shefford, and Stanbridge groups) that record the development of the Laurentian passive margin.

At surface, the autochthonous domain is bounded by an unconformity or by normal faults to the northwest. It is structurally overlain by the parautochthonous domain to the southeast, along the Saint-Barnabé and Aston thrust faults (Fig. 2). Strata of the external part of the allochthonous domain (Humber zone) overthrust the parautochthonous rocks along a major thrust fault zone delineating the Logan's Line. The Humber zone was destroyed by the collision of the Laurentian margin with volcanic island arcs during the Middle to Late Ordovician (St-Julien and Hubert, 1975) and it is now separated from the more internal part of the allochthonous domain (the Dunnage zone) by the Baie Verte – Brompton Line (Fig. 1).

Two different deformation styles are superposed in the study area. The older style results from a long-lived extensional regime and is characterised by syn-sedimentary normal faults (Bradley and Kusky, 1986; Lavoie, 1994; Séjourné et al., 2003). Some normal faults may also have been initiated or reactivated at the onset of the Taconian Orogeny during migration of the peripheral bulge (Jacobi, 1981; Chalaron and Malo, 1998), reflecting lithospheric flexure developed in response to the advancing Taconian orogenic wedge (Bradley and Kidd, 1991).

The Taconian Orogeny is commonly regarded as the only contractional event that led to significant deformation in the study area (Tremblay and Pinet, 1994). In Québec, biostratigraphic dating of the matrix of wildflysch occurring at the sole of major thrust sheets indicates that thrusting of the allochthonous domain took place in a northwest-propagating piggy-back sequence during Late Ordovician time (St-Julien and Hubert, 1975). Recent structural and biostratigraphic investigations have also shown that significant out-of-sequence thrusting took place during the Taconian Orogeny (Séjourné et al., 2003; Comeau et al., 2004). The autochthonous domain is little affected by shortening. The only contractional structures mapped at surface are the wide, open, Chambly-Fortierville Syncline to the north, and shorter scale folds to the south (Fig. 2).

Erosion has left little evidence of the post-Ordovician tectonostratigraphic history. Early Devonian sedimentation is indicated by Devonian fossils found in sedimentary clasts within Cretaceous intrusive breccias on Sainte-Hélène Island, near Montreal (St-Julien and Hubert, 1975). Direct evidence of later tectonic events, although documented elsewhere in the orogen, are either unrecognized or absent (Tremblay and Pinet, 1994). However, some strike-slip faults are tentatively correlated by Faure et al. (1996a) with the Middle to Late Devonian Acadian and the Late Carboniferous to Early Permian Alleghanian orogenies. Since the Late Permian to Early Triassic, the separation of North America from Africa is responsible for the reactivation of lithospheric faults in Québec (Kumarapeli, 1969a; Rocher and Tremblay, 2001). The emplacement of intrusive bodies that formed the Monteregian Hills and associated dykes and sills during Cretaceous is likely related to this extensional event (Bédard, 1985; Faure et al., 1996b).

GEOLOGY OF THE SAINT-DOMINIQUE SLICE

The Saint-Dominique slice was thrust to the west over flysch units along the Saint-Dominique thrust (Figs. 2, 4). The slice is overlain to the east by allochthonous rocks along a major thrust fault marking Logan's Line in Québec.

Stratigraphy

The Saint-Dominique slice comprises Lower to Middle Ordovician Beekmantown to Trenton groups strata (Kay, 1958; Clark 1964a; Fig. 3). The Beekmantown Group rocks change upward from massive, calcareous dolomicrite at the base into a well-bedded succession of limestone and dolostone strata at the top. The base of the Chazy Group comprises fine-grained, calcareous sandstone strata that give way in the upper section to well-stratified and fossiliferous shaly limestone, whereas the overlying Black River Group contains dolostone and coarsely crystalline and oolitic limestone. Finally, the Trenton Group is well stratified, with thin beds of shaly limestone alternating with shales in its uppermost levels. Sills and dykes are documented throughout the slice and are associated with the Mesozoic Monteregian intrusives (Foland et al., 1986).

Structural analysis

Poor exposure along the Saint-Dominique Fault was responsible for controversial interpretations, and the structure has been alternatively interpreted as a normal fault (Kumarapeli, 1969b) or as a thrust fault (Clark, 1964a; Prichonnet and Raynal, 1977). The second hypothesis is now commonly accepted (Séjourné, 2000). The structural style of the Saint-Dominique slice (Fig. 5) is dominated by asymmetrical folds, thrust faults and pressure-solution cleavage trending to the NNE (Figs. 6a-c, respectively). The nature and abundance of the contractional structures vary with rock types, so that it is possible to define informal lithostructural units within the slice (Fig. 5). Two units are recognized: (1) Massive carbonate units with little rheological contrast and exhibiting few, mainly brittle, deformation features are found in the lower Beekmantown (Fig. 5a), lower Chazy and Black River groups (Fig. 7a). (2) In contrast, the more thinly bedded and more argillaceous rocks are strongly faulted, folded and cleaved. They are located in the upper Beekmantown (Fig. 5a), upper Chazy (Fig. 5b) and Trenton (Fig. 5c). Although contractional features are dominant, extensional and strike-slip structures are also abundant. Normal faults (Figs. 5a, 5c) and tension gashes are NNE-trending (Figs. 6d, 6e). Strike-slip faults display no conspicuous vertical throw and are of two types (Fig. 6f): (1) front-perpendicular dextral and sinistral faults, and (2) front-parallel, mainly dextral faults (Figs. 5a-c, 7b). The distribution of these structures is not controlled by the lithology.

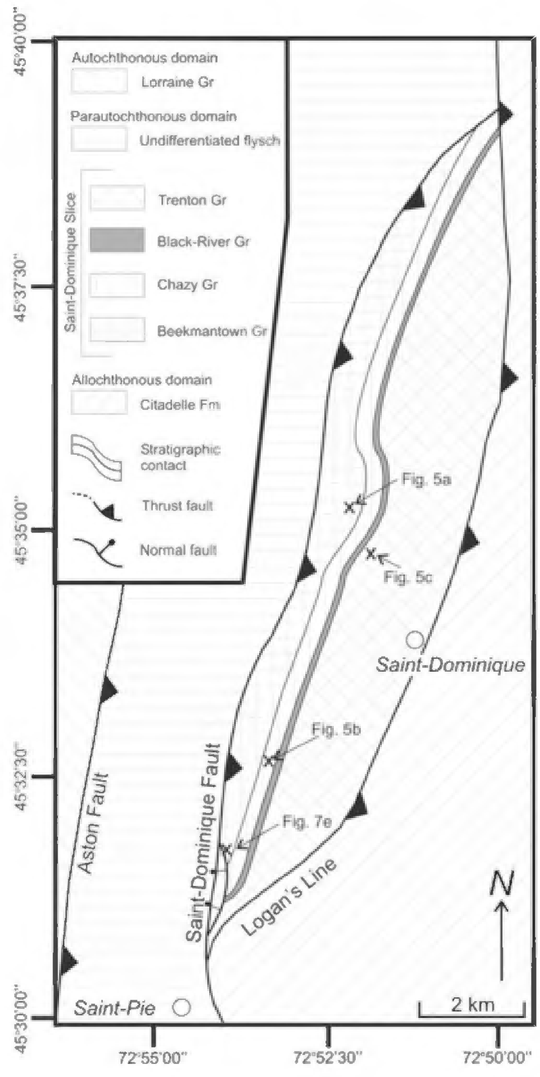


Figure 4. Simplified geologic map of Saint-Dominique slice and its surroundings, modified from Clark (1964a). Gr: Group, Fm: Formation.

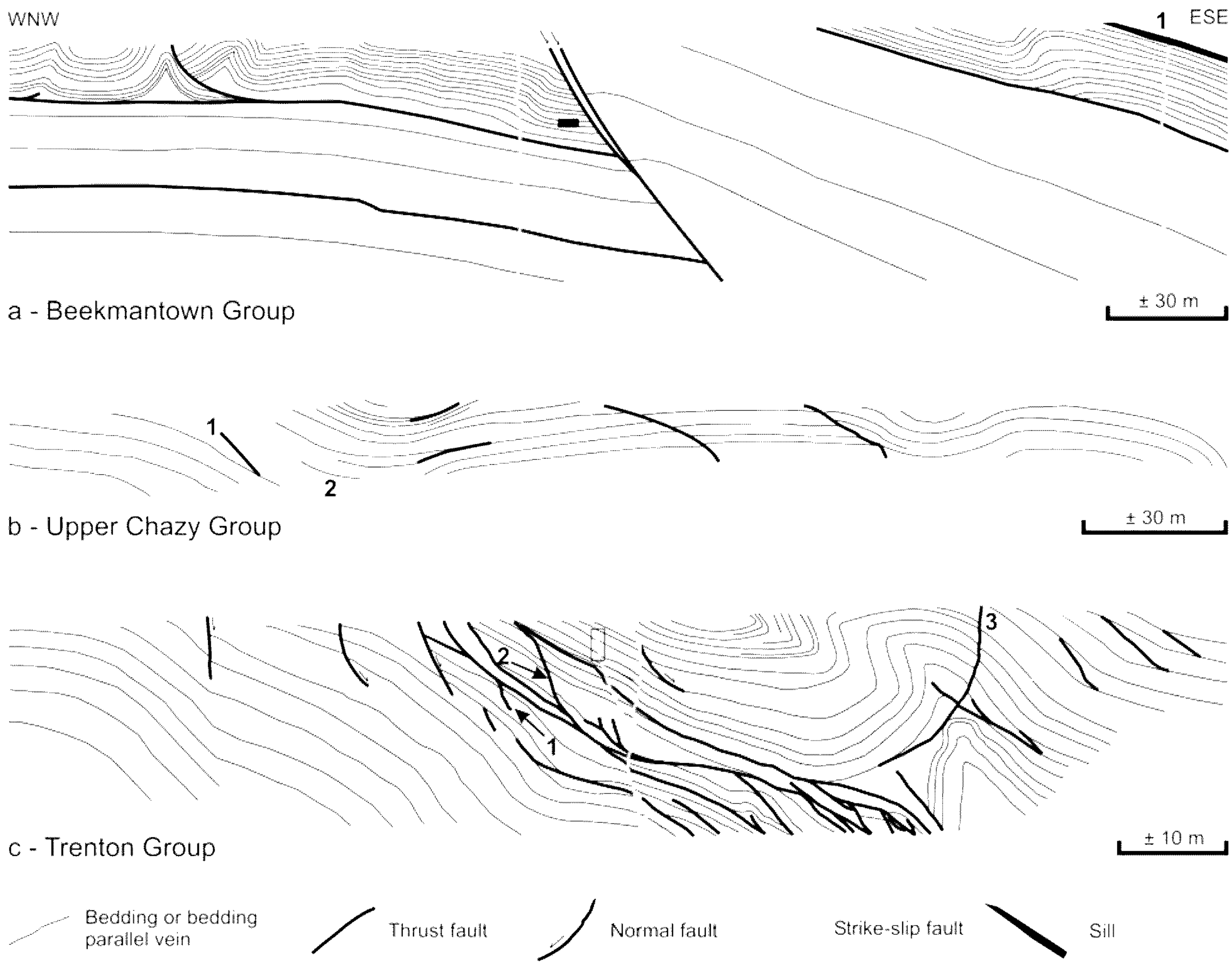


Figure 5. Cross sections assembled from field sketches illustrating lithological controls on structural styles in the Saint-Dominique slice. Refer to figure 4 for location of all cross sections. (a): Beekmantown Group: Thick beds of lower Beekmantown show little deformation (mainly bedding-parallel thrusts) compared to the well bedded and tightly folded upper Beekmantown. The abnormal stratigraphic offset indicates that the normal fault (based on slickensides) reactivated a reverse fault. Note the front-parallel, sinistral fault crosscut by a sill in the top right corner (refer to text for discussion). White and black boxes show location of figures 7a and 7c, respectively. 1 is a mafic sill crosscutting a sinistral fault (refer to text for discussion). (b): upper Chazy Group: the shaly limestone of upper Chazy is cleaved and displays thrust ramps and related folds. Lower Chazy and Black River groups are not shown. 1 is a bedding-parallel thrust fault ramping upsection, 2 is a moderately dipping front-parallel strike-slip fault (refer to text for discussions). (c): Trenton Group: the shales and shaly limestone are intensely cleaved, folded and faulted. White box in upper centre shows location of Fig. 7b. Normal and strike-slip faults develop in all lithostructural units. 1 and 2 are normal faults cut by thrust faults and 3 is a late backthrust (refer to text for discussions).

Chronological development of structural features

Through the detailed analysis of crosscutting relationships, five distinct structural events were recognized in the Saint-Dominique slice (Fig. 8).

There is little evidence of pre-contraction deformation apart from bedding-parallel stylolites and an isolated, NNE-trending growth fault in the upper Beekmantown (Fig. 7c). This meter-scale fault is sealed by centimeter thick beds of micritic limestone and was active during deposition of the upper beds (Fig. 7d).

The oldest contractional structures correspond to a NNE-trending pressure-solution cleavage (Fig. 8c) and some bedding-parallel slip planes. Small-scale imbricated contractional faults also developed to accommodate layer parallel shortening (Fig. 7e). Imbrication and folding followed during ongoing cleavage development. New bedding-parallel slip planes (mainly cemented by calcite and quartz) continued to develop to accommodate folding and thrusting, while older planes were reactivated or folded (Séjourné et al., 2005).

No crosscutting relationship was established between front-perpendicular strike-slip faults (Fig. 6f) and other structures, but the kinematics of these generally sub-vertical, dextral or sinistral faults indicates they acted as tear faults coeval with thrusting. The same syn-imbrication timing (during stress release periods following thrusting) is documented for two normal faults (labelled 1 and 2 on Fig. 5c) that cut the cleavage and bedding-parallel veins and are themselves cut by thrust faults (Chalaron and Malo, 1998). A similar alternation between coaxial horizontal compressional and extensional stresses is widely documented at various scales throughout the Saint-Dominique slice by mutual crosscutting relationships between contractional features (cleavage and bedding-parallel veins) and tensional features (bedding-perpendicular, front-parallel meter long veins, decimeter long tension gashes and centimeter to millimeter long veinlets).

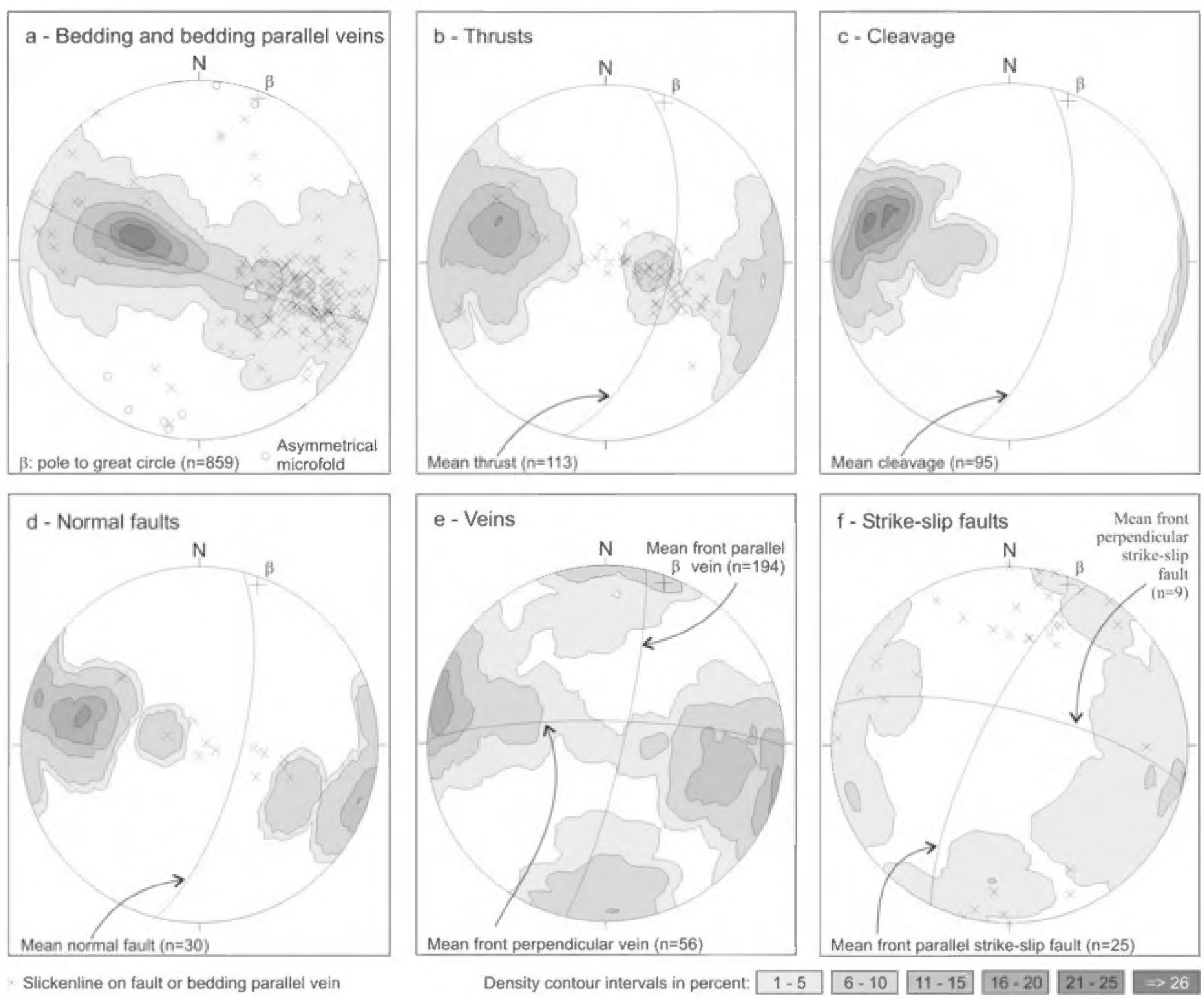


Figure 6. Stereographic projections of the main structural features in the Saint-Dominique slice (Schmidt projection, lower hemisphere).

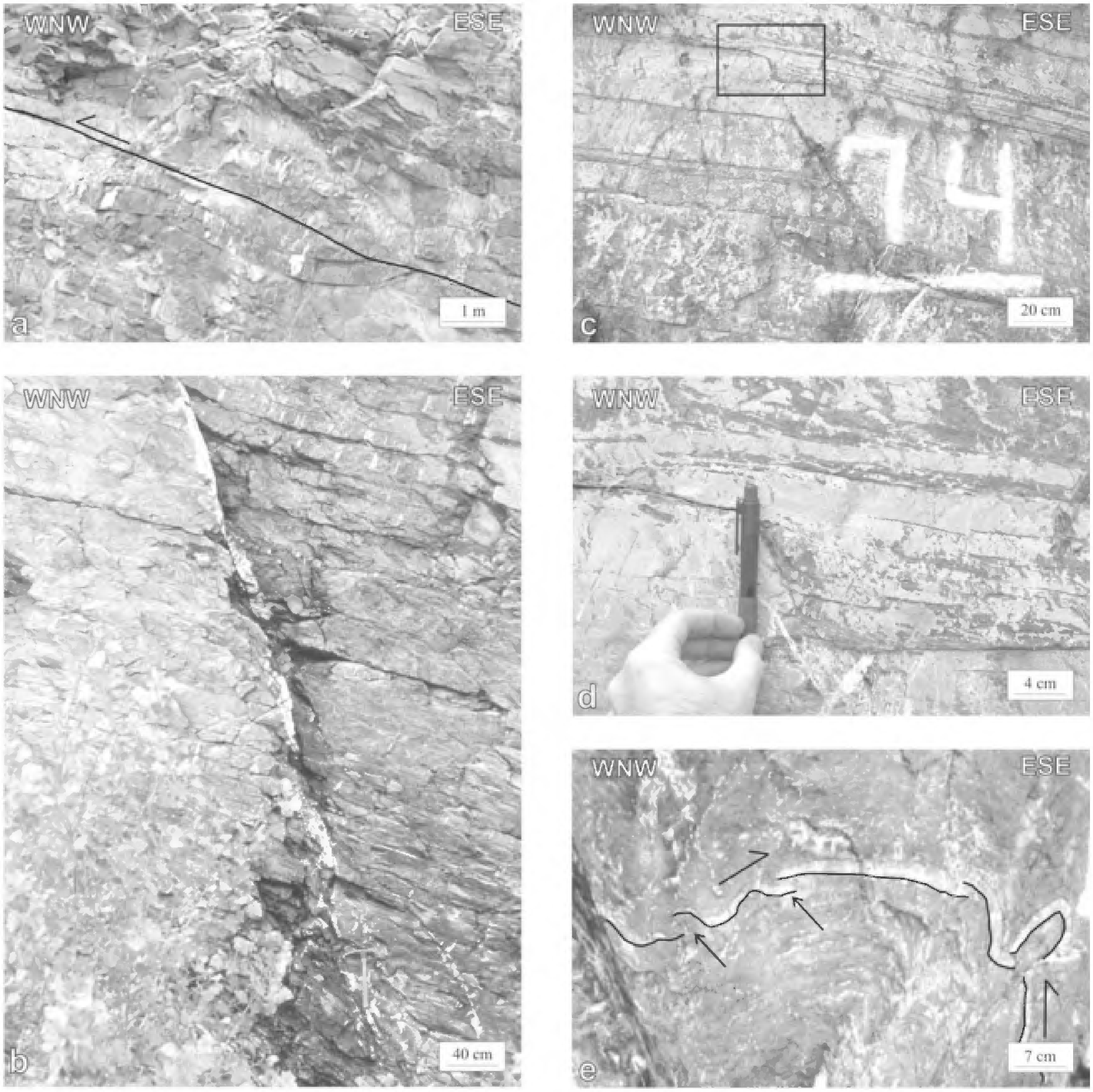


Figure 7. Field photographs of structural features in the Saint-Dominique slice. (a): Shallowly dipping thrust cutting across gently folded strata, a structural style typical of the thickly bedded dolostones of the lower Beekmantown (see text for discussion). Refer to white box on figure 5a for location. (b): Front-parallel (NNE-trending) dextral fault cutting Trenton Group strata. Bending of strata in the vicinity of the fault and occurrence of tension gashes restricted to the more competent beds suggest an early normal motion. Slickenlines, however, indicate that the last motion, at least, was sub-horizontal. Refer to white box on figure 5c for location. (c): Hinterland dipping (NNE-trending) growth fault developed in the upper Beekmantown strata. The fault plane is crosscut by tension gashes related to post-imbrication normal faulting. Refer to black box on figure 5a for location. (d): Enlargement of the upper section of the fault, showing thin beds of micritic limestone draped along fault plane (top of the pencil) and affected by incipient normal faults (black arrows) dipping to the foreland (probably coeval with sedimentation). Location is shown by the box on figure 7c. (e): Small scale thrust faults (black lines) dismembering a thin bed of mudstone. The WNW-directed imbrication probably accommodated layer parallel shortening in the upper Beekmantown Group strata prior to folding. Refer to figure 4 for location.

A piggy-back sequence of thrusting is locally indicated by folding of bedding-parallel thrust faults ramping upsection (labelled 1 on Fig. 5b). Local out-of-sequence faulting is also documented where folded bedding-parallel thrusts are cut by younger thrust faults. Finally, a few steeply-dipping, SSE-directed backthrusts (labelled 3 on Fig. 5c) developed at the end of the imbrication period (Fig. 8).

All the structures described above are cut by later normal faults and related structures (front-parallel veins, en échelon tension gashes, sigmoidal veins, bedding-parallel stylolites). Front-perpendicular veins and joints cut across these late normal faults and veins. Front-parallel strike-slip faults (Fig. 5) cut or reactivated contractional of extensional structures (no crosscutting relationship is documented with front-perpendicular strike-slip faults). The moderate dip of some of these front-parallel strike-slip faults (labelled 2 on Fig. 5b, Fig. 6f) is explained by reactivation of former thrust or normal fault planes. Some bedding-parallel veins were also reactivated in the vicinity of strike-slip faults (N- and S-directed slickenlines in Fig. 6a). In a single location, a sill of mafic composition crosscuts one of the sinistral faults (labelled 1 on Fig. 5a). Since dykes and sills in the area are Cretaceous intrusions (Clark, 1964a), at least some front-parallel strike-slip faults are inferred to be pre-Cretaceous in age.

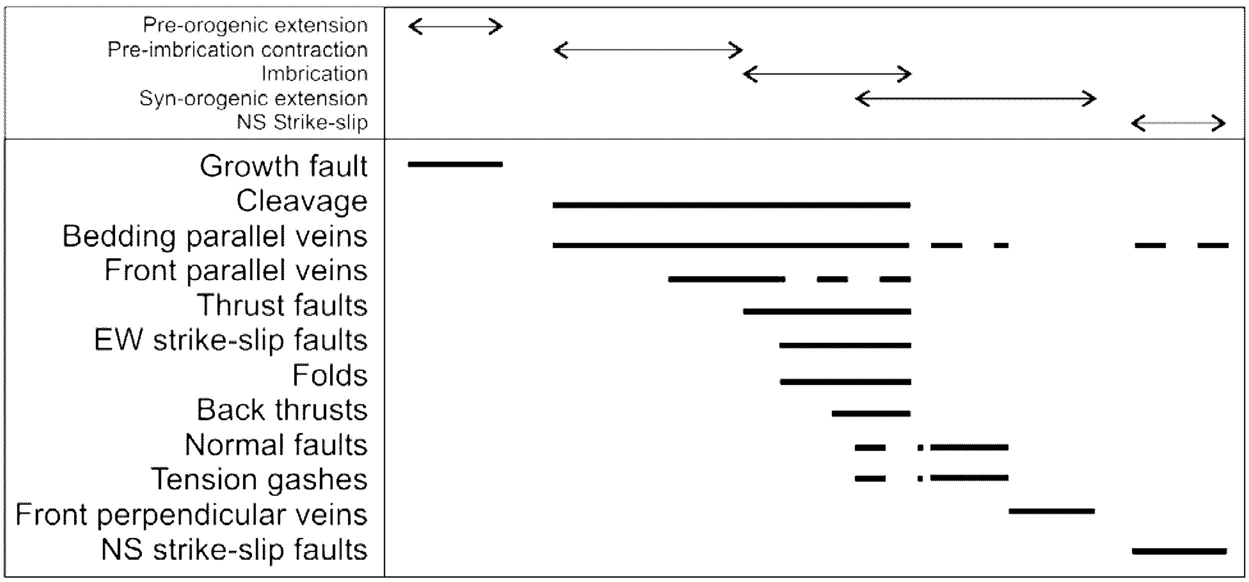


Figure 8. Relative chronology of main structural features in Saint-Dominique slice. See text for discussion.

Comparaison with the Highgate Springs slice

The sole thrust of the slice is not exposed in the Saint-Dominique area. In order to better understand the nature and characteristics of such a basal thrust fault, a comparison is made with the correlative Highgate Springs slice in Vermont. The basal thrust of this slice (referred to as theHighgate Springs Thrust) is well exposed in a quarry near Swanton (Fig. 2), where thickly bedded dolostone of the lower Beekmantown Group are thrust over calcareous shales. Along the footwall of the Highgate Springs Thrust, the vergence of NNE-trending mesoscopic folds and the sense of apparent movement on slickenlines along thrust faults and related bedding-parallel veins are all consistent with a transport direction toward the WNW. These structures are cut by N- and WNW-dipping normal faults (Séjourné and Malo, 2007) and by fewer N- to NNE-trending dextral strike-slip faults. The same brittle structures are recognized in the hanging wall. The Highgate Springs Thrust plane itself is sharp and gently undulating, and locally associated with lenses of intensely foliated dolostone tectonically imbricated with shale. The slice is overlain to the east by allochthonous rocks along a major thrust fault marking the Champlain Thrust in Vermont.

NATURE OF FLUIDS IN THE SAINT-DOMINIQUE SLICE

Families of structural cements

The fluid flow within the Saint-Dominique slice was investigated through a detailed study of fluid inclusions and geochemical analyses ($\delta^{18}O_{VPDB}$, $\delta^{13}C$ and $^{87}Sr/^{86}Sr$) of calcite, dolomite, and quartz cements that seal veins and faults (Séjourné, 2007). Herein, these cements where associated to structural features are called structural cements. Four distinct families of structural features are recognized. (1) Contractional structural features include thrust faults and veins associated to folding (bedding-parallel veins, non-bedding-parallel veins parallel and perpendicular to fold axis). (2) Extensional structural features comprise normal faults and related veins. (3) Strike-slip fault structural features are associated to front-parallel strike-slip faults. (4) Post-Mesozoic features include veins that crosscut Mesozoic dykes and sills. The contractional structural features were developed during the Saint-Dominique slice imbrication whereas extensional structural features occurred at the end of the imbrication. The last two families of structural features are clearly post-imbrication. Chronological development of structural features is summarized on Figure 9. Crosscutting relationships between these structural features, as well as with Mesozoic dykes and sills, will help to better constrain the evolution of fluid flow through time (Fig. 9).

The petrographic (conventional and cathodoluminescence microscopy) characteristics of the structural cements (calcite, dolomite, quartz) are summarized in Table 1. Sphalerite, pyrite and migrabitumen, which are often observed in structural cements, are shown on the general paragenetic sequence of the structural cements (Fig. 10). The development of structural cements is also shown in relation to tectonic stylolites (corresponding to regional cleavage).

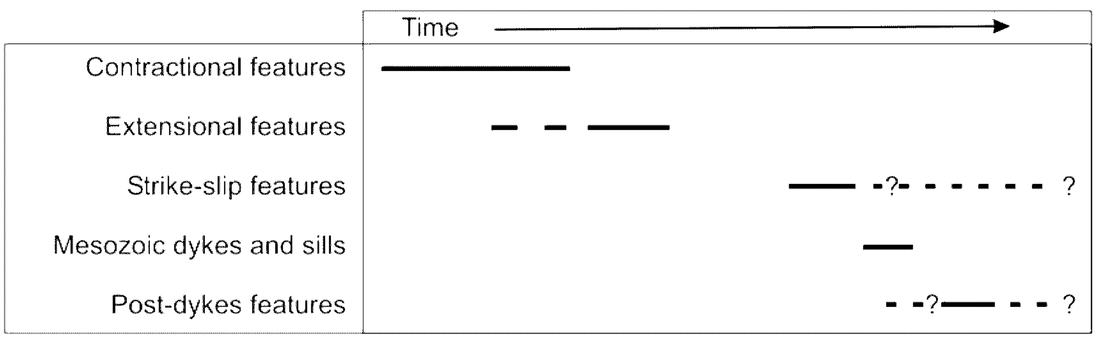


Figure 9. Crosscutting relationships between the main structural features documented in the Saint-Dominique slice. The horizontal axis corresponds to time. The relative chronology between strike-slip features and Mesozoic intrusive rocks is established in one case only where a strike-slip fault is crosscut by a sill, and it is possible that some structures be younger.

Fluid inclusions

Fluid inclusion assemblages were studied mainly in quartz cements (Figs. 11, 12). In carbonate cements, fluid inclusions are numerous but very small (≤2 µm), and only a few of them were analyzed. Two types of fluid inclusion assemblages were observed (Fig. 10): aqueous and gaseous (with methane).

Homogenization temperatures (Th) in structural cements along fault planes in the Trenton Group decrease from the reverse (Th = 178.5–235.9°C; Fig. 12a) to the normal (Th = 145.9–155.8°C: Fig. 12a), and the strike-slip faults (Th = 74.8–292.3°C; Fig. 12a). The salinities first decrease from the reverse faults (1.4–9.1 wt. % eq. NaCl; Fig. 12a) to the normal faults (1.7–3.4 wt. % eq. NaCl; Fig. 12a), and increase in structural cements along strike-slip faults (6.9–11.6 wt. % eq. NaCl; Fig. 12a). Fluid inclusions in the structural cement along a normal fault in the Beekmantown Group show similar values to those in the Trenton Group (Th = 128.8–184.3 °C, and salinities between 0.4–6.0 wt. % eq. NaCl; Fig. 12a).

Fluid inclusions from two bedding-parallel veins in the Trenton Group show salinities (3.1–6.0 and 5.0–8.5 % eq. NaCl; Fig. 12a) similar to those of the reverse fault (Fig. 11a), but both bedding-parallel veins show distinct Th (228.6–245.3°C, and 161.0–187.3°C; Fig. 12a) which are also distinct from those of the reverse fault (Th = 178.5–

235.9°C; Fig. 12a). Th of the sampled contractional vein in the Trenton Group (Th = 164.2–168.8°C; Fig. 12a) is similar to the Th of one of the two bedding-parallel veins, whereas salinities are lower (1.6–2.6% eq. NaCl; Fig. 12a). Fluid inclusions of both studied extensional veins in the Trenton Group show Th (150.0–165.5°C; Fig. 12a) similar to those from the normal faults (Fig. 12a), but the salinities are higher (4.6–5.3% eq. NaCl; Fig. 12a). Finally, fluid inclusions from one vein crosscutting a Mesozoic dyke show a Th between 154.3 and 178.4°C with salinities ranging between 6.4 and 13.4% eq. NaCl (Fig. 12a).

Structural feature		Conventional microscopy: Calcite	Conventional microscopy: Dolomite	Conventional microscopy: Quartz	Cathodoluminoscopy: Calcite	Cathodoluminoscopy: Dolomite	Cathodoluminoscopy: Quartz	Host rock
Contractional structures	Bedding parallel veins	anhedral to euhedral (1-5 mm) *pyramidal triangular (1-5 mm) fibrous (> 1 mm)	--	subhedral to euhedral (1-5 mm) fibrous or pyramidal (< 5 mm) bladded (1-5 mm)	dull (sometimes zoned or composite)	--	non-luminescent	microsparite dull to luminescent quartz non-luminescent isolated dolomite crystals zoned and luminescent
	Non-bedding parallel veins	anhedral (< 1 mm) subhedral to euhedral (> 5 mm)	anhedral (< 1 mm)	euhedral (< 1 mm to > 5 mm)	dull (sometimes zoned or composite)	dull	non-luminescent	
	Reverse faults	euhedral (> 5 mm)	--	subhedral to euhedral (1-5 mm)	dull	--	luminescent	
Normal faults Tension gashes		subhedral (< 5 mm) anhedral (> 5 mm)	--	subhedral to euhedral (1-5 mm) (associated with the subhedral calcite)	very dull and composite (some isolated, non-luminescent crystals)	--	luminescent	
Strike-slip faults		euhedral (> 5 mm) subhedral (< 5 mm)	euhedral (> 5 mm)	subhedral to euhedral (1-5 mm) (associated with the subhedral calcite)	dull	dull	luminescent	
Post-dyke veins		--	euhedral (1-5 mm) subhedral (1-5 mm)	euhedral (1-5 mm) (associated with the euhedral dolomite)	--	dull	luminescent	

Table 1. Petrographical characteristics of the structural cements and their host rock (*: Chazy Group only). Terminology adapted from Savard and Bourque (1989).

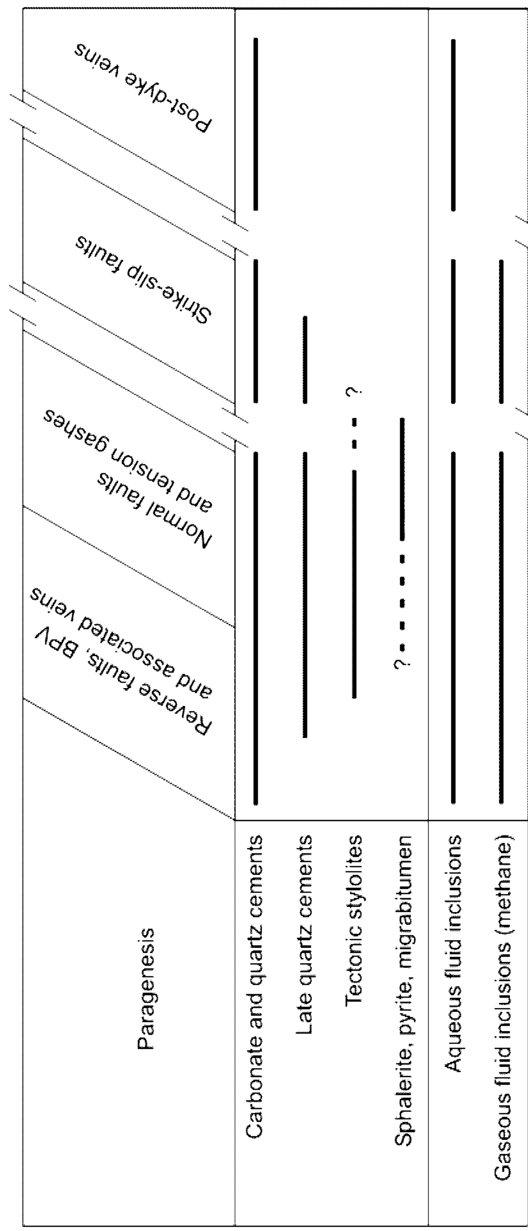


Figure 10. Crosscutting relationships between the main families of petrographic cements within each set of structural features. The horizontal axis corresponds to relative time. No evidence is available to constrain the timing of the onset of stylolitisation and the end of hydrocarbon- and sulfide-bearing fluids circulation. The order of appearance deduced for the fluid inclusions is shown for comparison purpose. BPV: Bedding-parallel vein.

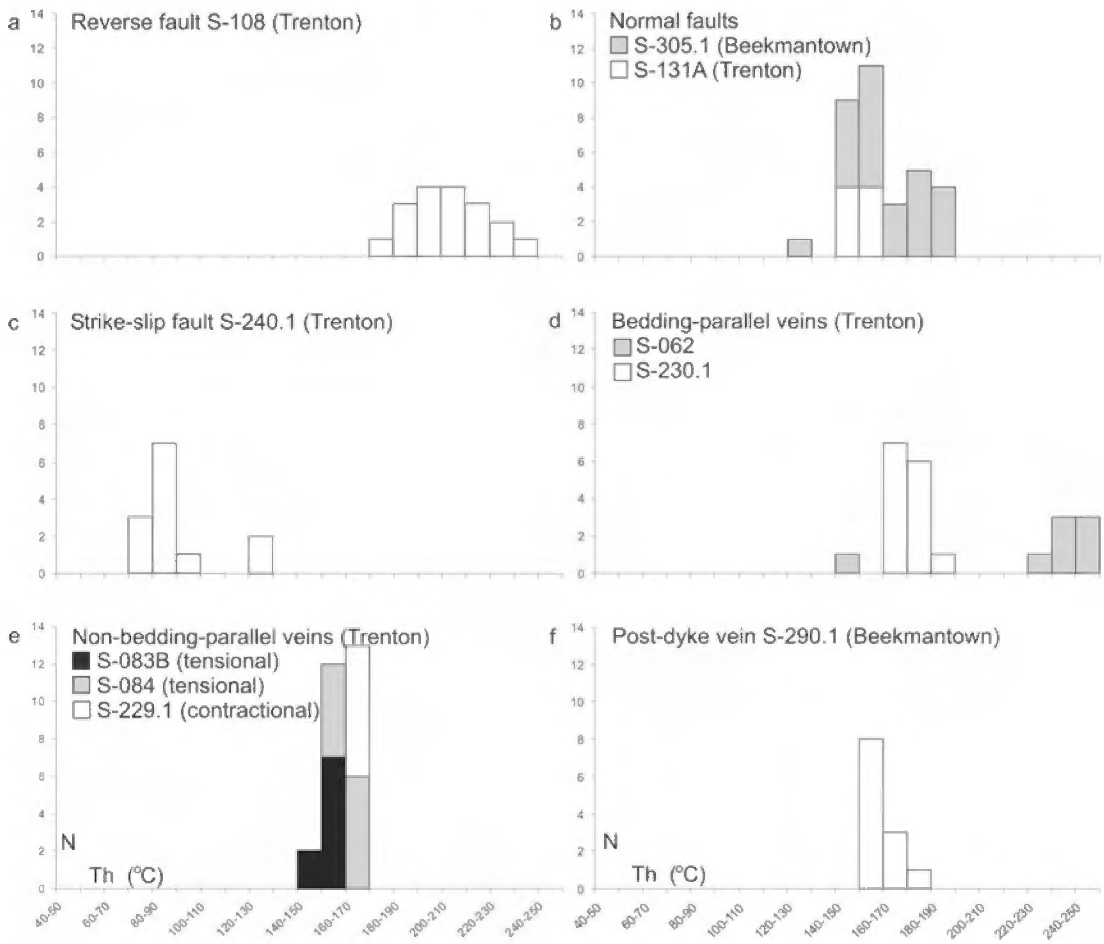


Figure 11. Homogenization temperatures (Th) measured for ten samples of quartzic structural cements in the Beekmantown and Trenton groups (except (b): quartzic and calcitic cements).

Geochemistry

Calcitic and dolomitic structural cements and host rock were analyzed for $\delta^{18}O_{VPDB}$, $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ isotopic ratios. Four major conclusions can be drawn from the comparison of the $\delta^{18}O_{VPDB}$ and $\delta^{13}C$ isotopic ratios for the calcitic structural cements and their host rock (Figs. 13, 14): (1) Compared to the Trenton Group, cements from the Beekmantown and Chazy groups show a great variability in their $\delta^{13}C$ ratios regardless of the nature of the structural feature investigated. (2) For a particular type of structural feature, the $\delta^{18}O_{VPDB}$ and $\delta^{13}C$ isotopic ratios vary accordingly (enrichment or depletion in heavy isotopes). (3) Within a stratigraphic group, the stable isotopes of the contractional and extensional structural features are superposed. (4) The stable isotopes of the strike-slip faults cements, although in part superposed over those of the contractional and extensional structural features, are characterized by a greater variability for the Chazy Group and a lack of variability for the $\delta^{13}C$ ratios in the Trenton Group. Based on field- and microscopic-scale crosscutting relationships, a general trend toward an enrichment in ^{18}O and ^{13}C is established for the progressively younger structural cements of Chazy and Trenton groups (Fig. 15). This unusual trend differs from the classical burial diagenesis evolution and its implications will be addressed later in the discussion.

$^{87}Sr/^{86}Sr$ isotopic ratios do not vary much for the structural cements of the Trenton Group and are similar to those of the host rock and the reference marine values (Fig. 16). In contrast, for the Beekmantown and Chazy groups, the $^{87}Sr/^{86}Sr$ ratios differ significantly from those of the host rocks and reference marine values, and display a greater variability for the Beekmantown Group compared to the Chazy Group. These variations from one stratigraphic group to the other echo the differences highlighted for the stable isotopes. The only exception noticed concerns the dolomitic cements of two post-dyke veins sampled in the Beekmantown and Trenton groups, which display similar $^{87}Sr/^{86}Sr$ ratios.

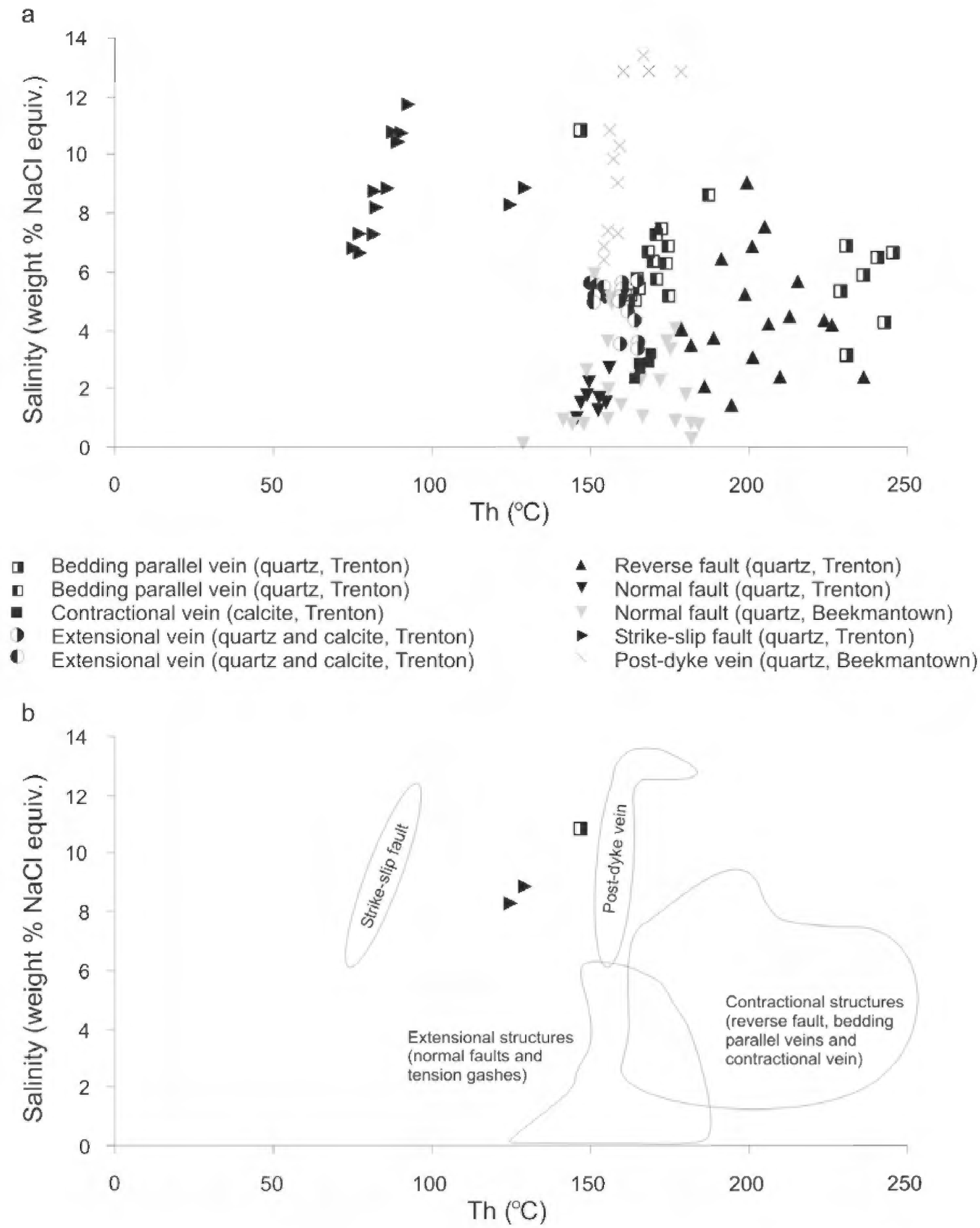


Figure 12. (a): Crossplot diagram correlating the measured homogenization temperatures (Th) and calculated salinities for ten samples of structural cements (Beekmantown and Trenton groups). (b): Corresponding fields for the main structural families (three samples show atypical values).

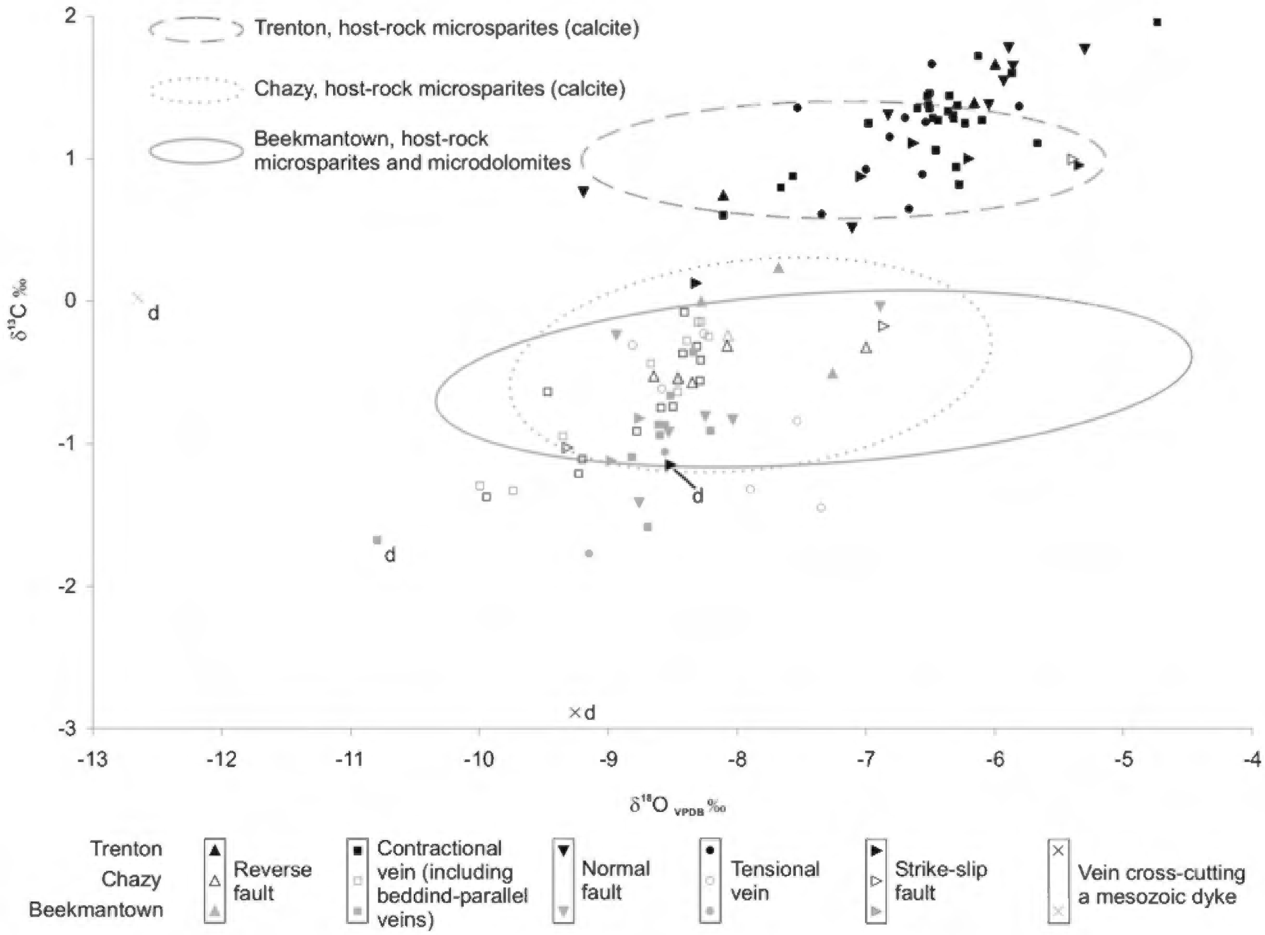
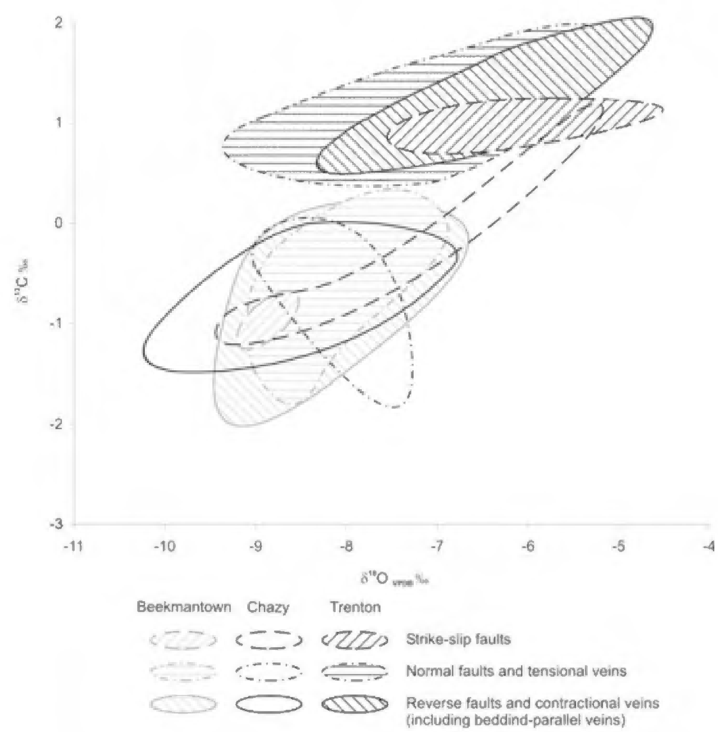


Figure 13 (above). Oxygen and carbon stable isotopic ratios for the structural cements in the Saint-Dominique slice, and ratios for the host-rock microsparites and microdolomites for the corresponding stratigraphic groups. All structural cements are calcitic except (d): dolomitic.

Figure 14 (right). Comparison of the oxygen and carbon isotopic ratios for the structural cements sampled in the Saint-Dominique slice. Refer to Figure 13 for the detail of the values.



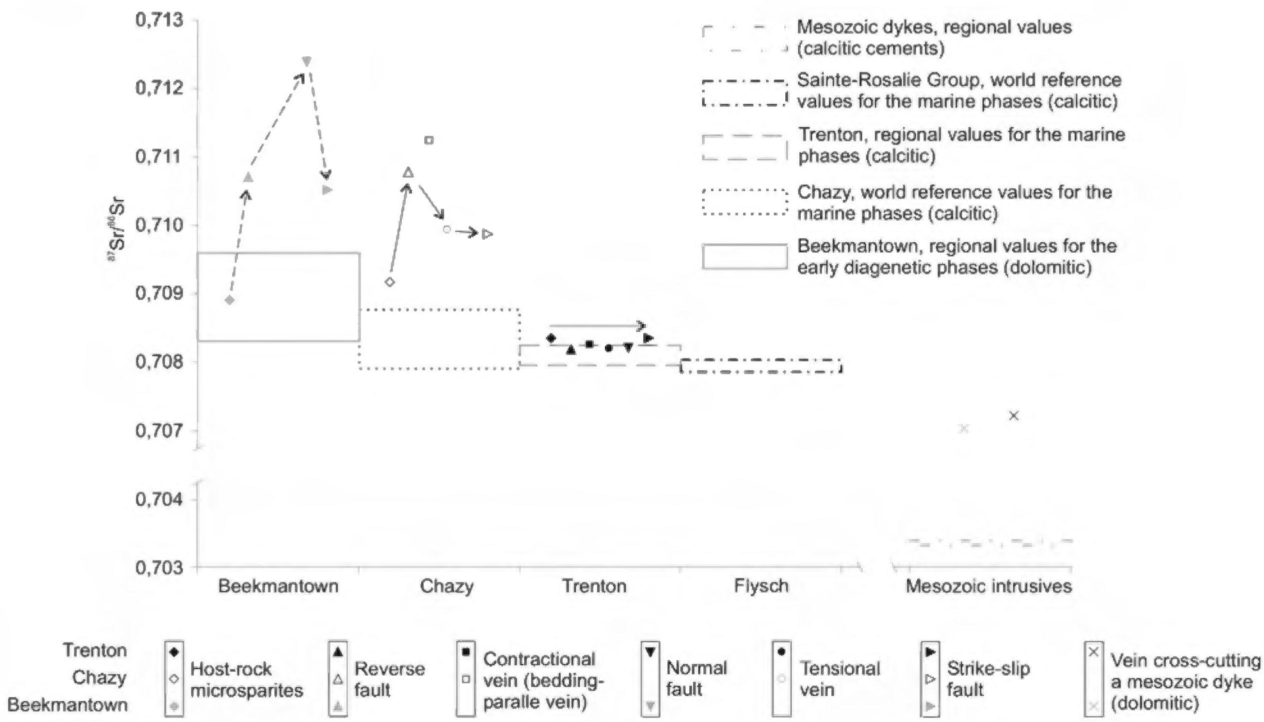
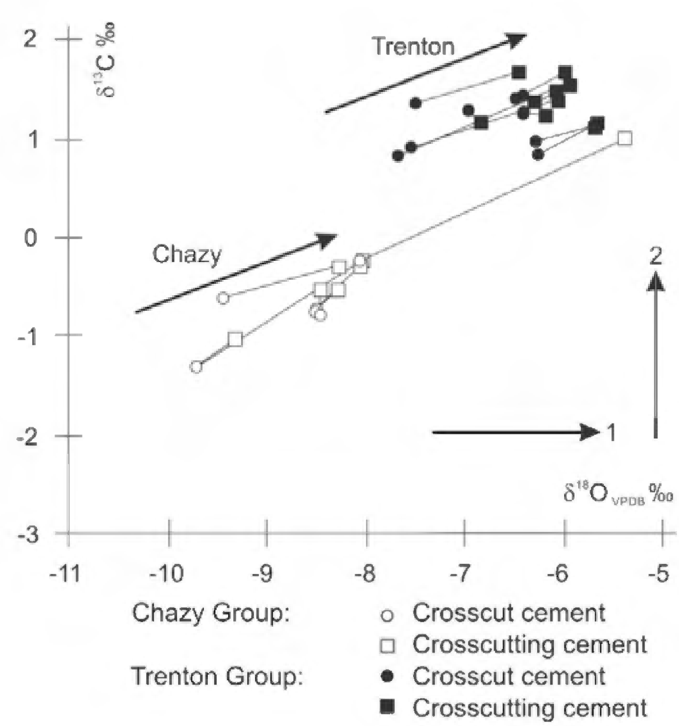


Figure 15 (right). Evolution of geochemical characteristics with relative timing of structural cements, as based on macro- and microscopic cross-cutting relationships. Arrows illustrate the possible mechanisms responsible for the observed variations: (1): introduction of a fluid with higher salinity or oxygen isotopes fractionation due to a temperature drop; (2): in-situ selective enrichment in ^{13}C by methanogenesis during early diagenesis or burial after the oil window stage, or, alternatively, precipitation from carbonate-derived, isotopically heavier fluids.

Figure 16 (above). Strontium isotopic ratios for the structural cements and their host-rock in the Saint-Dominique slice, along with published reference values for the corresponding stratigraphic groups. Arrows show the relative chronology of the studied structures. All cements are calcitic except where mentioned otherwise in the caption.



Nature of the fluids

For the host rock, the close relationship between the measured $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ isotopic ratios (and part of the $\delta^{18}O_{VPDB}$ ratios) and the published reference values for marine calcites and early diagenetic dolomites indicates that most of the cements analyzed in the host rock precipitated from a fluid whose chemistry was close to, or evolved from, seawater. Based on O'Neil et al. (1969) and Land (1983) equations, respectively for calcites and dolomites, the $\delta^{18}O_{VSMOW}$ of the parent water is estimated using an average 15°C precipitation temperature for seawater. The calculated ratios (Table 2 and Fig. 17) are in good agreement with those of the reference values for each stratigraphic group: -9.6 to -8.4‰ (-8.8‰ average) and -10.0 to -8.7‰ (-9.2‰ average) respectively for the early dolomites and the calcites of the Beekmantown Group; -7.0‰ for a unique sample in the Chazy Group and -7.5 to -6.2‰ (-7.2‰ average) for the limestones in the Trenton Group. Slightly lower $\delta^{18}O_{VPDB}$ ratios measured for some calcitic and dolomitic cements can be explained by precipitation or recrystallization during shallow burial. Using the equations above and the average $\delta^{18}O_{VSMOW}$ calculated for seawater, the burial temperature can be estimated for these late carbonate phases: 51, 44 and 31°C, respectively for the Beekmantown, Chazy and Trenton groups.

The influence of four distinct fluids (evolved seawater, basinal, metamorphic and magmatic fluids; Table 2) is recognized in the structural cements based on the fluid inclusions data, the isotopic values and the equations of O'Neil et al. (1969) and Land (1983). The influence of the evolved seawater is best preserved in the structural cements sampled in the Trenton Group. It is evidenced by the average salinity of 3 wt. % eq. NaCl calculated for some fluid inclusions assemblages and the similarity between the measured $^{87}Sr/^{86}Sr$ ratios for structural cements, host rock and reference marine values. The influence of the basinal fluid is evidenced for some fluid inclusions assemblages that display high salinity values (up to 9.1 wt. % eq. NaCl). The metamorphic fluid is recognized through the high $\delta^{18}O_{VSMOW}$ values (Sheppard, 1986) calculated for the parent fluids of the contractional and extensional cements in the Beekmantown and Trenton groups (between +10.0 and +15.2‰, Fig. 17). This influence is also documented in some fluid inclusions assemblages that display particularly low salinity values (as low as 0.2 wt. % eq. NaCl, Fig. 12). Although such low salinities generally correspond to meteoric fluids, they are also compatible with metamorphic fluids (Hoefs, 1987; Yardley and Graham, 2002). Finally, a magmatic fluid associated with the strike-slip faults and the post-dyke veins is evidenced through fluid inclusions assemblages with high salinities (up to 13.4 wt. % eq. NaCl) and unusual $\delta^{18}O_{VPDB}$, $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ ratios, that are intermediate between the ratios measured for older cements (host rock, pre- and late-imbrication structures) and the ratios measured for Mesozoic carbonatites (Deines and Gold, 1969; Grünenfelder et al., 1986; Carignan et al., 1997).

Type of fluid	Host Group	Salinity (% NaCl equiv.)	Temperature (°C)	$\delta^{18}O_{VSMOW}$ (‰)	$\delta^{13}C$ (‰)	$^{87}Sr/^{86}Sr$
Evolved sea water	Trenton (calcitic cements)	«2,1 to 4,2»	147 to 236	«-8,2 to -6,2»	+0,6 to +1,7	0,70834
	Chazy (calcitic cements)			«-7,9 to -7,0»	-1,9 to +1,0	0,70917
	Beekmantown (calcitic cements)			«-10,0 to -8,7»	-2,2 to -0,7	0,70892
	Beekmantown (dolomitic cements)			«-12,1 to -11,0»	-1,7 to -1,0	(0,70892)
Bassinal fluid	All	«5,0 to 9,1»	150 to 245	und.	und.	und.
Metamorphic fluid	All	«0,2 to 0,4»	129 to 194	«+10,0 to +15,2»	und.	(> 0,715682)
Magmatic fluid	Beekmantown and Trenton	«12,8 to 13,4»	160 to 178	«+2,6 to +6,7»	-5,9 to -3,9	0,70330 to 0,70335

Table 2. Synthesis of the main characteristics of the four fluids identified from microthermometric and isotopic data. The temperature intervals (T_h) correspond to the maxima and minima measured for the structural cements and do not necessarily reflect the temperature of the fluids before the onset of deformation. All values are measured except: und: undetermined, «...»: calculated, (...): deduced from data (and considered as minimum), ...: taken from Deines and Gold (1969) and Grünenfelder et al. (1986).

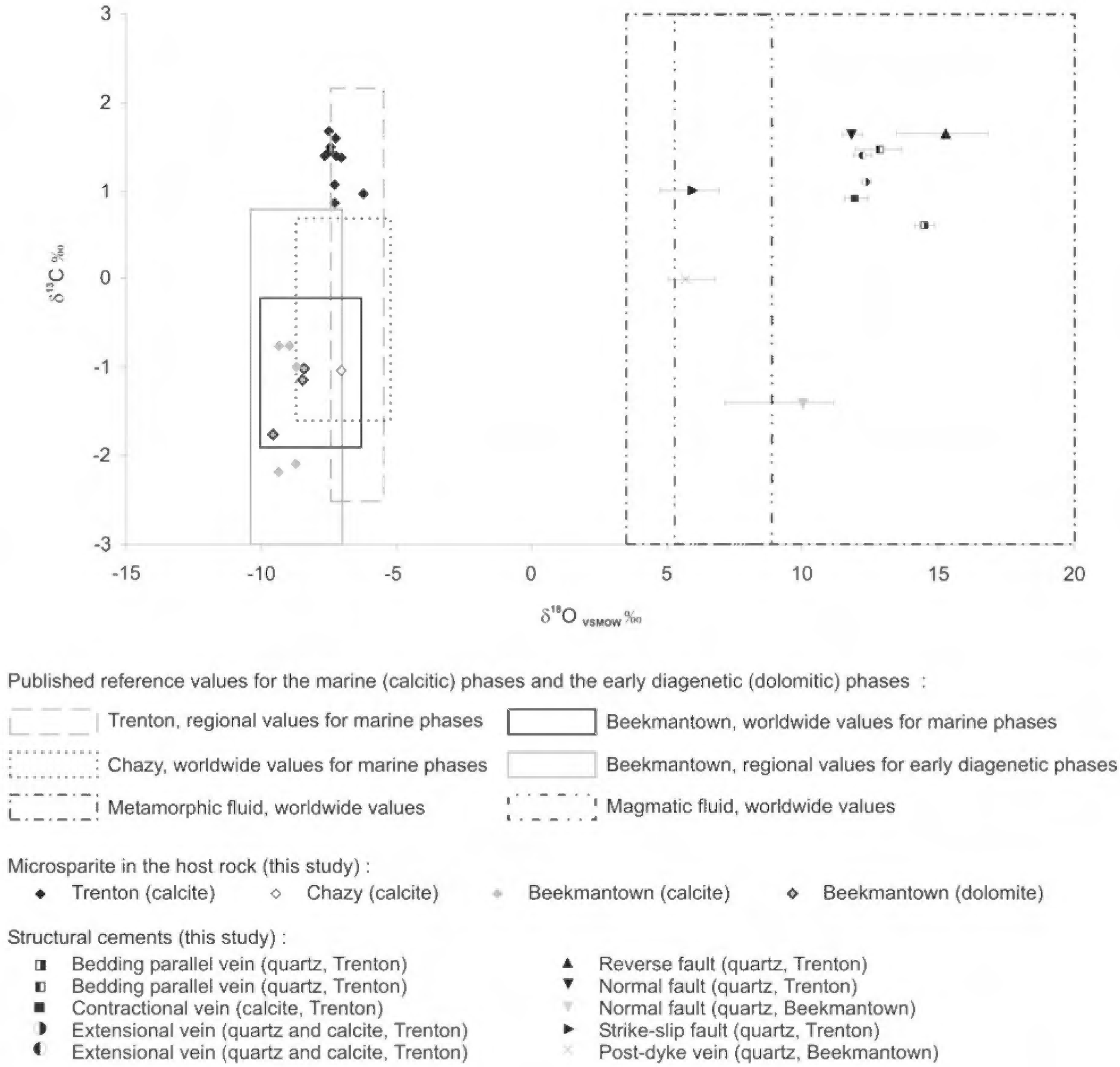


Figure 17. Isotopic characteristics of the parent fluids for the analyzed cements. The $\delta^{18}O_{vsmow}$ ratios of the parent fluids for the microsparites in the host rock are estimated for seawater at 15°C; Th and mean Th measured from fluid inclusions were used to estimate the isotopic ratios of the parent fluids for structural cements. Refer to Séjourné (2007) for the sources of the reference values.

Discussion

The petrographical analysis of structural cements sampled in the Saint-Dominique slice reveals that most of the cements are calcitic or dolomitic, but are often associated with small amounts of contemporaneous quartz. A late quartz phase is also documented.

Analysis of fluid inclusions and isotopic ratios of the structural cements show that basinal and metamorphic fluids mixed with the residual, evolved seawater during imbrication. Introduction of these exotic fluids must coincide with a progressive decrease of temperature during tectonic uplift to explain the covariation between $\delta^{18}O_{VPDB}$ and

$\delta^{13}C$ ratios. Finally, a fluid of magmatic origin, associated to the Mesozoic intrusions, percolated through the carbonate slice and mixed with the residual fluids to precipitate the cements that sealed the youngest structural features (typically the front-parallel strike-slip faults). This observation suggests that those strike-slip faults most probably developed during the Mesozoic.

The investigation also shows that hydrocarbon maturation in the study area took place in two stages (pre- and post-imbrication). During the pre-imbrication episode of maturation, liquid hydrocarbons were cracked into methane as only methane is preserved in the syn- to late-imbrication structural cements. In turn, migrabitumen are documented in stylolites crosscutting these cements but are absent from the latest structures, thus indicating that the second episode of maturation took place between Silurian and Mesozoic.

Finally, the data collected allow to establish the geological basis of the diagenetic evolution of the Saint-Dominique slice throughout its structural evolution and help refining and clarifying the general diagenetic evolution of the carbonate slices that was only constrained by regional (thermal maturation) and local studies (cores from the Saint-Flavien slice). The general tectonic and diagenetic (fluid flow) evolution of the carbonate slices in southern Quebec is outlined in the following section.

STRUCTURAL AND DIAGENETIC EVOLUTION OF THE SAINT-DOMINIQUE SLICE

Pre-orogenic evolution

Structure. The tectonodiagenetic history of the carbonate slices began long before the Taconian Orogeny, with the deposition of platformal strata over the Grenvillian basement during Cambrian and Ordovician. Tectonism at that time was mostly characterized by the development and reactivation of basement-involved normal faults, which continued at least till the deposition of syn-orogenic flysch strata during late Ordovician (approximately 450 Ma). Although only one syn-sedimentary normal fault was documented in the Saint-Dominique slice (Fig. 7c), similar structures are recognized in the autochthonous domain at surface (St-Julien, 1982; Mehrtens, 1988a, 1988b; Lavoie, 1994) and subsurface investigations confirmed that the general architecture of the St. Lawrence platform before its imbrication was defined by graben and half graben fault systems linked by oblique normal faults (SOQUIP, 1982, 1984; St-Julien et al., 1983; Séjourné et al., 2003; Castonguay et al., 2006). The orientation and location of these faults are in part responsible for the geometry and compartmentalization of the slices because either (1) normal faults were reactivated in strike-slip or reverse faults, (2) they isolated fault-blocks with variable sizes and thicknesses, or (3) they acted as ramps during thrust propagation. Their effect is documented at the outcrop-scale south of the study area in the Vermont and New York states (Hayman and Kidd, 2002), as well as in the Philipsburg slice (Séjourné and Malo, 2007) and to the north-east in the Quebec City area (Diego Rodriguez, Université Laval, Québec, Master thesis in progress). As a consequence, the heterogeneous stratigraphic and structural morphology of the margin before the onset of the imbrication is one of the major causes that explain the final architecture of the carbonate slices.

Diagenesis. The diagenetic evolution of platform rocks prior to their imbrication essentially corresponds to the classic evolution of a sedimentary basin, but is also strongly influenced by the development of the Appalachian orogen. In particular, stacking of the thrust sheets in the hinterland was associated with the propagation of a peripheral bulge in the foreland during middle Ordovician (Jacobi, 1981; Bradley and Kidd, 1991; Dix and Al Rohdan, 2006) and karstification took place locally through the circulation of meteoric fluids (Fig. 18a; Paradis and Lavoie, 1996; Chi et al., 2000; Kirkwood et al., 2000; Bertrand et al., 2003; Paradis et al., 2004). Tectonic burial in the hinterland began at the onset of the Taconian Orogeny. Hot, saline and reducing basinal fluids were then tectonically expelled from the orogen and contributed to the porogenesis in foreland basin strata through thermochemical reduction of sulfides and to the development of MVT deposits (Tassé and Schrijver, 1989; Héroux and Tassé, 1990; Paradis and Lavoie, 1996; Paradis et al., 2004). Such phenomena are documented in the autochthonous domain throughout southern Quebec and in south-eastern Ontario (Dix et al., 1998; Dix and Robinson, 2003), as well as in the thrust-imbricated Saint-Flavien and Upton carbonate slices (Paradis and Lavoie, 1996; Bertrand et al., 2003; Paradis et al., 2004). Along with the earlier migration of the peripheral bulge, it is plausible that the horst and graben architecture of the basin was in part responsible for the location of the meteoric water input zones and for the circulation of the basinal fluids (through the compartmentalization or juxtaposition of aquifers and seals along normal faults). Therefore, the early diagenetic evolution of the future carbonate slices is in part linked to the initial architecture of the basin.

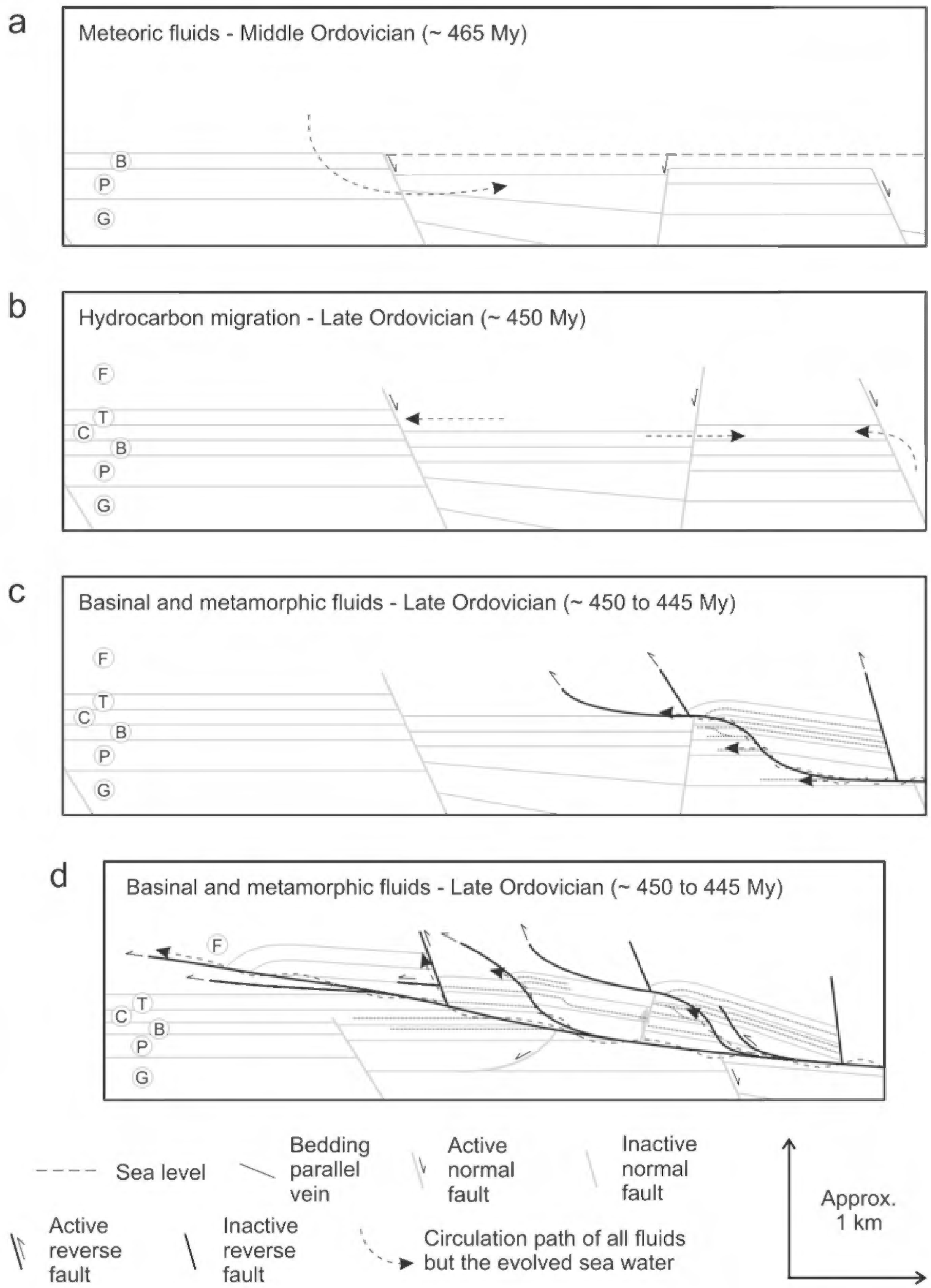
Poronecrosis is also a major phenomenon in the diagenetic evolution of the carbonate slices. This phenomenon mainly took place during burial (middle to late Ordovician) and rapidly prevented the circulation of exotic fluids so that the evolved seawater was preserved in the host rock till the onset of imbrication, as is the case in the Saint-Dominique slice (Table 2).

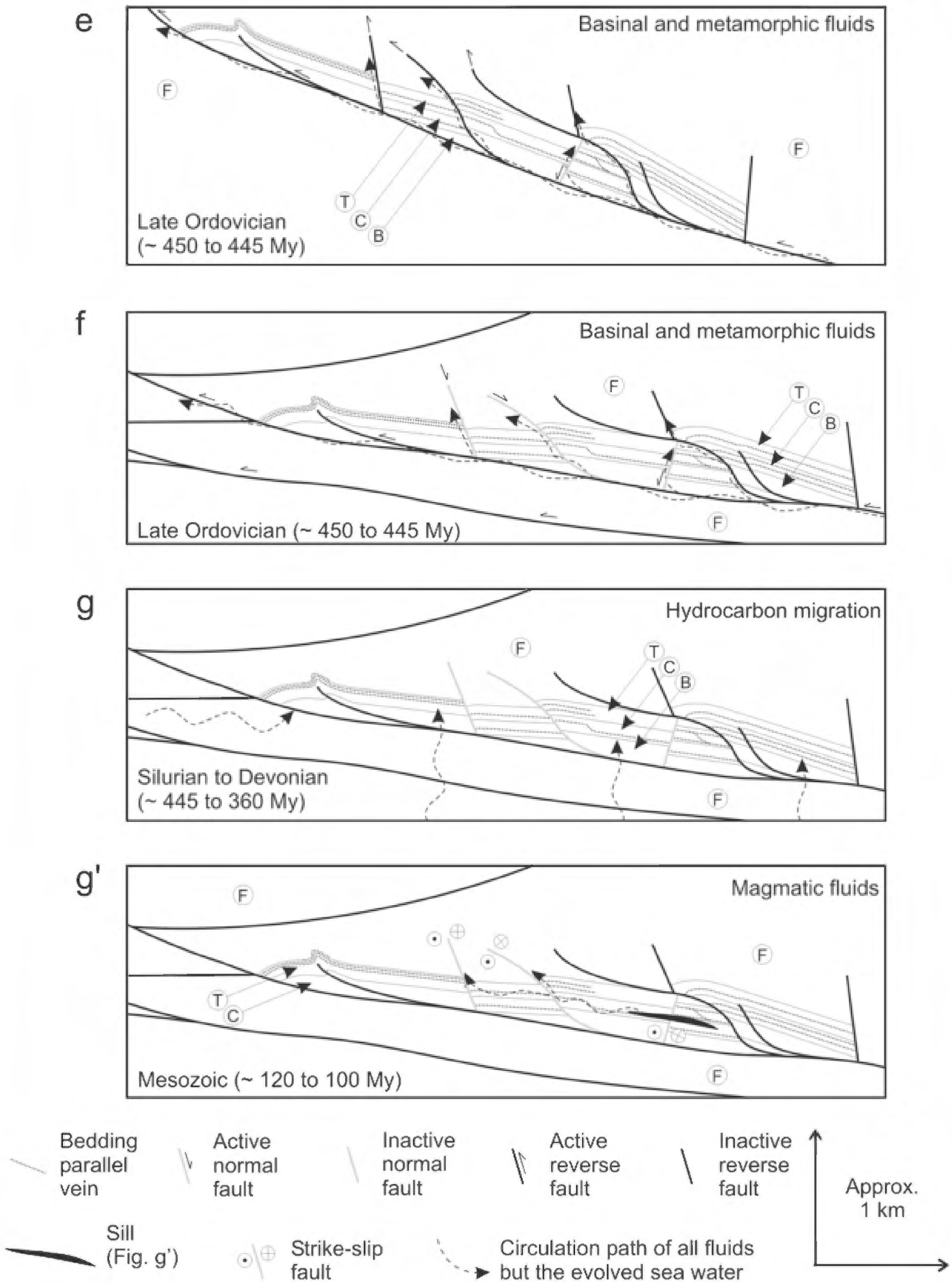
Most of the organic matter maturation also took place during sedimentary and tectonic burial before the imbrication (Héroux and Bertrand, 1991; Bertrand and Lavoie, 2006). In the case of the Saint-Dominique slice, maturation reached the level of dry gas to anchizone (Yang, 1991). Liquid hydrocarbons generated before this stage (Fig. 18b) were then cracked before they could migrate through the fracture network, as only methane is preserved and found in fluid inclusions in the structural cements.

Syn-orogenic evolution

Structure. Field investigation revealed the tectonic evolution of the Saint-Dominique slice. Combined to the results of past regional seismic interpretations (Laroche, 1983; Séjourné et al., 2003; Castonguay et al., 2006) and to published data for the Saint-Flavien and Philipsburg slices (Malo et al., 2001a, 2001b; Bertrand et al., 2003; Séjourné and Malo, 2007), these observations allow to define a common model for the structural evolution of the carbonate slices in southern Quebec during the Taconian Orogeny (late Ordovician, between 450 and 445 Ma, Figs. 18c-f). The general structure of the slices is dominated by long basal décollement planes and by hinterland-dipping duplexes. The internal structure is complex and reflects multiple episodes of deformation. The onset of the deformation, before the actual imbrication, corresponds to the development of cleavage and bedding-parallel veins. It is followed by thrust and tear faults and by shear veins that are not parallel to bedding. Folding and thrusting are also responsible for the reactivation and neoformation of bedding-parallel veins. Overthrusting by thrust sheets, the imbrication itself, folding and episodic stress relaxation are responsible for the development of tension gashes, newly formed normal faults, and the negative inversion of reverse faults (Fig. 5a) during and after imbrication. The original architecture of the slices, already compartmentalized by inherited normal faults, is therefore overprinted by the superposition of contractional and extensional structures. Mutual crosscutting relationships between those two structural families are particularly obvious in the Saint-Dominique and Saint-Flavien slices (Chalaron and Malo, 1998; Bertrand et al., 2003; Séjourné and Malo, 2007).

Figure 18 (next two pages). Schematic cartoon illustrating the structural evolution and associated fluid flow of a platform carbonate slice imbricated along the southern Quebec Appalachian thrust front. (a): After deposition of Beekmantown Group rocks, local subaerial exposure favors the percolation of meteoric water in the platform strata. (b): Following the drowning of the platform and deposition of Chazy to Lorraine groups rocks, progressive burial lead to organic matter maturation and hydrocarbon migration from the top of the Trenton Group and the Utica Shale (the main undifferientated flysch unit; Fig. 3) into the platform strata. (c): The onset of imbrication is characterized by folding, thrusting, veining parallel to bedding, and by the inversion of normal faults. For clarity purpose, contemporaneous veins that are not parallel to bedding, tectonic stylolites and cleavage are not shown on this figure. Metamorphic and basinal fluids circulate in the carbonate slice through the thrust fault planes and mix with the evolved seawater preserved in the host rock. (d): Continuous imbrication, development of previously mentioned structures and development of normal faults during stress relaxation. (e): Continuous imbrication and progressive drop in temperature during tectonic uplift. (f): Last phase of imbrication, mostly characterized by stress relaxation and development of normal faults (either newly formed or through negative inversion of reverse faults). (g): Burial below the post-orogenic sediments (possibly during Devonian times) and organic matter maturation in the autochthonous domain. Migration of the hydrocarbons into the carbonate slice through stylolites and cleavage planes. (g'): intrusion of Mesozoic dykes (not shown) and sills, and reactivation of weakness planes (typically, the normal and reverse faults) in a strike-slip motion. Magmatic fluids mix with residual fluids along the strike-slip fault planes. G: Grenvillian basement, P: Potsdam Group, B: Beekmantown Group, C: Chazy Group, T: Black River and Trenton groups, F: undifferentiated flysch (Utica Shale, Sainte-Rosalie Group, Lorraine Group), M: molasse (Queenston Group), N: undifferentiated Taconian nappes.


a
Meteoric fluids - Middle Ordovician (~ 465 My)
B
P
G
b
Hydrocarbon migration - Late Ordovician (~ 450 My)
F
T
C
B
P
G
c
Basinal and metamorphic fluids - Late Ordovician (~ 450 to 445 My)
F
T
C
B
P
G
d
Basinal and metamorphic fluids - Late Ordovician (~ 450 to 445 My)
F
T
C
B
P
G
Sea level
Bedding parallel vein
Active normal fault
Inactive normal fault
Approx. 1 km
Active reverse fault
Inactive reverse fault
Circulation path of all fluids but the evolved sea water



e
Basinal and metamorphic fluids
F
F
T
C
B
Late Ordovician
(~ 450 to 445 My)
f
Basinal and metamorphic fluids
F
T
C
B
F
Late Ordovician (~ 450 to 445 My)
g
Hydrocarbon migration
F
T
C
B
Silurian to Devonian
(~ 445 to 360 My)
F
g'
Magmatic fluids
F
F
T
C
Mesozoic (~ 120 to 100 My)
F
Bedding parallel vein
Active normal fault
Inactive normal fault
Active reverse fault
Inactive reverse fault
Approx. 1 km
Sill (Fig. g')
Strike-slip fault
Circulation path of all fluids but the evolved sea water

Based on seismic interpretation in the vicinity of the study area (Séjourné et al., 2003), development of major thrust faults started to the east and propagated toward the Laurentian margin in a piggy-back sequence. The same sequence of thrusting is also documented in southern Quebec at a larger scale (St-Julien and Hubert, 1975; Lebel and Kirkwood, 1998). Out-of-sequence thrusts are also documented in the parautochthonous domain (but not in the Saint-Dominique slice) in southern Quebec (Comeau et al., 2004; Castonguay et al., 2006; Séjourné and Malo, 2007) and in New England (Bosworth et al., 1988; Stanley et al., 1999; Hayman and Kidd, 2002). The relative timing of the out-of-sequence thrusts is not known. They could possibly reflect the continuous activation of thrust fault planes at the rear of the Taconian front, or alternatively be linked to the Devonian Acadian Orogeny.

Diagenesis. The onset of the deformation and subsequent imbrication of the carbonate slices started during burial at a relatively high temperature (at about 6.2 km and 245°C in the case of the Saint-Dominique slice; Fig. 11) and coincide with the circulation and mixing, through fractures (Figs. 18c-18f), of at least two exotic fluids (Table 2 and Fig. 12a): (1) a basinal fluid which had been expelled from the heart of the basin during sedimentary and tectonic burial and (2) a metamorphic fluid, which had most probably been expelled from the deepest part of the basin during reactivation of basement-involved faults. These two fluids are well documented through fluid inclusions from structural cements in the Saint-Dominique slice (Fig. 12a), notwithstanding the buffering effect of the host rock, while only metamorphic fluids are documented in the Saint-Flavien slice (Bertrand et al., 2003).

The imbrication of the slices is accompanied with a progressive diminution in the burial depth and temperature of the system (to 4.1 km and 150°C in the case of the Saint-Dominique slice; Fig. 11). Temperature drop during tectonic uplift does not seem to be unique to the southern Quebec Appalachian, as a similar evolution is established for the Variscan front in France (Kenis et al., 2000) and the Canadian Rockies (Roure et al., 2005).

Post-Taconian evolution

Structure. The progressive denudation that followed the building of the Appalachian orogen and that continues until now was only interrupted by a magmatic episode during Mesozoic (120 to 100 Ma). Dykes and sills documented in the Saint-Dominique slice are contemporaneous of this event. Front-parallel strike-slip faults most probably developed during Mesozoic as well, at an estimated 2.5 km depth. Strike-slip motion is also locally associated to reactivation of bedding-parallel veins. Similar post-Taconian front-parallel strike-slip faults are documented in other carbonate slices, thus emphasizing their importance at a regional scale, from Vermont to the south (Stanley, 1974), and through the Philipsburg slice (Séjourné and Malo, 2007) to the Upton slice in Quebec (Paradis and Faure, 1994). A similar timing is also tentatively interpreted for north-north-east trending strike-slip faults that compartmentalize the Saint-Flavien slice south-west of Quebec City (Séjourné, 2007).

Diagenesis. The cements that seal the structures developed after the end of the Taconian Orogeny (front-parallel strike-slip faults and veins crosscutting the Mesozoic dykes) formed from the residual fluids still present in the host rock, that partly mixed with magmatic fluids (Table 2 and Fig. 12a).

Late- to post-Taconian sedimentary burial related to the erosion of the Appalachian orogen till the Devonian is probably responsible for a second episode of organic matter maturation. This event was mostly restricted to the autochthonous domain (Bertrand and Lavoie, 2006) and had little impact on the carbonate slices, in which organic matter had already reached a mature to supramature level. Yet, liquid hydrocarbons generated in the autochthonous domain migrated into the carbonate slice rocks through stylolites and cleavage planes (Fig. 18g), where they are now found as solid migrabitumen, thus indicating that the second episode of maturation continued after the oil window stage. The Saint-Flavien slice reservoir was probably charged with methane at the same time (Bertrand et al., 2003). Thermal maturation reached a peak before the Mesozoic, as migrabitumen are absent from the front-parallel strike-slip faults.

ACKNOWLEDGEMENTS

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ROAD LOG

From Quebec City, take Autoroute 20 Ouest (West) towards Montreal and leave the highway at Sortie 141 (toward Sainte-Rosalie). Zero your odometer on the bridge and refer to road map (Fig. 19).

0.0 km Exit 141; follow the Route 116 Ouest toward Sainte-Rosalie and Saint-Hyacinthe.
6.4 km In Sainte-Rosalie, turn left at the traffic light on Route 137 Sud.
9.6 km At the traffic light, turn left to follow Route 137 Sud / Avenue Saint-Louis toward Saint-Dominique. On your way, note the tree line and small hill ahead, which mark the limit between the flat-lying, autochthonous lowlands and the parautochthonous Saint-Dominique slice.
15.5 km In the village of Saint-Dominique, Route 137 Sud / Avenue Saint-Louis becomes Route 137 Sud / Rue Principale. The quarries are to the left and the office to the right. Stop at the office of the "Carrières Saint-Dominique" (700, Rue Principale) and ask permission to visit the quarries (stops 1 and 2).

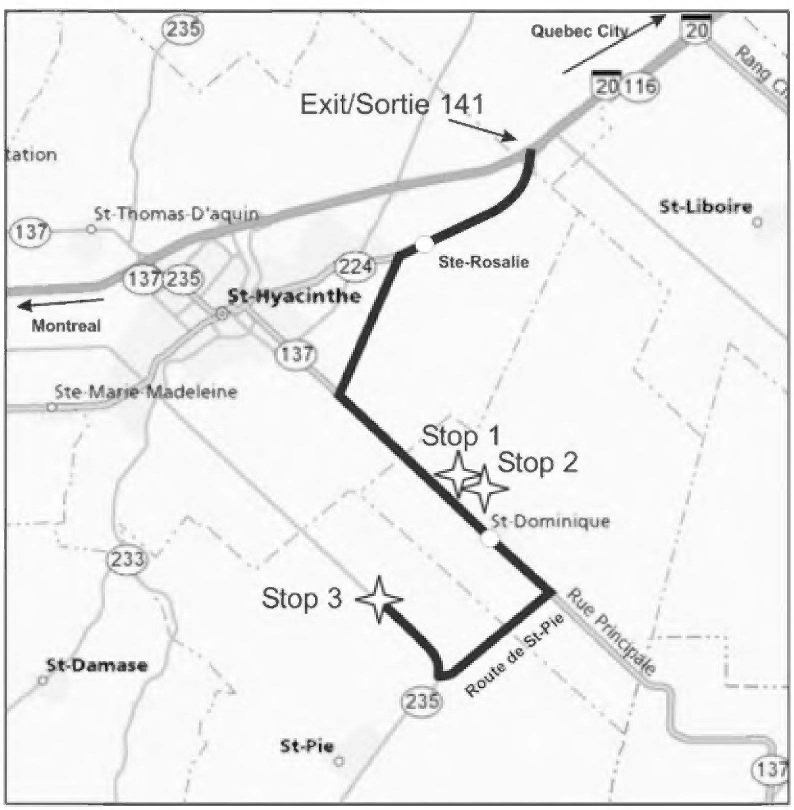

Figure 19. Road map.

STOP 1. Saint-Dominique quarries (northwestern pit)

This quarry pit exposes the Beekmantown Group rocks in a normal sequence, from the Theresa to the Beauharnois formations (lower and upper Beekmantown Group, respectively). The lower Beekmantown is comprised of thick dolostone and dololimestone beds with few shaly interbeds. The upper Beekmantown consists of decimeter-thick beds of limestone, dolostone and lesser sandstone and shale. Refer to figure 4 for location (labeled "Fig. 5a") and to figure 5a for a cross section illustrating the different structural styles characteristic of the lower (Theresa Formation) and upper (Beauharnois Formation) Beekmantown Group. Contractional, extensional and strike-slip structural features are documented in this outcrop. Contractional features are mostly characterized by shallowly dipping thrusts cutting across gently folded strata and by parasitic folds in the few shaly interbeds in the lower Beekmantown (Fig. 7a), while the well bedded upper Beekmantown Group rocks are tightly folded into boxes and chevrons with either east or west vergence, and display a weak cleavage. Extensional features are comprised of numerous veins, either conjugated or in relays, in the southeastern part of the quarry. A major, front-parallel normal fault (based on slickensides) dipping to the hinterland can be followed across the whole outcrop. Note the abnormal stratigraphic offset indicating that this fault reactivated a reverse fault. Several front-parallel strike-slip faults are also evidenced in this outcrop, although they display very little deformation away from the slip plane. Finally, several dykes and a gabbro sill crosscut all previous structural features. Pictures displayed in figures 7a, 7c and 7d were taken from these outcrops but the original models are no longer visible due to continuous activity in the quarry.

STOP 2. Saint-Dominique quarries (south-eastern pit)

This quarry pit exposes the shales and shaly limestones characteristic of the upper part of the Trenton Group (Montreal Formation). Refer to figure 4 for location (labeled "Fig. 5c") and to figure 5c for a cross section illustrating the structural style characteristic of the upper part of the Trenton Group. To ensure consistency with figures 5a and 5b, figure 5c is reversed compared to the actual outcrop orientation. Numerous crosscutting relationships help deciphering the structural evolution of the Saint-Dominique slice. Contractional features are characterized by intense cleavage and solution seams, by high-angle thrust faults that locally anastomose or form imbricate fans, by occasional backthrusts (3 in Fig. 5c), by a major fault-propagation fold, and by numerous bedding-parallel veins developed at various stages. Note that most, but not all, bedding-parallel veins extend across the hinge lines of the folds. Extensional features consist of filled to open tension gashes, normal faults crosscut by thrust faults (1 and 2 in Fig. 5c) and normal faults crosscutting the thrusts. A major, front-parallel strike-slip fault crosscut all previous features (white box on Fig. 5c and Fig. 7b). Bending of strata in the vicinity of the fault and occurrence of tension gashes restricted to the more competent beds suggest an early normal motion. Slickenlines, however, indicate that the last motion, at least, was sub-horizontal. This fault is best visible on the northeastern wall of the quarry. A few dykes are also observed in this outcrop.

LUNCH at Stop 2

0.0 km From the office of the Carrières Saint-Dominique (700, Rue Principale), zero your odometer and continue on Route 137 Sud toward stop 3.
4.2 km From Route 137 Sud, turn right on Route de Saint-Pie.
8.2 km At the second stop, turn right on Route 235 Nord.
11.1 km Stop and park along the road on Route 235 Nord, just past the downward slope. Outcrops are on both sides of the road: watch out for cars and trucks, especially those coming from uphill.

STOP 3. Road 235

From northwest to southeast, this road cut exposes the upper part of the Beekmantown and the contact with the calcareous sandstones at the base of the Chazy Group, the shaly limestones that form the bulk of the Chazy Group, and finally, incomplete sections of the Black River and the Trenton groups. Refer to figure 4 for location (labeled "Fig. 5b") and to figure 5b for a cross section illustrating the structural style characteristic of the Chazy Group. To the northwest, the shaly limestones of upper Chazy Group are cleaved and display thrust ramps and related folds. Bedding-parallel veins developed at various stages of the imbrication are either continuous across the hinge lines or die out in the limbs of the folds. Some also ramp upsection and can be referred to as bedding-parallel thrusts. A moderately dipping front-parallel strike-slip fault is also visible. To the southeast, the Trenton Group rocks are intensely cleaved, and display reverse faults and numerous tension gashes coated with calcite, quartz and saddle dolomite crystals.

END OF THE TRIP

From Stop 3, retrace your steps toward Autoroute 20 Est (East) if you go back to Quebec City, or continue on Route 235 Nord (North) into Saint-Hyacinthe to catch up with Autoroute 20 Ouest (West) if you go towards Montreal.

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CASE OF GROUNDWATER CONTAMINATION BY TCE IN THE VALCARTIER AREA, QUEBEC, CANADA

by

René Lefebvre and Richard Martel, Institut national de la recherche scientifique, Eau, Terre et Environnement, 490 de la couronne, Québec, QC G1K 9A9, Canada
Michel Parent, Geological Survey of Canada, GSC-Québec, 490 de la Couronne, Québec, QC G1K 9A9, Canada

GENERAL CONTEXT

One of the most widespread contaminants in groundwater in North America is trichloroethene (TCE, C_2HCl_3). This chemical has been widely used as a degreasing agent, for dry cleaning, and in other industrial applications. The water solubility of TCE is 1100 mg/L at 25°C and its density is 1460 kg/m^3 (Pankow and Cherry, 1996). TCE is on top of the EPA contaminant priority list and presents remediation challenges when forming a DNAPL (Cohen and Mercer, 1993; Pankow and Cherry, 1996). A case of a large dissolved TCE plume has been detected in the Valcartier area, located 35 km north of downtown Quebec City.

The study area (Fig. 1) comprises the Valcartier military base, the Valcartier research facilities of Defence R&D Canada (DRDC), the SNC TEC former industrial plant, and the municipalities of Shannon to the west and Quebec City to the east (former Val-Bélair). The area is mostly flat and is bounded to the west by the Jacques-Cartier River and to the east by the Nelson River. Mount Brillant is the highest topographic area to the east, and Mount Rolland-Auger is located to the South.

In 1997, TCE was found in groundwater at the Valcartier military base. Further field studies were carried out in the surrounding area, which led to a better understanding of groundwater flow at the site and to the discovery of TCE in private wells in December 2000 in Shannon. Starting in early 2001, private wells were sampled in Shannon by the Quebec Ministry of the Environment, and several wells were found to have concentrations above 50 μg/L. Houses affected by TCE contamination exceeding 5 μg/L were first equipped with filters and later linked to the aqueduct system of the Valcartier base.

CHARACTERIZATION

A major characterization program was carried out during the summer and fall of 2001. This program aimed to define the extent of the TCE plumes, to refine the understanding of the geological and hydrogeological contexts, and to better identify potential TCE sources. Table 1 shows the extensive characterization data on which this study is based. About 809 observation wells have been installed over the area, and about 2000 chemical analyses were conducted to define the TCE distribution. 212 Geoprobe stations were sampled and provided a mean to establish contamination profiles with depth. Figure 2 presents an example of an east-west TCE concentration profile at DRDC North.

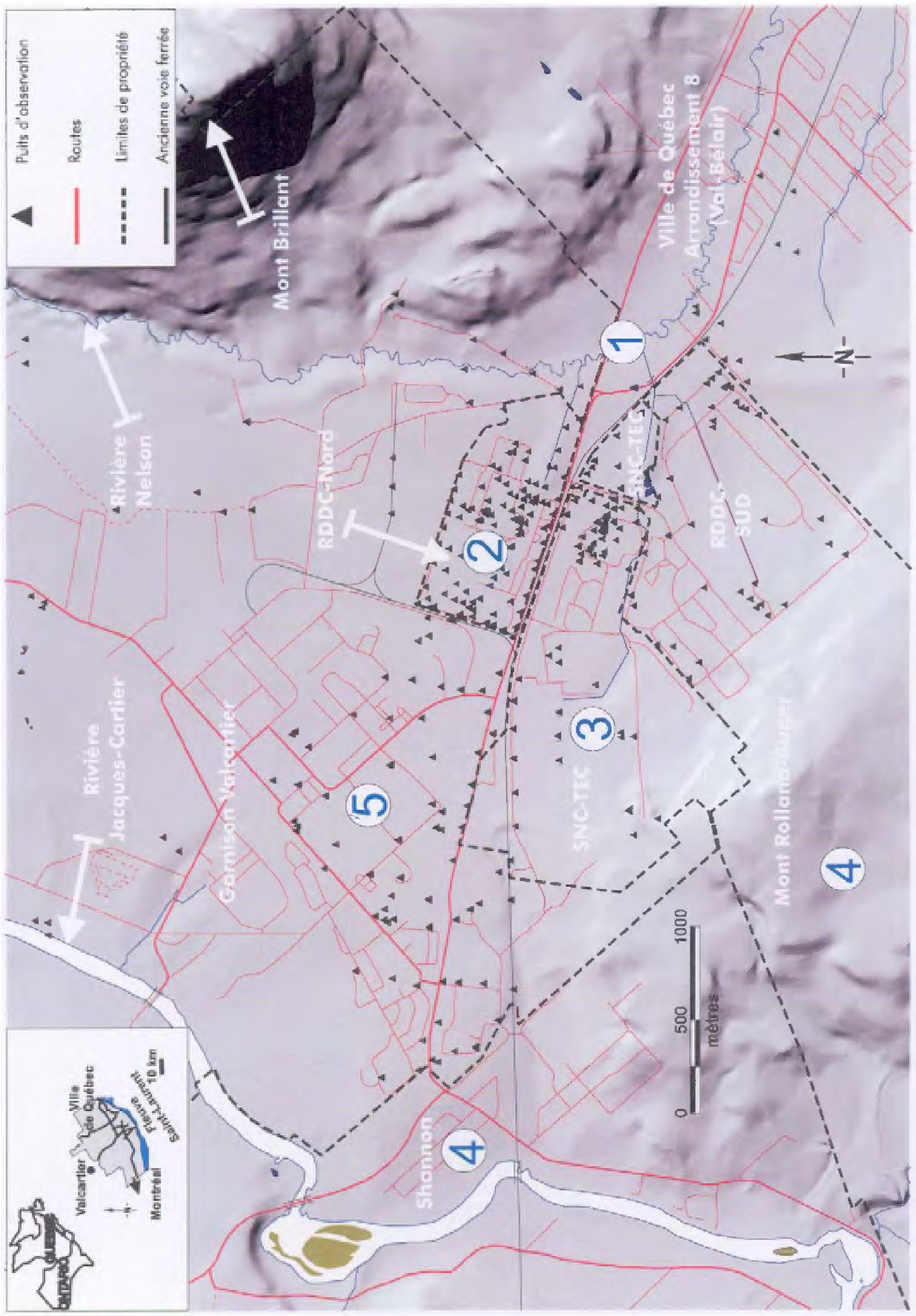


Figure 1. Study area and location of stops.

		DND Property				Others sectors	All
	Type of data	Site	Before fall 2001	During fall 2001	Total	Others sites	Total sector
Boreholes & wells	*Rotasonic boreholes*	1	0	27	27	N.A.	≥65
		2	0	38	38		
	Observation Wells	1	≈140	167	≈659	≈150	≈809
		2	105	247			
Hydrogeochemistry	*Water VOC analysis*	1-2	≈400	≈600	1000	≈1000	≈2000
	Geoprobe sampling station	1	0	1	1	29	212
		2	0	182	182		
Hydrogeology	*Water level*	1-2	≈200	≈600	≈800	≈150	≈950
	Slug test	1-2	28	260	288	N.A.	288

Table 1. Characterization data.

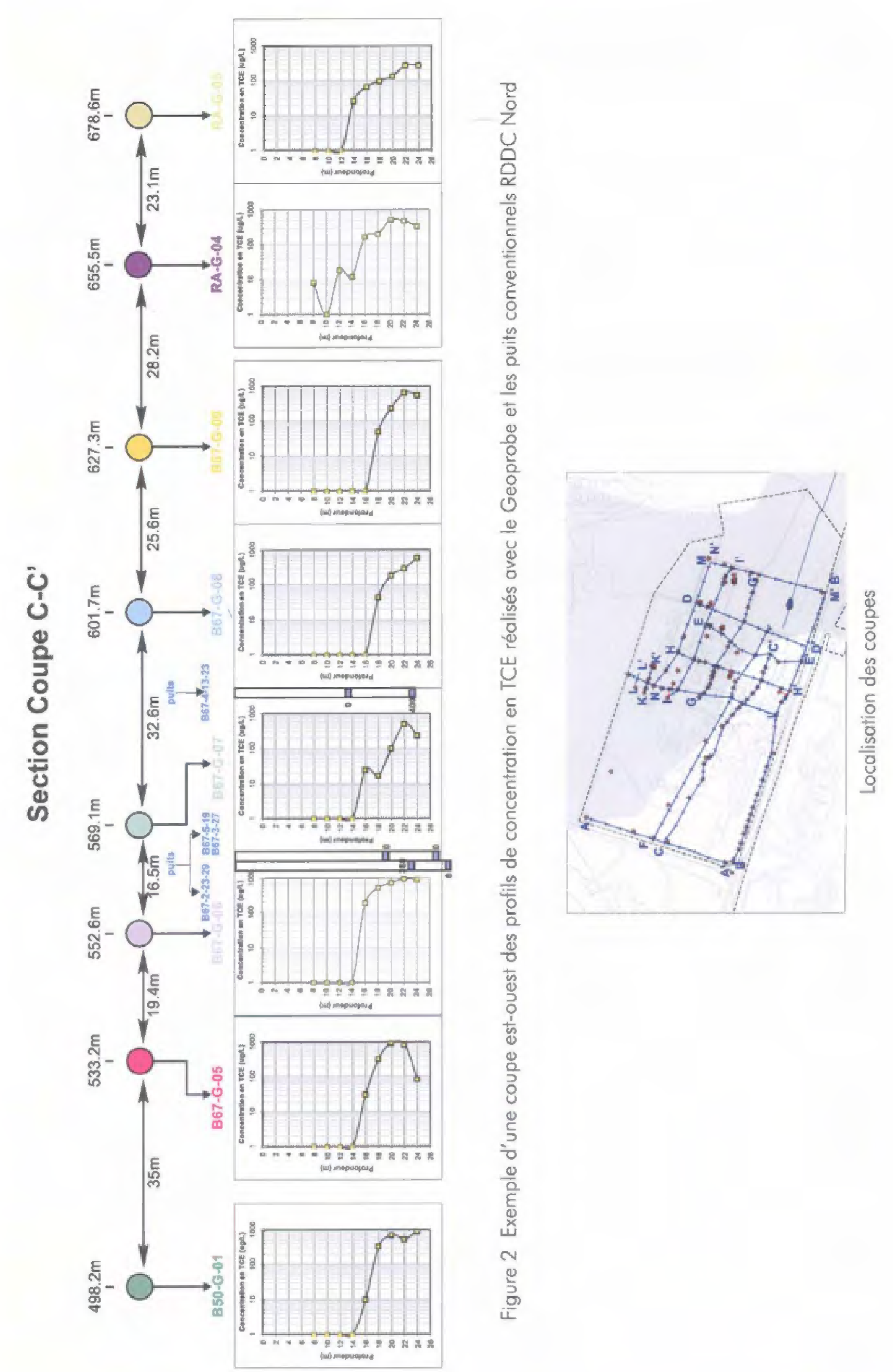
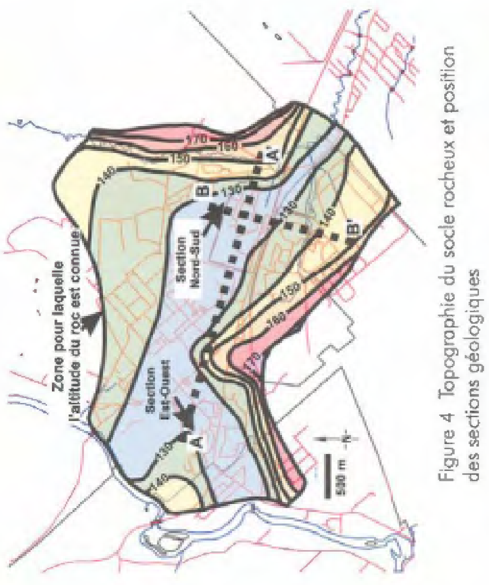
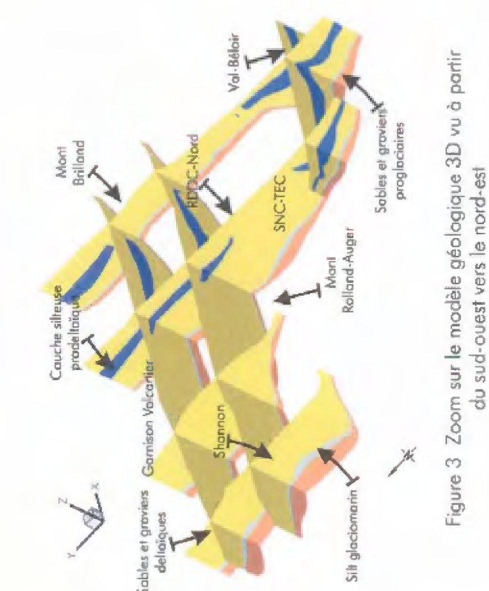


Figure 2. East-west TCE concentration profile at DRDC North. The section C–C' is located in the small map.

HYDROSTRATIGRAPHIC CONTEXT

A buried valley filled by more than 50 m of glacial sediments underlies the area. The main aquifer unit is made up of 1.5 m to 30 m of very permeable deltaic sand. In the eastern part of the area, this unit is subdivided in two by a silty prodeltaic layer, which can reach 14 m in thickness locally. Above the silty unit, and where it is absent, unconfined conditions are present, whereas semi-confined conditions prevail under the silty unit. Generally, groundwater flow converges to the center of the area both from the north and south and then turns either east or west on each side of a groundwater divide line that is present in the eastern part of the area. The bedrock topography exerts an important control on groundwater and channels its flow. Figures 3, 4, 5, 6, and 7 show the details of the stratigraphy and the groundwater flow in the area.





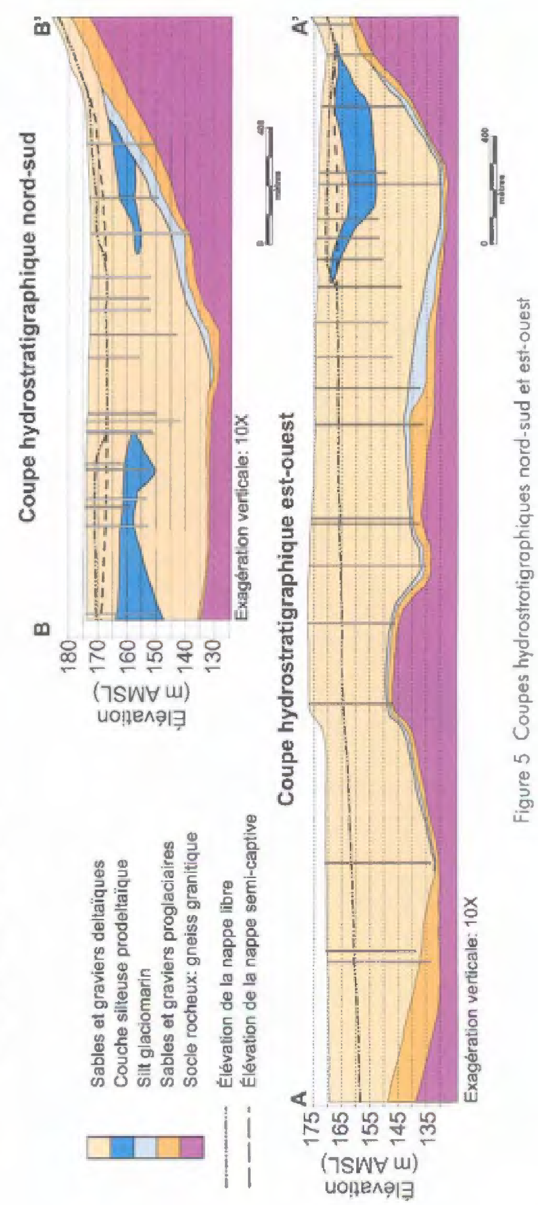


Figure 3. 3D geological model view from the southwest looking northeast.
Figure 4. Bedrock topography and location of geological section.
Figure 5. N-S and E-W hydrostratigraphy sections.

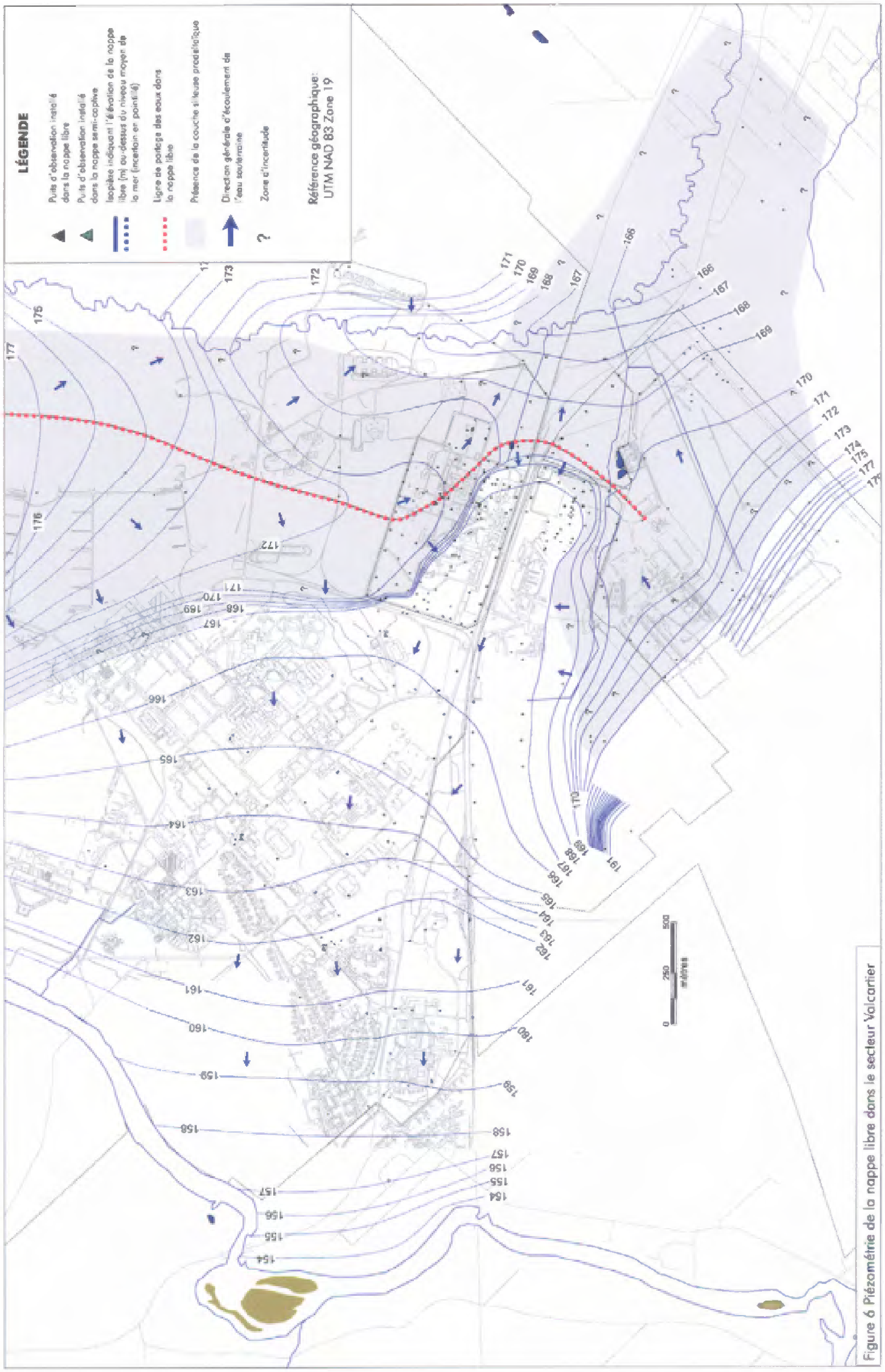


Figure 6. Piezometry of the non-confined aquifer in the Valcartier area.

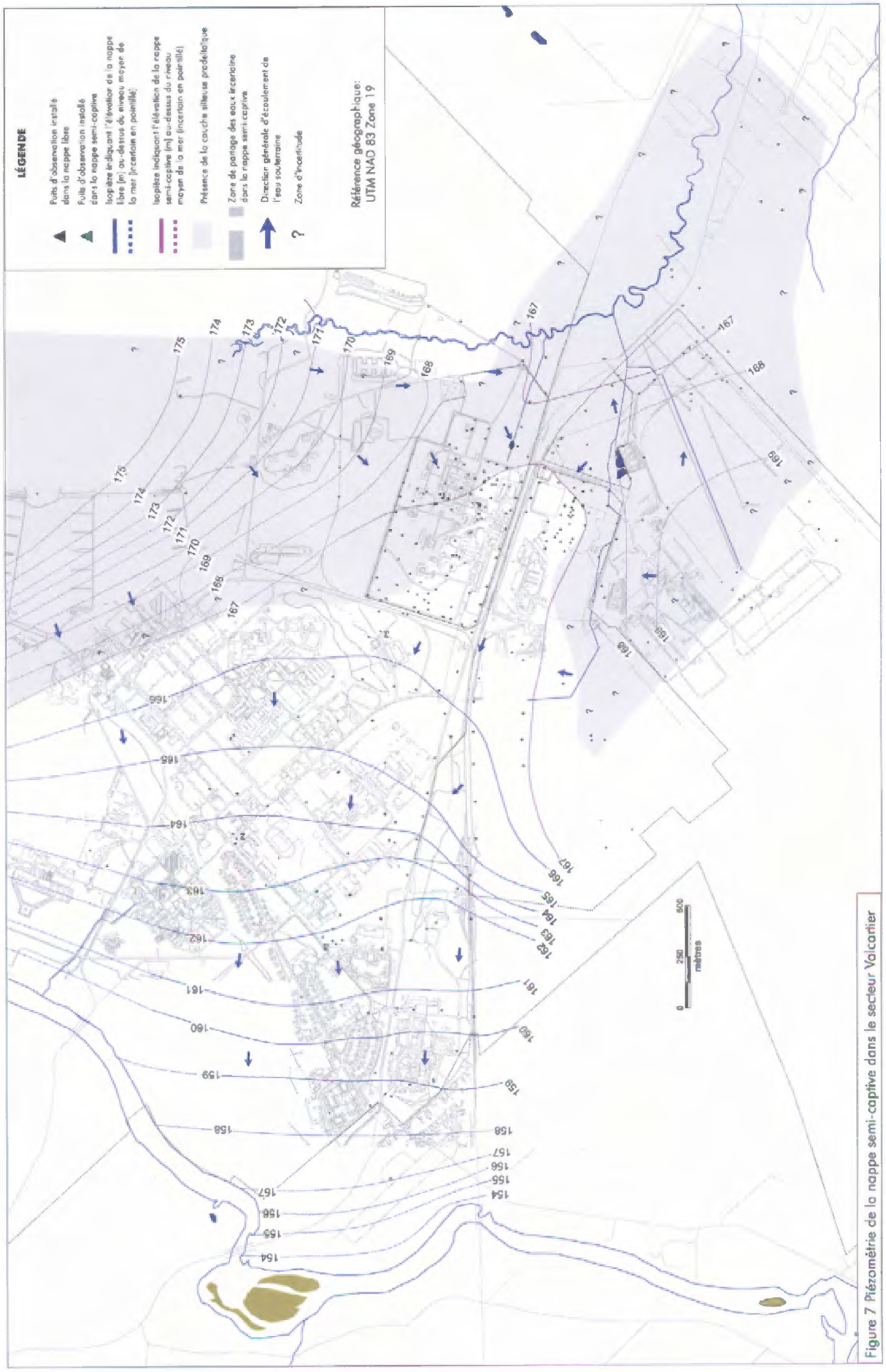


Figure 7. Piezometry of the semi-confined aquifer in the Valcartier area.

TCE GROUNDWATER CONTAMINATION

Figure 8 shows the TCE-contaminated groundwater plume, which has been divided into three zones: (1) a zone in which TCE concentrations generally go from the detection limit to 50 µg/L, (2) a zone in which TCE concentrations are mostly between 50 and 500 µg/L, and (3) a zone in which TCE concentrations generally exceed 500 µg/L. The value of 50 µg/L is the maximum concentration limit (MCL) for TCE in drinking water in Canada (CCME). The TCE plume in groundwater originates from source zones located within the property boundaries of DRDC North and SNC TEC (Sector 214 and Lagoon C). TCE-contaminated groundwater released from these source zones reaches the Valcartier base and the town of Shannon, to the west, as well as Quebec City, to the east. The TCE plume thus formed has a total length exceeding 4 km and a total width of 650 m at the boundary between the Valcartier base and Shannon, of which 330 m have concentrations exceeding 50 µg/L. The plume thickness is about 20 m and it contains a contaminated volume of groundwater exceeding the MCL estimated at 8.6 million m^3 containing more than 1500 kg of dissolved TCE.

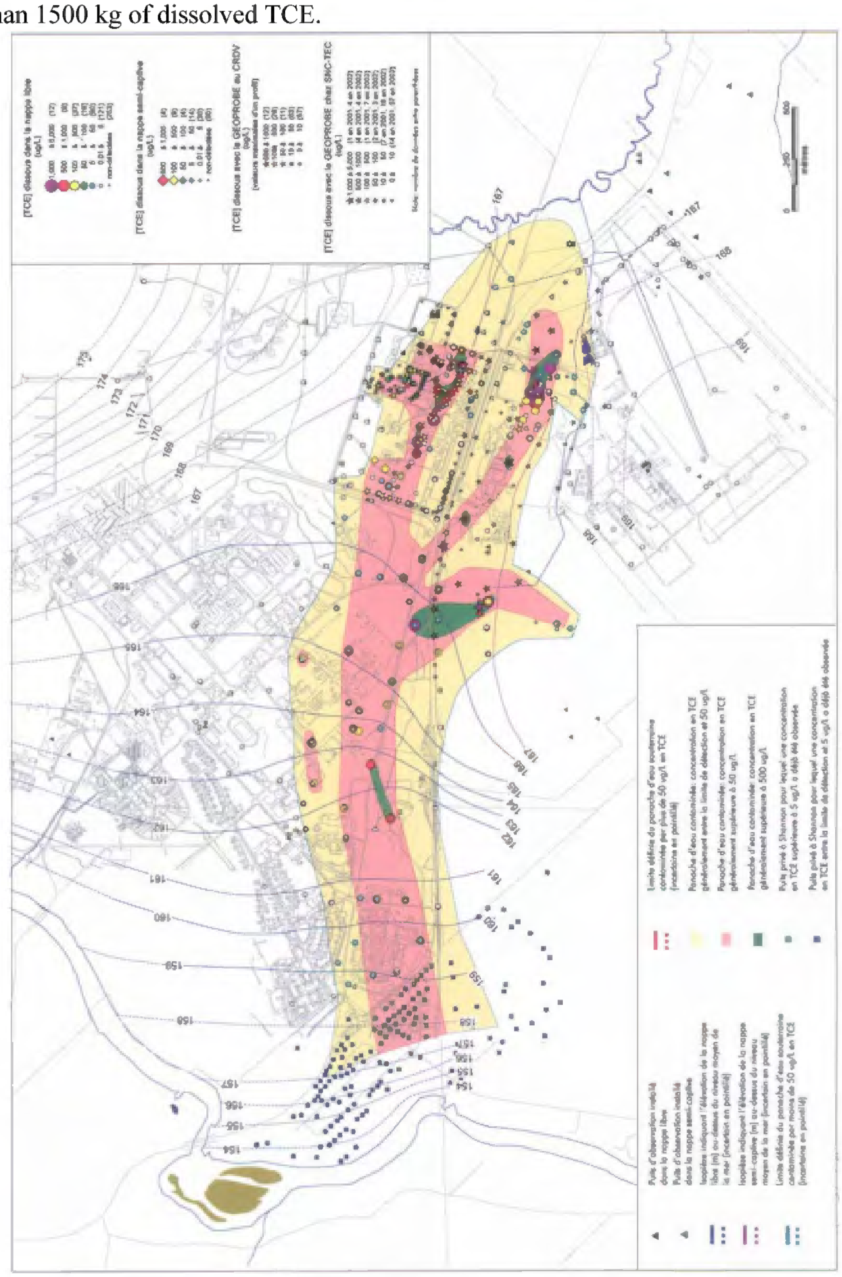


Figure 8. TCE-contaminated groundwater plume in the Valcartier area.

TCE releases in groundwater in the Valcartier area have led to its migration from source zones to the east and to the west following groundwater flow directions (Fig. 9). On the eastern side, TCE contamination reaches Quebec City (former town of Val-Bélair). However, TCE concentrations detected thus far in Quebec City are all lower than 50 µg/L. The maximum extent of the plume as well as TCE concentrations within Quebec City need to be further defined. Even though some TCE migration occurs to the east, most of it takes place towards the west. At least part of this TCE plume reaches the town of Shannon, which has led to the contamination of private wells located within the extent of the plume. TCE-contaminated groundwater is likely to pursue its migration beyond Shannon and thus reach the Jacques-Cartier River. Data are lacking in Shannon to define the western extent of the plume.

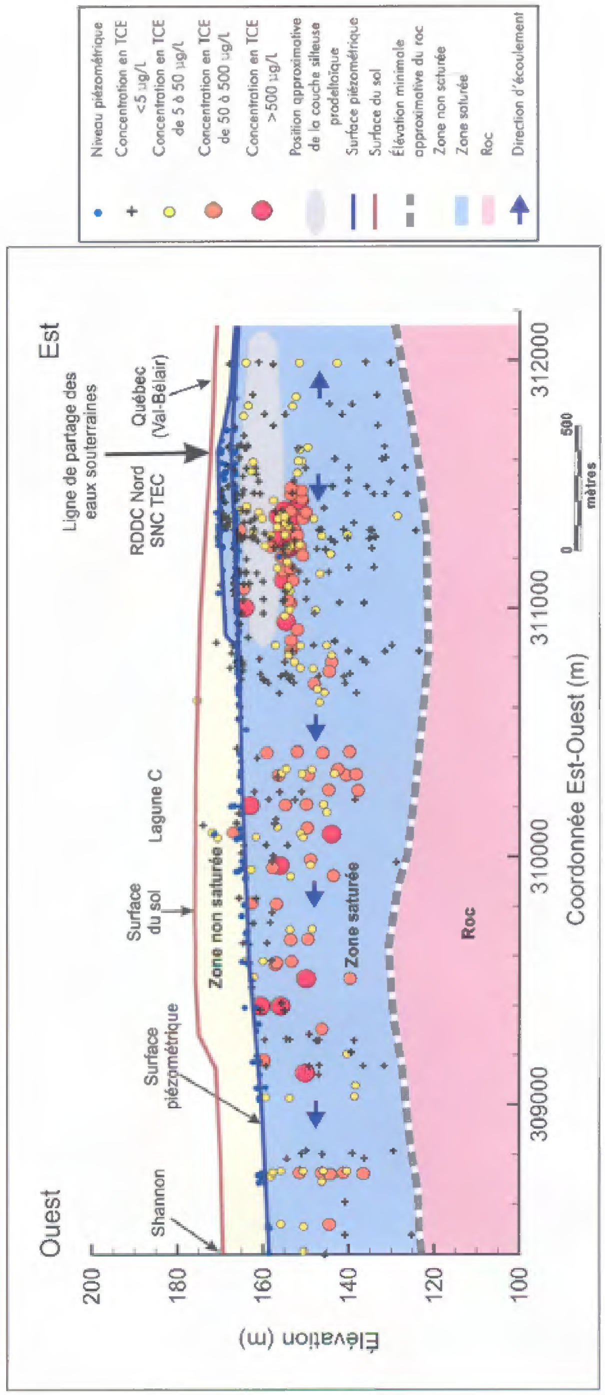


Figure 9. E-W cross-section of vertical distribution of TCE in the study area.

Groundwater underlying DRDC North is contaminated over almost its entire area, and maximum TCE concentrations vary between 800 and 1300 µg/L near presumed source zones, among which the main ones are related to Buildings 98 and 67 as well as the Blue Lagoon. The migration of dissolved TCE from these source zones occurs predominantly towards the west in the semi-confined and the regional unconfined aquifers. There is apparent degradation of TCE from the source zones during its transport since concentrations reaching the western limit of DRDC North are reduced to a value of about 270 µg/L. The presumed source zones identified at DRDC North do not seem to be related to on-going present-day activities. Figure 10 shows the TCE contours obtained by interpolating TCE concentrations at DRDC North. Figure 11 links potential source areas and the TCE plume subdivision. Finally, the 3D distribution of dissolved TCE plumes in DRDC North is represented in Figure 12.

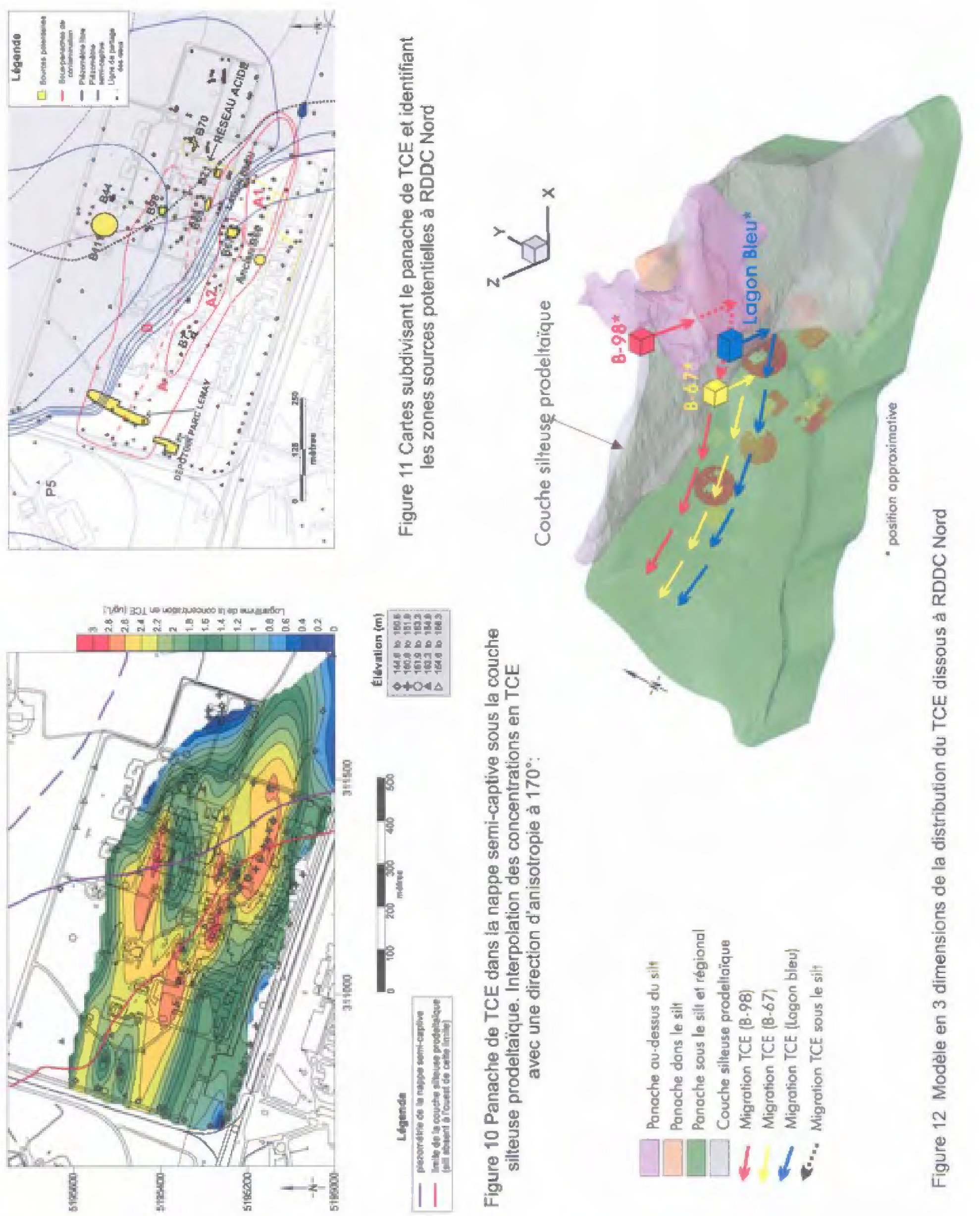


Figure 10. TCE contours at DRDC North.
Figure 11. Potential source areas and the TCE plume subdivision.
Figure 12. 3D distribution of the dissolved TCE plumes in DRDC North.

Two known source zones are present within the property limits of SNC TEC bordering the Valcartier base: Sector 214 and former Lagoon C. The maximum concentrations measured in the fall of 2001 in Sector 214 were between 100 and 4500 µg/L (a maximum concentration of 13,500 µg/L was detected in May 2001). A pump-and-treat system operates seasonally in this sector since 1998. The Sector 214 source zone practically lies on the groundwater divide between flow to the west (Valcartier base) on one side, and flow to the east (Quebec City, former Val-Bélair), on the other side. TCE migration from Sector 214 thus occurs both to the west to feed the TCE plume present under the Valcartier base, as well as to the east, thus reaching Quebec City. The other source zone within the SNC TEC property is former Lagoon C.

Maximum TCE concentrations measured in 2001 in that vicinity were 1600 µg/L in an observation well and 2600 µg/L in a Geoprobe profile. The TCE plume related to Lagoon C is well delineated: it has a width of 50 m at concentrations exceeding 50 µg/L near the source zone, whereas the plume reaches a width of 350 m with concentrations between 690 and 970 µg/L close to the property limit between SNC TEC and the Valcartier base.

The groundwater plume migrating to the west within the Valcartier base had a maximum concentration of 1200 µg/L in 2001, but most of the high concentrations vary between 560 and 920 µg/L in the core of the dissolved TCE plume within the Valcartier base. At the property boundary between the base and the town of Shannon, maximum concentrations measured in 2001 were from 260 to 340 µg/L. No other TCE contamination source zones have been formally identified within the Valcartier base following the fall of 2001 characterization.

ROAD LOG

STOP 1. Quarry east of Valcartier – Geological context. (50 MINUTES). Regional geological context: Quaternary map. Stratigraphy: Stratigraphic column and 3D model poster. Nature of units: Samples of all units to look at and *K* values. Local context: Bedrock, till, and proglacial unit in quarry. (M. Parent).

STOP 2. DRDC parking lot – Characterization methods. (60 MINUTES). Overview of data available in Valcartier area. Demonstration of various characterization methods, most of which have been used in the Valcartier area: Direct push rig with CPT, pneumatic slug tests, water sampling, field analysis, Geoflo for GW velocity and direction, infiltrometer, seepage meter. (R. Martel).

STOP 3. DRDC South – TCE source zones. (75 MINUTES). SNC TEC environmental facilities: High security cell (Source zone). Explanation of DRDC source zones and 3D plume model. (R. Lefebvre, DRDC Rep., V. Blais).

LUNCH in Val-Bélair. L'Azalée, 843-3101.

STOP 4. Vanier sandpit – Main aquifer and GW flow. (35 MINUTES). Observation of cuts in the sand pit exposing sedimentary structures in the deltaic sand, the main aquifer unit. Explanation of groundwater flow patterns in the area. (M. Parent, R. Lefebvre).

STOP 5. Bike trail bridge on Jacques-Cartier River – Receptors. (20 MINUTES). Observation of sand cliffs with seeps from the aquifer to the Jacques-Cartier River. Explanations on the extent of the TCE plume and on the receptors in the area. (R. Lefebvre).

STOP 6. Bridge on Gosford Road – Local history. (30 MINUTES). Historical stop of ancient electricity plant and opportunity to see the bedrock outcropping close by the river. (All organizers available for questions).

BEER in Sainte-Catherine de la Jacques-Cartier. (45 MINUTES). Dazibo Resto-Bistro, 58 Rte Duchesnay, 875-3301. (Sponsored by Roctest).

Return to hotel

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QUEBEC FORTIFIED CITY: GEOLOGICAL AND HISTORICAL HERITAGE

by

Pascale Côté and Andrée Bolduc
Geological Survey of Canada, GSC-Québec
490, rue de la Couronne, Québec, QC G1K 9A9, Canada

INTRODUCTION

Built atop a rocky promontory, the Fortifications of Quebec tower over the St. Lawrence River. Visitors can stroll along the 4.6-km-long walkway and enjoy the splendid views. Like nowhere else in North America, the City of Quebec's defence system follows a classic urban style, characterized by flanking defence and defence in depth, and was adapted to the city's topography. More than just the vestiges of the military art of war, the Fortifications of Quebec also bear witness to the era of fortified cities between the 17th and 19th centuries. Inside Quebec's walls, you can get a feeling for how the military's presence dominated the city. The parade grounds, esplanades, military arteries, barracks and warehouse, in which munitions and artillery paraphernalia were stored in the 18th and 19th centuries, are remnants of a city's past that was punctuated by the beat of the war drum.

Quebec, a UNESCO World Heritage Site, is the only city in North America to have retained the major parts of its defence system. This picturesque setting with its superb vistas serves as the backdrop for an exploration of the region's billion-year-old geological history. At different sites, visitors can discover traces of an ancient ocean, the transportation of enormous rocky masses over long distances to the threshold of the city itself, and the passage of colossal glaciers that covered the area for thousands of years. The legacy of this eventful past is some of the most spectacular attractions in the region, along with an environment that is occasionally at the mercy of nature's whims.

This fieldtrip provides a geological overview of the Quebec City area with reference to its landscapes. The geoscape of this region provides the backdrop for explaining how landscape components come into being or change over time. The notions of geology that we discuss are linked to our immediate environment, Old Quebec, and to the spectacular events that sometimes make regional headlines, such as earthquakes and rock slides. We will weave together these various aspects of Quebec's geological history and general history to show how they are connected and to learn new facts.

The itinerary comprises a tour of Old Quebec with 10 stops (Fig. 1). Scientific concepts are explained in detail at each of them and complement with historical information (Fig. 2). Complementary points of interest or landmarks are mentioned along the route, between stops, but without going into details. They are identified with an asterisk.

Figure 1. Location of stops in Old Quebec

Figure 2. Between the St. Louis and Ursulines bastions, stands the Esplanade Powder Magazine (1815), restored and open to the public. The effectiveness of fortifications largely depends on the location of their powder magazines. This is why the British would distribute them strategically around the city, while at the same time avoiding having an overly large concentration of gun powder in one place. In 1816, there were 12 powder magazines in the City of Quebec. To protect the surrounding area, the walls of the powder magazines are 1.5 meters thick, their ceilings are arched and they are surrounded by a thick outer wall. National Archives Canada, c. 1830, J.P. Cockburn.

STOP 1. Maison Cureux

The Cureux House (Fig. 3), at 86 Rue St. Louis, was built in 1729 by innkeeper Michel Cureux. It is the second oldest residence on Rue St. Louis. The house standing today is a reconstruction of the original one, which was destroyed in 1709 to make way for fortifications. It was only after a long trial followed by the whole colony that the French government was forced to back down and rebuild the house.

Maison Cureux is one of the rare examples of houses constructed from what was called "pierre du cap" or "Cap stone" the first type of building stone used in Quebec City. When the early settlers built their homes on the promontory, they dug the foundations, reserving the excavated stone to build the walls. This very fissile stone is weakened and splits easily when exposed to air and water. It is therefore not conducive to providing good quality exterior masonry. To ensure that houses made of cap stone will last longer, they must be sheathed in wood or covered with parget, as was done with this house up until 1968.

Figure 3. The Cureux House

* 69 Rue d'Auteuil: Built in 1867 by Thomas Fuller, one of the architects of the original Parliament Buildings in Ottawa. The facade is made of buff-coloured sandstone from the Nepean area, near Ottawa. The same stone was used to build the Parliament Buildings in Ottawa. Cross-bedded structures can be seen in the blocks of stone. As the richly ornamented facade shows, this type of stone can be finely sculpted.

* At the corner of d'Auteuil and Saint-Louis streets: fossiliferous limestone containing lacy, branched or domed bryozoans along with stylolites (compressional structures).

* 91 Rue d'Auteuil: predominance of Ange Gardien sandstone which exhibits a rust brown weathering. The stratification (bedding), or division into strata, is visible in the blocks of stone.

* 28 Rue Saint-Denis: fossiliferous limestone containing the large white shells of brachiopods.

STOP 2. Québec Citadel

Engineers and military strategists have always considered the heights of the Plains of Abraham to be a strategic location. The French occupied the heights as early as 1693, when they built the Cap Diamant Redoubt. The redoubt is one of the oldest military structures in Canada and remains an integral part of the Quebec Citadel (Fig. 4). The British also sought to fortify the strategic site. In 1789, they built a temporary citadel, which they replaced in 1832 with the permanent one that still stands today. After the construction of the Citadel, Quebec City became known as the Gibraltar of the Americas. Nowadays, the Citadel is home to the Royal 22nd Regiment and is the location of one of the official residences of Canada's Governor General. Did you know that the Citadel is the largest

Figure 4. Québec Citadel, Parks Canada/ P. Lahoud

fortification in Canada built during the English regime? The star-shaped stone polygon was built to protect the city against a possible American attack, but also to contain a rebellion by the city's French-speaking population. This is why the Citadel faces Old Quebec's centre as much as its periphery.

The Quebec Citadel was constructed from Sillery sandstone obtained from quarries located between Cap-Rouge and the promontory of Quebec as well as in the Lévis region. Since Sillery sandstone is no longer quarried to obtain building stone, a similar type of stone must be found to replace damaged blocks.

From this vantage point, we can get a general idea of the diversity of the Quebec City area's geology. Three different physiographic regions can be identified: the Canadian Shield, the St. Lawrence Lowlands and the Appalachians: they correspond roughly to geological provinces (Fig. 5). A geological province is characterized throughout by a similar geologic history and similar structural features. Nonetheless, the boundaries of a geological province may differ from those of a physiographic region.

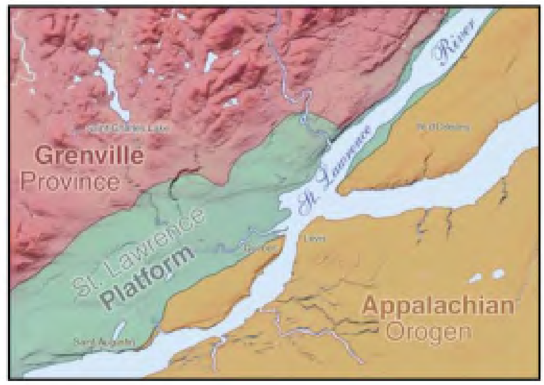


Figure 5. Geological subdivisions near Quebec City

The **Canadian Shield** is represented here by the Laurentians. This chain of mountains corresponds to the **Grenville geological province**, the youngest of the Canadian Shield provinces. The rocks of the Grenville Province are the oldest in the region. They are largely metamorphic rocks, i.e. igneous rocks or sedimentary rocks that were transformed and modified at great depths in the Earth, under high pressures and high temperatures. Intrusive rocks, i.e., igneous rocks that were emplaced at depth, also occur in this province. The Grenville rocks represent the deep roots of a mountain belt that has been smoothed out by erosional processes. Although some high peaks still exist, such as Mont Ste Anne, their current elevation is merely a fraction of what it was about a billion year ago. At that time, Mont Ste Anne was part of a mountain belt similar to the Himalayas. The rocks of the Grenville Province stretch over an area of more than 4,000 km (from Labrador to Texas); in some areas they are overlain by younger rocks while in other areas they are exposed at the surface.

The **St. Lawrence Lowlands**, wedged between the Laurentians and the Appalachians, are made up of sedimentary rocks that have undergone little or no deformation. Fossils are especially abundant in some layers of limestone, a very common rock type in the Quebec City area. Long ago when the limestones of the St. Lawrence Lowlands were forming, life was restricted to the oceans; consequently, marine species are the only fossil species found in the Quebec City area. These limestones formed in a rift valley, on the continental shelf of an ancient continent. The Lowlands are part of the geological province called the **St. Lawrence Platform**, and they form a plain that can be seen north of Ile d'Orléans and in the Beauport and Vanier districts of Québec city and in the municipalities of Ancienne-Lorette and St-Augustin. These rocks formed over a period of 150 million years and are much younger than the rocks of the Canadian Shield.

The relief of the Appalachian mountains can be seen in the distance. Yet the **Appalachians province** reaches right into Quebec City, where it is represented by the thrust sheets, or "nappes", of the Quebec promontory, Lévis and Ile d'Orléans. The entire south shore of the St. Lawrence and most of Ile d'Orléans are part of the Appalachians, although the relief is fairly flat. Quebec City is located at the northern edge of the maximum extent of the Appalachians. The boundary between the Appalachians and the St. Lawrence Platform is marked by a major fault, called Logan's Line. This fault runs to the north of the Quebec promontory, and, from our present vantage point, we can see the relief that it forms on the Sainte-Pétronille side of Ile d'Orléans. For geologists, the Appalachians are more than the mountains; they encompass all the thrust sheets or "nappes" that were transported over great distances onto the rocks of the St. Lawrence Platform, as this mountain range was forming. The rocks of the Appalachians comprise mostly deformed and folded sedimentary rocks, which were transported over dozens of kilometres along nearly horizontal faults during the mountain-building process (Fig. 6).

When climbing from the Lower Town to the Upper Town, we are actually going from the St. Lawrence Platform to the Appalachians. The steep hills of the Quebec promontory resulted from the formation of the Appalachians. When climbing the bluffs in Québec City, e.g. Côte Salaberry, Côte d'Abraham and Henri IV Boulevard, like the stairs from the Lower Town, we are moving from one geological environment to another.

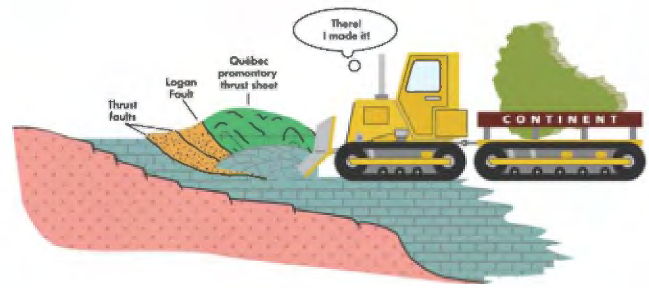


Figure 6. Cartoon of tectonic processes in the Quebec City area

FROM OBSERVATION TO INTERPRETATION: THE GEOLOGICAL HISTORY OF THE QUEBEC CITY AREA

In Grenville times: Quebec at the highest peaks

The Canadian Shield has not always existed in its present form; it arose from the continent called Laurentia, which was part of the supercontinent Rodinia, i.e. a group of continents that joined together (Fig. 7). This supercontinent existed a billion year ago (in the Proterozoic era). When Laurentia collided with some other continents, a mountain chain similar to the Himalayas was created; this was the Grenville mountain range, now completely eroded.

The St. Lawrence Platform: Quebec in the Tropics

Some 900 million years ago, the Grenville mountain range dominated Laurentia. The continent gradually became unstable and broke apart (Fig. 8). After that, the motion of the tectonic plates reversed, and a new cycle began as the continents started to drift apart. About 500 million years ago (in the Paleozoic era), sediments accumulated on the continental shelf in the Iapetus Ocean (Fig. 9), the forerunner of the present-day Atlantic. This was a passive continental margin environment. This assemblage was centred on the Equator; hence, the area that is now Quebec City was located in a tropical sea environment much like present-day Rio de Janeiro. The rocks of the St. Lawrence Platform are all that remain of the vast sedimentary cover that blanketed much of the Canadian Shield and can be detected as far away as Lac Saint-Jean and Lac Manicouagan. This sedimentary cover resulted from erosion of the Shield (detrital sediments) and the accumulation of calcareous sediments from the shells of marine organisms (algae, corals, etc.) that populated the warm, calm and shallow sea.

Origin of the Appalachians: mountain building forces

Some 500 million years ago (in the Paleozoic era), the tectonic plates began moving in the opposite direction once again and a new cycle began. The Iapetus Ocean closed up again and a new chain of mountains formed (in an active continental margin environment; Figs. 10 and 11). Sea-bottom sediments from dozens of kilometers off Laurentia were pushed toward the continent and forced up onto the rocks of the St. Lawrence Platform. The Quebec City area was then situated at the foot of mountains, which reached right up to it. The mountain-building process for the Appalachians, which stretch 3,500 km from Newfoundland to Alabama, took place over a period of 250 million years. These mountains are now past history, but the world still evolves (Fig. 12).

PAST AND PRESENT… PLATE TECTONICS

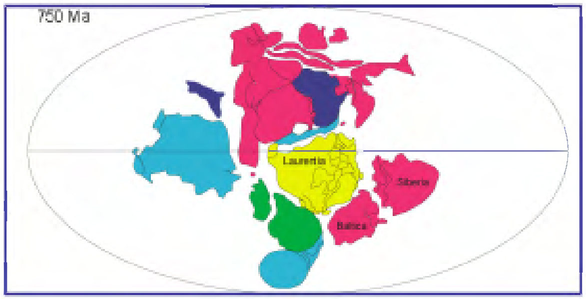


Figure 7. Rodinia is one of the oldest-known supercontinents. It formed some 1,100 million years ago.

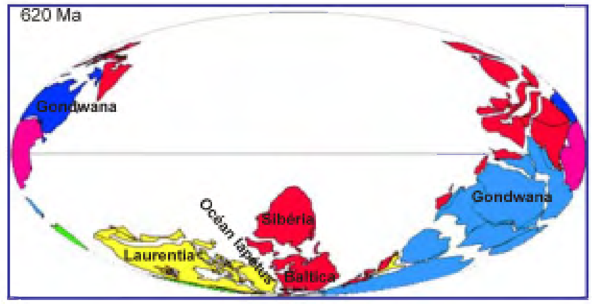


Figure 8. From 750 to 540 million years ago, the Rodinia supercontinent broke up into different pieces, including Baltica, Siberia and Laurentia (Canadian Shield), and the Iapetus Ocean was formed.

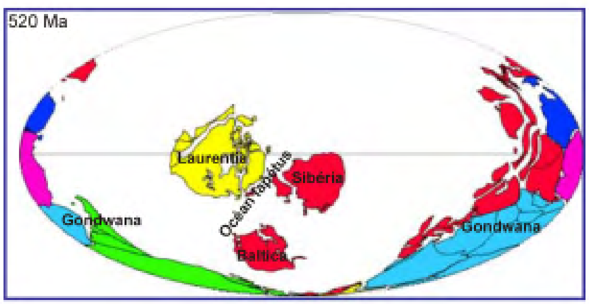


Figure 9. From 540 to 460 million years ago, the Iapetus Ocean kept spreading, and the rocks of the St. Lawrence Platform were formed.

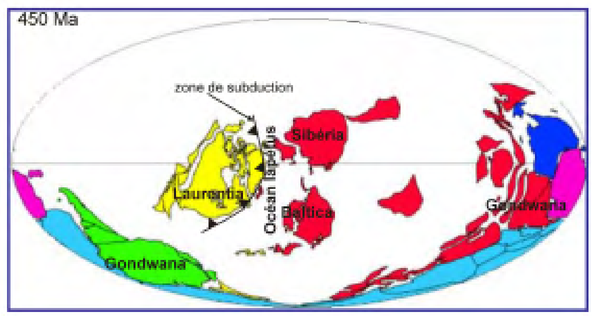


Figure 10. From 475 to 380 million years ago, the Iapetus Ocean closed up. The Appalachians formed.

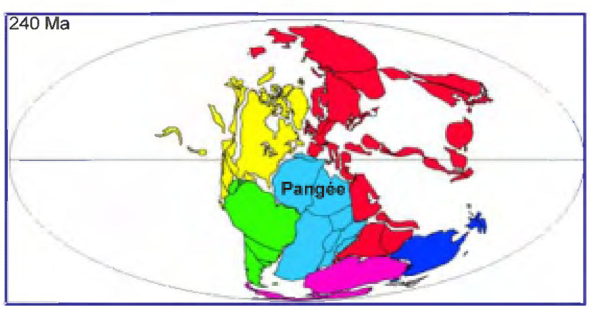


Figure 11. Then, some 360 million years ago, after the Appalachians formed, all the continents once again came together, forming the supercontinent Pangaea, which subsequently broke up into the continents as we know them today.

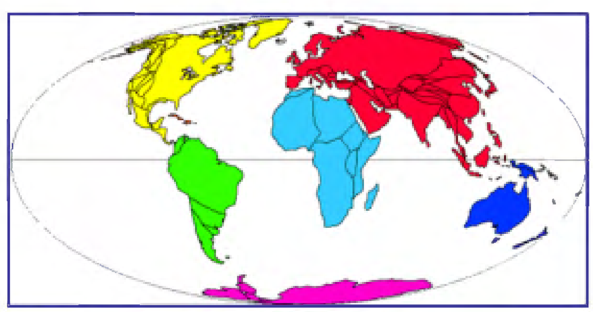


Figure 12. The natural environment is not static. The landscape has changed drastically over time. Mountain ranges have been created and then eroded, and new mountains are still forming around the world.

Indeed, the landscape is constantly changing, but on a human time scale these changes are not very noticeable. Geological time is measured in thousands or millions of years. Nothing is static in nature, not even rocks. The major cycles during which the continents came together and then separated have occurred and will continue to occur on a very large scale and over a very long time period (Figs. 7–12). They can be likened to other broad natural cycles, such as the water cycle and the rock cycle. The Earth is a dynamic planet that seeks to maintain equilibrium. From time to time, sudden events remind us of this fact, such as earthquakes, floods or landslides which brutally change the landscape. During this fieldtrip in Old Quebec, examples will be given of the influence that Quebec's geological heritage has had on the town's history and development, with reference to the use of resources and human safety issues.

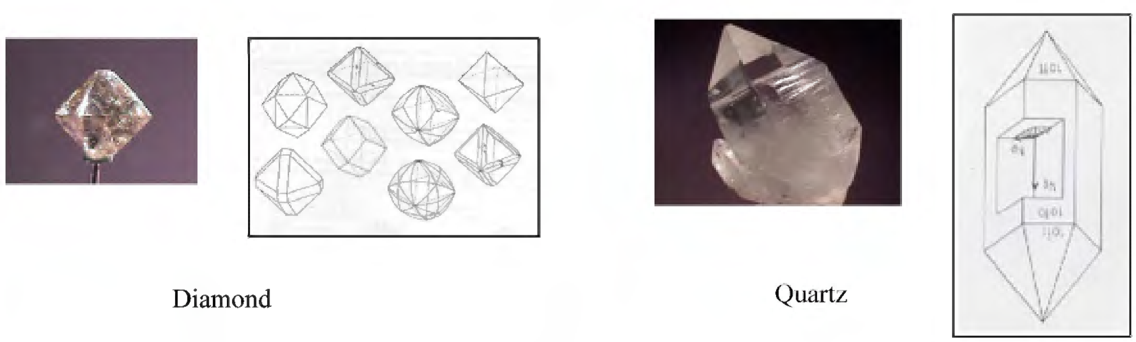
STOP 3. Rue des Carrières

At the base of the park, take the stairs leading to Rue des Carrières. At the foot of the staircase, on the left, there is an outcrop of fine-grained argillaceous limestone. When two pieces of cap stone are struck together, the sound is like porcelain breaking and the break has a conchoidal appearance (rounded like a broken bottle base). Cap stone reacts with diluted hydrochloric acid, indicating the presence of calcite. There is an odour of methane and sulphurous gas when the rock is broken.

Figure 13. Former quarry

This is the site where black cap stone was quarried beginning in the 17th century, under the French regime (Fig. 13). The quarry workers nicknamed this stone "stinking stone" because of the odour of methane and sulphur that is released when the stone is crushed. This odour is due to the fossil fuels (gas, oil) that are present in the folded sedimentary rocks of the Appalachians, but the quantities encountered are rarely sufficient for development purposes. Bedding or stratification is very evident along with organ-pipe structures on some surfaces (rounded structures). Quarry development within the town entailed many risks, particularly rock slides. It appears that one of the most important black cap stone quarry sites of the time was on rue Berthelot, or more precisely Ilot Berthelot. In this pretty little park, there is a panel describing this use of the stone, and outcrops can be seen there.

The dark-coloured rocks of Cap Diamant contain numerous fissures, crevasses and cavities, in which a number of minerals can be identified. The best known of these is bipyramidal quartz crystals (Fig. 14), many of which are well formed. When Jacques Cartier found some of these crystals in New France, in 1542, he thought he had discovered diamonds—hence the French expression "Faux comme les diamants du Canada," which means "as phony as Canadian diamonds." (As an aside, following many years of geological research, we now know that quality diamonds do exist in Canada, and even in Quebec, at suitable sites in the North.) There is also a local legend which says that the good fairy waved her magic wand, causing a star to burst, the fragments of which created the diamonds of Cap Diamant.



Diamond

Quartz

Figure 14. How to distinguish between diamond and quartz? Diamond is harder than quartz, in fact it is the hardest mineral in existence (hardness of 10). Quartz has a hardness of 7. Their crystal structure and their composition differ greatly as well. Quartz (SiO_2: silica and oxygen) has a hexagonal structure, whereas diamond (C: carbon) has a cubic structure.

Rue des Carrières separates the Governors' Garden (Fig. 15) from the Dufferin Terrace (Fig. 16). The Garden dates back to the colony's early days, first appearing on maps in 1660. Under the Iroquois threat, French authorities decided to build enclaves, and later a wooden palisade in the park to protect the inhabitants. Other defensive structures were also built in the Governor's Garden, including several stone structures. In the 18th century, the privacy of the governor and his guests was ensured by the walls enclosing the area. The Garden was first opened to the public in 1838, on Lord Durham's orders. The obelisk in the Jardin des Gouverneurs (or Governor's Garden), west of the Château Frontenac, is the oldest monument in Quebec City. It was built from Pointe-aux-Trembles limestone in 1828 to commemorate Wolfe and Montcalm.

Figure 15. Governor's Garden. National Archives of Canada, 1829, J.P. Cockburn.

* At the Château Frontenac, two large gastropods can be seen in the wall, which is made of limestone from a former quarry on the Island of Montreal. One can also see stones that were not laid on bed (i.e. they were laid perpendicular to the strata) and stones that were laid on bed (parallel with the bedding planes and in a better position to support the weight of a building). Limestone can be identified by its brown alteration and honeycomb weathering of the dolomitic nodes. The greenish tinge of the walls was caused by copper leaching from the roof. The bricks that make up most of the walls were kiln-fired, making them better able to withstand inclement weather and the passing of time. This can be likened to the process of metamorphism, which makes rocks more resistant.

STOP 4. Dufferin Terrace

At this stop, we will introduce the Quaternary, the geological period extending right to the present which was characterized by extensive glaciations. The course of the St. Lawrence River will be used to illustrate the history of deglaciation in the Quebec City area. Indeed, the river's position can be linked to ancient fractures of the Earth's crust, but its current location is an artifact of the last period of glaciation, as we will explain below.

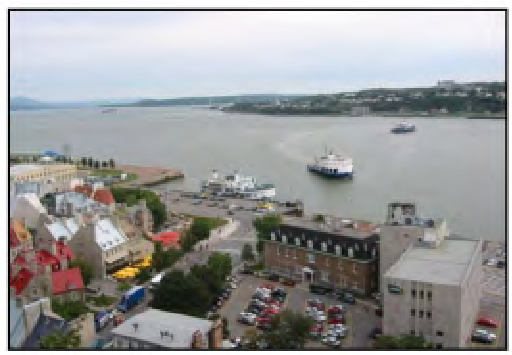


Figure 16. View from the Dufferin Terrace

The remains of the St. Louis forts and chateaux, the governors' residences until 1834, can be found under the Dufferin Terrace. Fort St. Louis was first built in 1621 by Samuel de Champlain, and was modified and repaired several times, by both the French and the British, to adapt it to its new functions. In fact, it was in the Château St. Louis that Governor Frontenac made his infamous 1690 statement: "Je vous répondrai par la bouche de mes canons." ["I will reply from the mouth of my cannons."] The structure burned down in 1834, and Lord Durham had a terrace built in 1838 to cover the ruins of Château St. Louis (Fig. 17). The terrace was extended in 1878, and was henceforth known as the Dufferin Terrace.

F

Figure 17. Archaeological excavation at the Dufferin Terrace. Parcs Canada.

A key part of the St. Louis Forts and Châteaux National Historic Site, the Dufferin Terrace is one of the most popular tourist attractions in Quebec City. It has been open to the public since 1838, when it was 50 meters long, and has since been extended to its current length of 433 meters [1,420 feet]. Since its official inauguration on June 9, 1879, the Terrace has offered a panoramic view of the St. Lawrence River and Quebec City's surroundings to the millions of visitors that stroll down the boardwalk every year.

18,000 years ago, Quebec City sleeps under tons of ice

After being located successively in Tropics and then at the foot of tall mountain peaks, the Quebec City area lay under tons of ice (Fig. 18). Between 1,800,000 and 10,000 years ago, several periods of glaciation took place, each burying almost all of the northern part of the continent under an impressive build-up of ice. The most recent of these glacations, the Wisconsin glaciation, began nearly 75,000 years ago and ended about 10,000 years ago. Some 18,000 years ago, the region lay under an ice sheet 3,000 meters thick. This was the glacial maximum. The weight of this ice sheet depressed the continent, and Quebec City was located more than 200 m below sea level.

Like a gigantic bulldozer, the glaciers smoothed out everything in their path. The slowly creeping ice sheets, or continental glaciers, helped erode the Grenville and Appalachians mountains and plateaus. The glaciers scoured debris from the bedrock, leaving behind till deposits (a heterogeneous mixture of clay, sand, gravel and boulders) and erratic blocks which are scattered over the three physiographic regions. The Jacques-Cartier and Montmorency river valleys have the typical U-shape of glacial cut valleys. Striae and grooves on rock outcrops bear witness to the direction of ice sheet movement.

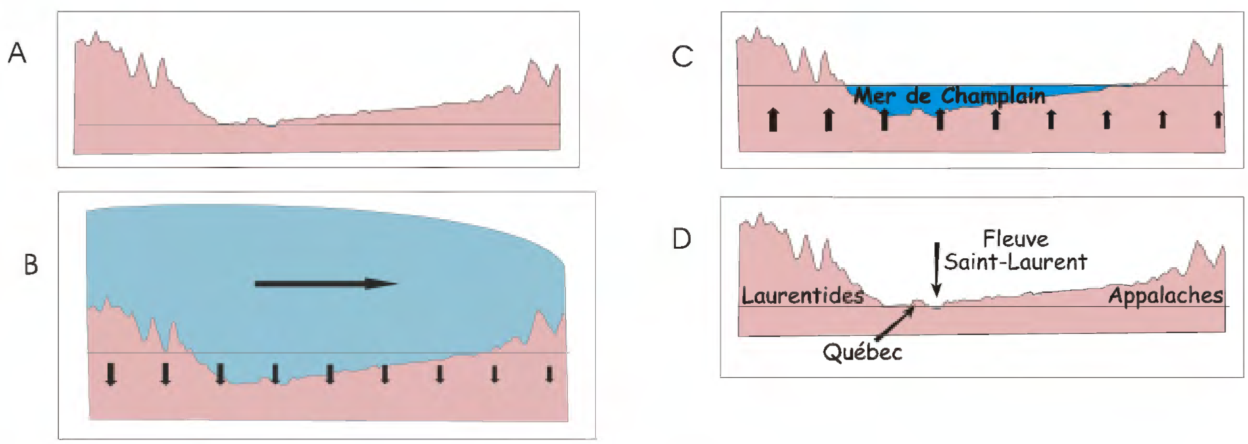


Figure 18. (a) Relief of the Québec region 80,000 years ago, before the Wisconsin glaciation. (b) 18,000 years ago, at the glacial maximum, the continent subsided under the weight of an ice layer three kilometres thick. Québec City was located more than 200 meters below sea level. (c) The Champlain Sea occupied the St. Lawrence Valley, sea level declined gradually, isostatic rebound occured. (d) The circle is completed in the space of 80,000 years and equilibrium is attained.

Isostasy is the response of the Earth's crust to being depressed by (subsidence) or relieved of (rebound) an enormous weight that disrupts crustal equilibrium. More specifically, glacio-isostasy is due to the development and the melting of Quaternary ice caps. Under the weight of an ice cap that was 2 km to 3 km thick at its maximum extent, the original topography of the St. Lawrence Valley (Fig. 18a) was depressed by several hundred meters (Fig. 18b). When the glacier melts, since glacio-isostatic rebound does not occur instantly, the depressed valley becomes invaded by a postglacial sea (Fig. 18c). Freed from the weight of the glacier, the crust rises as it seeks to regain its forer state of equilibrium (Fig. 18d), and the sea is forced to recede towards the ocean. The time it takes the Earth's crust to regain its equilibrium in the new situation created by the formation or retreat of an ice cap has been estimated at 20,000 years.

12,000 years ago, Quebec City under water

Approximately 12,000 years ago, after the glaciers retreated, water of the Atlantic Ocean invaded the St. Lawrence Lowlands and formed the Champlain Sea (Fig. 19). It covered some 55,000 km^2, from Québec City to Pembroke, Ontario, and from the Appalachians to the Laurentians. The average water temperature in the Champlain

Sea was similar to that of James Bay, between -1 and 8°C. It was a cold sea, home to marine mammals such as beluga, boreal whale, walrus and different species of seals. As it retreated (Figs 19–22), the Champlain Sea covered the St. Lawrence Lowlands with a thick layer of sediments, which gave rise to the fertile soils of today. The present-day course of the St. Lawrence is the result of a long tectonic, glacial and marine history!

Figure 19. The glaciers retreated as the Earth's climate experienced a warming trend, leaving behind depressions deeper than sea level. The waters of the Atlantic Ocean then invaded the St. Lawrence Valley, forming the Champlain Sea. As the glacial melt waters mixed with the seawater, the Champlain Sea eventually reached its maximum extent 12,000 years ago.

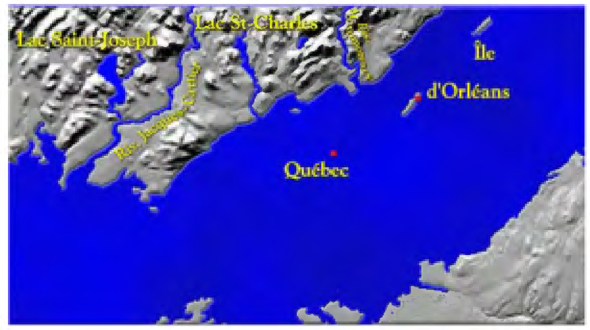


Figure 20. The area that is now Quebec City gradually rose as a result of isostatic rebound, and the Champlain Sea began receding. The first two high points on Ile d'Orléans emerged.

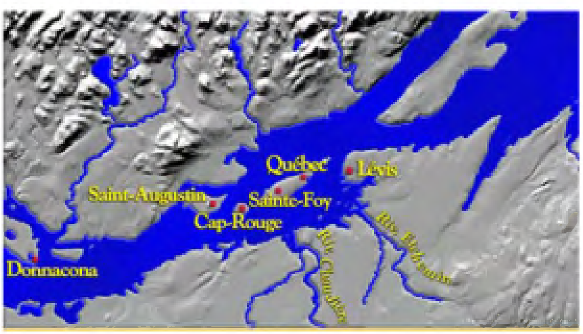


Figure 21. The sea kept receding, making way for an estuary and then a system of rivers representing the forerunner of the St. Lawrence. This happened 9,500 years ago. The highest points in the region, namely Saint-Augustin, Cap-Rouge, Sainte-Foy, Quebec City and Lévis, existed as islands at one point in their history. Today, Île d'Orléans alone bears witness to the islands scattered around Quebec City long ago.

Figure 22. The level of the St. Lawrence has fluctuated, changing by tens of metres several times over the last 9,000 years, in response to climatic changes which were minor compared with the glaciations but had a considerable effect on riparian ecosystems.

Walking from Asia to Quebec via…?

The latter part of the Quaternary is also the interval during which North America was first occupied by people. Although alternate scenarios have been proposed, most evidence suggests that people entered North America from northeast Asia. During glaciation, the huge amount of water stored in the continental glaciers caused sea-level to drop substantially, exposing extensive areas of terrain along the present coastlines that are now again under water. During the Wisconsin glaciation, the Bering Strait, between the Chukchi Peninsula in Siberia and the Seward Peninsula in Alaska, was dry. Shallow coastal areas around Alaska and Siberia were also dry, and formed part of a northern landmass called Beringia, across which humans traveled and entered North America.

The timing of this arrival in North America remains a matter of great debate (Fig. 23). So far, no relevant archaeological sites in northeast Asia or Alaska have been shown conclusively to date from before the last glaciation. The best hypothesis is that people first entered Alaska sometime after the last glacial maximum, that is, after 18,000 years ago, although the oldest sites presently known in Alaska date to around 12,000 years ago.

Besides the timing of entry of people into North America, a second debate exists around the route they took. With lower sea level and a more extensive coastal area, people could have traveled down the west coast of North America and from there inland, perhaps up major river valleys. Rich coastal and in-shore marine resources would have provided ample food. Any archaeological sites associated with such travel would now probably be underwater, since these coastal areas were inundated during deglaciation. To compound the problem, there are no archaeological sites known from the northwest coast that date to the right time to record the migration. Some parts of the journey, for instance along the southern coast of Alaska, would probably also have required travel by water. Although it is not impossible that people in this region had boat technology at the time, there is no archaeological evidence for it.

An alternate view is that people migrated from interior Alaska and Yukon into interior North America south of the ice-sheets using an inland route east of the Rockies. This hypothesized route was known as the "ice-free corridor". Certainly this route would have been impassable at the height of glaciation when the Laurentide Ice Sheet abutted against the mountain front and ice from the mountains flowed eastwards. At some point in deglaciation, however, land east of the Rockies did become ice-free. The deglaciation patterns and archeological evidences found in southern Alberta do not enable a good correlation between the final opening of the ice-free corridor and the age of the sites.

The discussion about how, when and where people first entered North America is unlikely to end any time soon! What is certain, however, is that by the end of the last ice-age people were well-established in areas south of the Laurentide ice sheet and poised to take advantage of new terrain and opportunities as land became available during deglaciation.

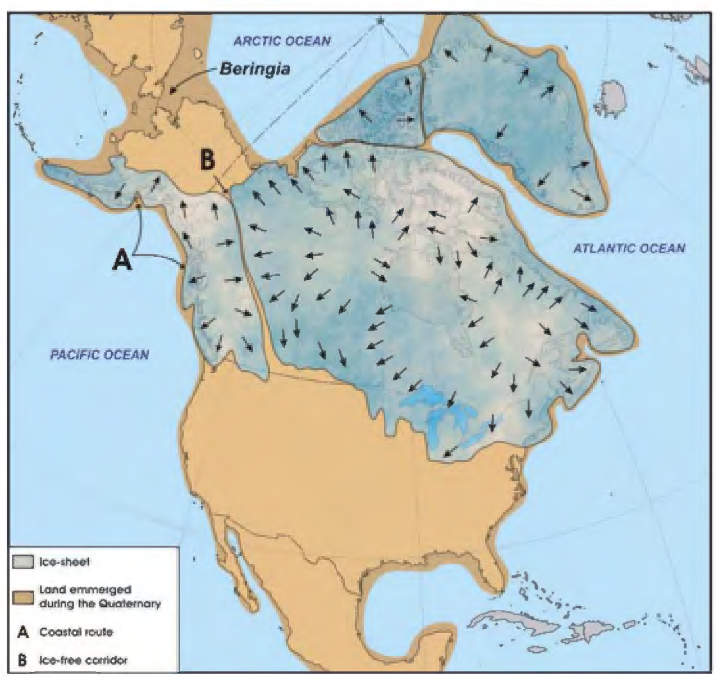


Figure 23. The map shows a schematic representation of the extent of ice during the Quaternary, showing the two routes of human migration. It should be noted that both routes can not have co-existed and are represented together on the map only to support the text.

* The Champlain Monument on the esplanade in front of the Château Frontenac is a gift from France that was made out of Château-Landon limestone in 1898 and has a stepped base made of Vosges granite. This is the same limestone that was used for the Arch of Triumph in Paris and for the Montmartre Basilica. Time has taken its toll on the monument, as evidenced by the many signs of age and wear. Did you know that no official portrait of Quebec City's founder exists? A false portrait of Samuel de Champlain bears the features of Michel Particelli, an unscrupulous French finance inspector, from a 1654 portrait. The monument was created by Paul Chevré, a survivor of the 1912 Titanic shipwreck off the coast of Newfoundland.

* The thrust sheets of the Appalachians are what gave rise to the city's scarped relief. The stairs from the Lower Town and the steep hills allow us to climb up or down the thrust sheet forming the promontory of Quebec (Figs. 24 and 25). The funicular also provides a way to go between these two different levels. The geology of Quebec City has played a role in urban development. At the start of the colony, most of the houses were located in Place-Royale and in the Petit-Champlain district. This facilitated port exchanges along with access to water supplies and resources. Only dignitaries and government and religious institutions were located in the Upper Town, which guaranteed their safety and set them apart socially.

Figure 24. Not far away, in Côte de la Montagne, General Prescott ordered the 1797 construction of a gate that would better control access to the Upper Town, and to which he lent his name. The Prescott Gate is one of five entrances to the Upper Town, along with the St. Louis, St. Jean, Hope and Du Palais gates. The original gates were far narrower than those that exist today. After it was demolished in 1871, a footbridge was erected by Parks Canada in honour of the Prescott Gate, during the 375th anniversary of the City of Quebec. The new gate's architecture blends stone and concrete. Its construction, however, made use of the geological resources of the Quaternary period: sand and gravel. National Archives of Canada, 1873, W.O. Carlile.

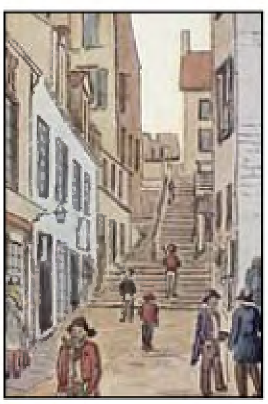


Figure 25. The Break-Neck Stairs were one of the first links between the Lower and Upper Towns. On a 1660 map of the city, the stairs are shown as "l'escalier Champlain." The current name dates back to the 19th century and stems from a nickname given to the stairs by American visitors to the city. National Archives of Canada, 1830, J.P. Cockburn.

STOP 5. Verrerie La Mailloche building

This building, located at the intersection of rue Sous-le-Fort and the Break-Neck Stairs (escalier Casse-Cou) is constructed of very fossiliferous limestone in which brachiopods are visible (Fig. 26). This limestone from Saint-Marc-des-Carrières was used in preference to Beauport limestone, because it occurs in massive banks from which large solid blocks can be cut.

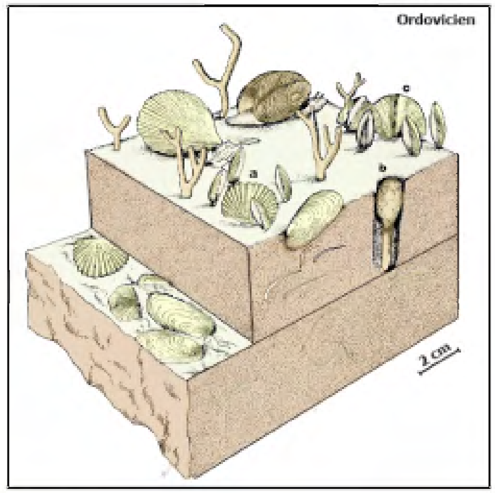


Figure 26. Brachiopods were small invertebrates with a shell. The drawing on the left shows their habitat (d, e, f), among the marine fossil species that populated the Iapetus Ocean in the Paleozoic era. *The Ecology of fossils.*

STOP 6. Parc Félix-Leclerc

This stop (Figs. 27 and 28) marks the site of a former quarry where the black stone (called "Cap stone") typifying Quebec was extracted. Back in the days when the quarry was in operation, the waters of the St. Lawrence River reached the foot of the cliff. It is believed that ships took on loads of stone during low tide and set sail at high tide. The river is now some distance from the cliff. Besides the fill that was dumped in the river to create land on which to build Champlain Boulevard, natural variations in sea level, such as those associated with the most recent glacio-isostatic adjustments, help to explain the river's retreat since colonial times.

Current ripples in the rocks that form the pavement of the park are evidence of a former beach environment.

Figure 27. Parc Félix-Leclerc.

Figure 28. You are currently in the Petit Champlain district, which was long held to be the gateway of Irish immigrants in the 19th century. It topped all other districts with a 72% Irish population. The nearby harbour, shipyard and lumber coves provided employment for the district's low-skilled workers. Managed by Parks Canada, the Old Port of Quebec Interpretation Centre located on Quai Saint-André is a testament to the golden age of Quebec City's timber trade in the 19th century. National Archives Canada, 1833, J.P. Cockburn.

Gravity at work

The landslides at Cap Diamant caused numerous deaths and considerable property damage, particularly in the early days of the colony. The two most serious slides on the site of present-day Champlain Boulevard were the one on May 17, 1841, in which six houses were destroyed and 27 people killed, and the one on September 19, 1889, in which 45 people lost their lives (Fig. 29). The area around rue du Petit-Champlain has also seen some dramatic events, the most memorable of which took place in 1841 and 1889. A number of conditions led to these catastrophic slides: the very steep cliff and unstable slope, the highly friable sedimentary rocks (argillaceous limestone and shales) and the bedding plane (corresponding to the plane of weakness) was parallel to the slope (Fig. 30). Vegetation that would otherwise help to retain the debris and stabilize the slope could not become established easily. Furthermore, in the early days of settlement, the river waters lapped against the houses at high tide. Owing to the limited space available for building, workers would excavate deeply into the cliff base, thereby increasing the instability of the upper slope. Climatic conditions such as heavy rains and freeze–thaw action played a role in triggering landslides, as did the vibrations associated with earthquakes or, historically, cannon shots.

Figure 29. Landslide of September 19, 1889. Société historique de Québec.

Effective techniques were employed to minimize the risk of landslides all along Champlain Boulevard and rue Sault-au-Matelot: unstable material was removed in order to create a gentler slope, and draped wire mesh, rock bolts and fences were installed.

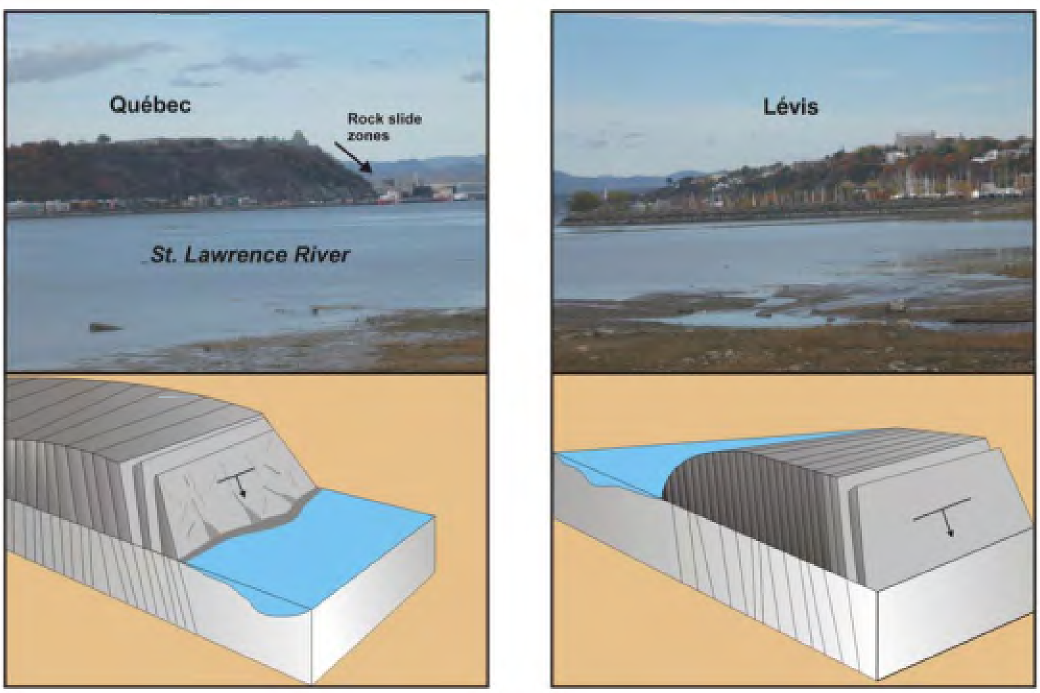


Figure 30. Tilting or dipping layers cause more of a landslide hazard on the north shore of the St. Lawrence River. On boulevard Champlain, the strata tilt along slope, amplifying the landslide hazard. On the contrary, on the south shore, they tilt inwards into the cliff, providing cramping and giving greater stability.

About seismicity in Quebec

Seismic activity in Quebec is centred in the Charlevoix/Kamouraska region where a meteorite once struck, weakening the Earth's crust. It is expressed mainly through reactivation of the faults that delimit the St. Lawrence rift valley, which is undergoing readjustment owing to isostatic rebound. In Quebec City, the seismic risk is limited and the effects are weak. However, the city is not immune to earthquakes. On November 5, 1997, an earthquake of magnitude 5.2 shook the city and even stopped the parliament clock at 9:34 pm, which is when the event occurred. Its epicentre was located in the Cap-Rouge area. In 1988, it was an earthquake centred in the Saguenay that rattled the capital. The sectors at risk in Quebec City are the Cap Diamant cliff (risk of landslide) and the Saint-Charles River valley, whose clay sediments tend to amplify seismic waves and cause liquification. Buildings constructed directly on bedrock can withstand seismic waves better.

STOP 7. Maison Parent

To see all of the rocks that typify the Quebec City region, it is necessary to cover a lot of ground. Many of them were used in constructing the Maison Parent (Fig. 31). Located at the corner of rue Saint-Pierre and rue Sous-le-Fort, this house was rebuilt in 1761, after being demolished during the siege of Quebec City by the British in 1759. The exterior wall coverings contain various stones, some of which were salvaged from the former building. They include Ange-Gardien calcareous sandstone of varying grain size whose ochre and red coloration is attributable to oxidation of ferruginous minerals, Beauport limestone, Sillery sandstone, Rivière-à-Pierre granite and "cap stone." The door and window frames are made of Pointe-aux-Trembles limestone.

Figure 31. Maison Parent

* The Royal Battery can be found right next door to the Parent House. Built in 1691 on Governor Frontenac's orders, it was intended to fill a defensive void. The British invasion led by Phips in 1690, though driven back, pushed Frontenac to improve Quebec's defences. The Royal Battery was in the shape of a bastion, as can be seen from its present-day configuration, and was once at risk of falling into the St. Lawrence River. It was reconstructed in 1977 and now includes replicas of French cannons. Remarkably, the space has encroached on the St. Lawrence River over the years.

It was only in 1967 that the Quebec government decided to restore Place Royale and its surroundings (Fig. 32). Since the neighbourhood was poor and dilapidated, the provincial government took charge of the restoration and reconstruction of the buildings in the area to restore the New France ambience, and thus recall the urban development of Quebec's beginnings. Nowadays, Place Royale is largely a tourist and commercial district; the site of the city's early colonization now lives to the rhythm of the tourist season, because few people live there.

Figure 32. Place Royale. Photo S. Careau.

* The bust of Louis XIV is anchored on Stratford Green granite, the pillar is made out of royal Canadian red granite from Manitoba and the base is made of grey Saint-Sébastien granite. The steps in the circular base are made of grey Stanstead granite and the middle of the upper level in Royal Canadian Red granite. Granite, an igneous rock with large crystals, is highly resistant in cold temperate climates, and resistant to water, more so than sedimentary rocks like sandstone and limestone. That is why the piers of the Pont de Québec (Quebec Bridge) were carved from Rivière-à-Pierre granite.

* Place de Paris. The monument entitled "Dialogue avec l'histoire" features white marble blocks from Greece. Marble is limestone that has undergone metamorphism. The marble blocks are separated by bands of black South African granite.

STOP 8. Côte de la Montagne

The cliff located at the junction of Côte de la Montagne and rue Sault-au-Matelot displays an olistostrome, a rock that features blocks of various sizes contained in a matrix of argillaceous rock (Fig. 33). The argillaceous matrix originated as mud deposited in the depths of an ancient ocean. This ocean was flanked by a mountain range in formation (the Appalachians). Because of the relief resulting from the rising mountain range, and gravity-induced erosion, large rock masses were detached from the flanks of thrust sheets and slided to the sea. These blocks slided then were stuck in the mud, similar to chocolate chips in cookie dough. They were gradually buried under sediments, that continued to accumulate above them, then the nappes themselves overthrusted them. Submitted to high pressures and temperatures due to burial, the sediments were transformed into rock (diagenesis).

Figure 33. Olistrostrome in Côte de la Montagne

Place d'Armes (Fig. 34), located close to the Château Saint-Louis, once the seat of political and military power, was the main assembly grounds for the soldiers who were needed to respond quickly in the event of an attack. Quebec's main streets (Saint-Jean, Saint-Louis and Sainte-Anne) lead away from Place d'Armes toward the fortifications, in the European tradition. During the British period, in the 19th century, Place d'Armes became an urban park complete with horseback riding and public hangings. Nowadays, the centre of Place d'Armes features the Monument de la Foi [Monument to Faith], built in 1916 to commemorate the 300th anniversary of the Récollet fathers' arrival in Quebec City.

Figure 34. Place d'Armes. Société historique de Québec.

* Côte de la Montagne was built by Champlain in 1620. It was the first official link between the city's Lower and Upper Towns. The different levels modelled Quebec City's development along the lines of a medieval town: an Upper Town for the political, military and religious elite, and a Lower Town for the merchants, craftspeople and workers.

* On rue Saint-Pierre, note the different finishes of the limestone blocks in the building facades: hammered, sanded, vermiculated, etc.

* The position of rue Saint-Pierre is the exact extent of high tides in the beginnings of the colony. Markers have been installed in the cobblestones in rue Saint-Antoine where the water was at its maximum in 1600, 1700, and 1800. A portion of the lowering of the St. Lawrence level indicated by the markers is due to the fact that all the houses east of rue St-Paul were built on embankments. In addition, work conducted in the Montmagny area has shown that since the ice retreat, the level of the St. Lawrence level has fluctuated several times compared to today's level. The sea retreat is thus another factor that contributes to the lowering of the level of hight tides.

STOP 9. Rue Sous-le-Cap

In rue Sous-le-Cap and at the intersection of rue Barricade and rue Sault-au-Matelot, there is an outcrop of the thrust sheet that forms the Quebec promontory (Figs. 35 and 36). Massive argillaceous limestone is interbedded with thin layers of black shale and there are vein veneers on some beds. The rocks underwent considerable deformation (folding, faulting).

Figure 35. The lane between rue Sous-le-Cap and rue Sault-au-Matelot is now blocked and fencing was recently installed to prevent accidents connected with the landslide hazard. Draped wire mesh, rock bolts and fences installed in the cliff along rue Sault-au-Matelot serves as a reminder that the Place-Royale sector of Cap Diamant is unstable. Corrective work was carried out to make the site safer, including the removal of unstable boulders, the construction of a retaining wall (rue Sault-au-Matelot) and the installation of rock bolts.

The Library of Congress, 1786, J. Trumbull

Figure 36. When the Americans invaded Quebec City in 1775, during the American Revolution, Benedict Arnold's troops landed with the intention of overtaking the city and preventing the British from deploying reinforcements to the 13 colonies. Arnold was joined by General Richard Montgomery, who had already conquered Montreal in early December. While Montgomery launched an attack on the Cap Diamant side, Arnold attacked near Rue Sous le Cap, at the Sault au Matelot barricade on the other side of town. Arnold succeeded in seizing several barricades, but in the end was defeated by Captain Dumas and his militia. The Americans laid siege to the City of Quebec in 1775. Knowing that the contracts of several of their soldiers would expire at the end of the year, the two American generals launched the attack on December 31, 1775 during a snowstorm. The Rue Sous le Cap attack was a complete failure and marked the end of the American military drive.

* After going up Côte de la Montagne, we climb up the Baillargé staircase beside the Main Post Office. Note that the wall of the staircase is made of Rivière-à-Pierre granite.

* The main post office of Quebec City, also called the Louis-S.-Saint-Laurent building, was constructed between 1871 and 1873. It is faced with hammered fossiliferous limestone blocks from Saint-Marc-des-Carrières. The interior walls and counter are made out of grey-blue marble (metamorphosed limestone) from Philipsburg in the Eastern Townships containing contains mounds of algae (thrombolites). The lower part of the counter is made of black marble.

* The Daily Telegraph building, constructed in 1907, is located at the corner of rue Buade and rue du Trésor. It is a brick building with olive green stone from the Miramichi region of New Brunswick, which forms the string course, lintels and the pediments of the facade. This very porous sandstone is not very resistant to freeze–thaw

activity and road salt, both of which cause it to disintegrate. Some stones have been replaced with buff-coloured limestone, which contrasts sharply with the olive green.

* The old Quebec Palais de Justice (courthouse) was built between 1883 and 1887. The architectural style is that of French Renaissance châteaux. Quite a variety of stones were used in its construction (three types of sandstone, a limestone and three types of granite). Can you identify them?

* The Maisons de Beaucours, at 33 rue Saint-Louis, was constructed from limestone that comes from Chambord, in the Saguenay region. Many fossils can be seen in the stones with sanded surfaces: cephalopods, gastropods, etc. The stone is very clayey and hence vulnerable to alteration.

* At 26 rue Saint-Louis, bryozoans stand in contrast to the altered surface of the stone.

* Musée d'art inuit. Tourist attraction with an interesting collection of Inuit soapstone sculptures.

* Aux anciens Canadiens. The oldest house on the promontory, made of cap stone covered with parget.

STOP 10. Price Building

The building's exterior covering consists partly of Saint-Marc-des-Carrières limestone and Queenston limestone from the Niagara escarpment (Fig. 37). Queenston limestone is pearl-gray in colour on a fresh surface, and pink calcite crinoid stalks are easy to identify in the columns (Fig. 38). Queenston limestone is rougher to the touch and it is more altered than Saint-Marc-des-Carrières limestone. The latter develops a light beige patina, whereas Queenston limestone takes on a brownish-buff colour as it becomes altered. Stone from Ontario was probably used because the quarries in Saint-Marc-des-Carrières could not meet the demand. Note that this resource is non-renewable and it is important to preserve it.

Figure 37. The Price Building was built in 1929 by the Price Brothers pulp and paper company, at a cost of $1 million. The 17-storey building was the tallest in Old Quebec for a long time, and spawned a 1932 municipal by-law prohibiting the construction of any building taller than 20 metres [65 feet], to protect the visual landscape of the Old Town.

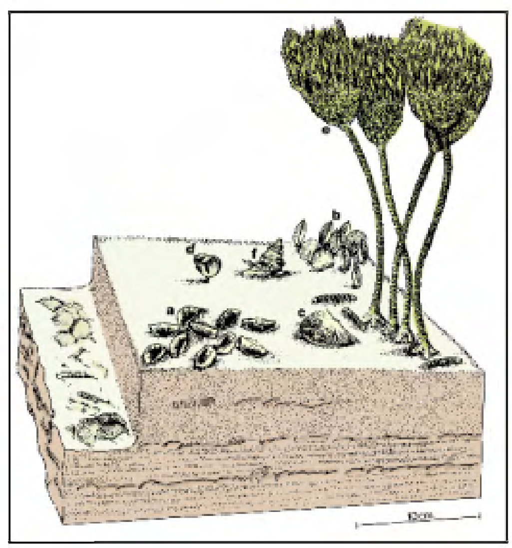


Figure 38. Crinoids belong to the class of echinoderms, as do sea urchins. They typically have a calyx composed of regularly arranged plates, movable arms and a stalk for attaching themselves. Though they may in rare cases be found whole, they are usually found as debris, particularly stalk fragments called entrochites. The drawing shows their habitat (e), among the marine fossil species that lived in the Iapetus Ocean during the Paleozoic era.

The Ecology of Fossils

National Archives Canada

Figure 39. The Jesuit College could once be found across from the Price Building, where City Hall currently stands. Following the 1759 Conquest, British military authorities transformed the Jesuit College into soldiers' barracks. As was the case for the Dauphine Redoubt and the new barracks in the Artillery Park in the Old Town, the British occupied the Jesuit College until 1871. In addition to the barracks, the site holds a guardhouse, an armourer shop, a bakery and a parade ground, among others. The Jesuit College was destroyed in 1877 to make room for City Hall.

CONCLUSIONS

But just who was Logan?

Providing an introduction to William Logan is a fitting way to end this geological overview of the Quebec City region. He was one of the first geologists to study the diverse geology of the area and the fault that bears his name. In 1842, Logan founded the Geological Survey of Canada (GSC), which he directed for 27 years. He was a well-known geologist and a great explorer whose studies took him across Canada from the Atlantic to the Pacific.

Logan was born in Montreal in 1798, the son of a baker who had immigrated to Canada from Scotland. After studying for a short time at the University of Edinburgh and working in England and Wales, Logan became interested in how to find coal and began studying geology, which at the time was a young discipline. Logan was 44 years old in 1842, when he was appointed to conduct a geological survey of the Province of Canada. During his early years with the Geological Survey, Logan and an assistant travelled across much of the Province of Canada, which at the time consisted of the southern half of the present-day provinces of Ontario and Quebec. During the period spanned by Logan's career, the GSC offices were located in Montreal.

Although William Logan was a rich man, he paid little attention to his physical well-being and his attire. At times he was taken for a vagabond, and there are many confirmed cases where his appearance led strangers to believe that he was mentally unbalanced. On one of these occasions, Logan was doing some field work while staying in a hotel in Quebec City. On the first morning, he asked the hotel clerk to arrange for a horse-drawn carriage, or calèche, to pick him up. At the sight of Logan coming out of the hotel, the driver immediately assumed that this was a patient from the insane asylum in Beauport coming back from an outing. Without heeding Logan's protests, the driver began heading for the asylum. Logan's problem was that people thought he was crazy. So the founder of the GSC decided to take advantage of this situation. He pulled out his geologist's hammer, and brandishing it near the driver's head, he demanded to be taken to his chosen destination. The driver obeyed. At the end of the day, Logan asked the driver to take him back to the hotel. While the director of the GSC unloaded his rock samples, the driver told his fellow drivers about the awful day he had spent in the company of this dangerous lunatic. Without saying a word, Logan went up to the driver, paid him his due and added a large tip. Upon leaving his hotel the next morning, he found a crowd of drivers all wanting to provide conveyance for a generous lunatic.

For more information:

Sir William Logan 1798-1875: **http://cgc.rncan.gc.ca/hist/logan/index_e.php**

No stone unturned. The first 150 years of the Geological Survey of Canada :
http://cgc.rncan.gc.ca/hist/150_e.php

William E. Logan and the Geological Survey of Canada: Written in stone :
http://www.collectionscanada.ca/logan/index2-e.html

Life of a Rock Star: **http://www.collectionscanada.ca/rock/index2-e.html**

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USEFUL LINKS

Earth Sciences Sector

GSC Bookstore
http://gsc.nrcan.gc.ca/bookstore

The GSC bookstore is a distribution outlet for GSC publications and it also gives access to NRCan geoscience knowledge. It provides the scientific community, teachers and the general public a one-stop access to information: on-line directories and datasets, sale and free downloads, educational tools.

GEOSCAN
http://ess.nrcan.gc.ca/esic/geoscan_e.php

This database comprises more than 55,000 records of scientific publications from the Geological Survey of Canada and the Canada Centre for Remote Sensing.

Geoscience Data Repository
http://gdr.nrcan.gc.ca

Discover, view and download, free of charge, the following information:

- **Maps: MIRAGE (PDF and MrSID format); Digital geoscience maps (on WMS)**
- **Geological surveys: Aeromagnetic; gravity; radioactivity; seismic and magnetotelluric data**
- **Geochemistry: NGR National geochemical reconnaissance data; Geochemical survey metadata**
- **Other geoscience data: Mineral deposits; Energy – Fossil Fuels data discovery tool; Canadian geochronology knowledge base; Physical Rock Properties**
- **Marine geoscience: ED Expedition Database; Physical archive database; Canadian Marine Multibeam Bathymetric Data**
- **Other resources: Lexicon of Canadian Geological Names; GeoPub; GeoGratis; GeoBase; GeoConnexion; Geomagnetic Data; Canadian Landscapes Photo Collection; Canadian Diatom Database; Borehole geophysical logs in surficial sedements of Canada (GSC compilation); BASIN (petroleum exploration); Seismic data; Climate Change; Natural hazards; Urban geology**

GeoInfo
http://esic.ess.nrcan.gc.ca/search/

Union catalogue of the Earth Sciences Sector Libraries.

Information Circular
http://gsc.nrcan.gc.ca/bookstore/circ/index_e.php

Published monthly to announce the publication of new reports and maps (and reprints), and the release of Open Files.

OTHER USEFUL LINKS

GeoGratis
http://geogratis.cgdi.gc.ca

The geospatial data are grouped in collections and are compatible with the most popular geographic information systems (GIS). The free data will be useful whether you are a novice who needs a geographic map for a presentation, or an expert who wants to overlay a vector layer of digital data on a classified multiband image, with a digital elevation model as a backdrop.

Atlas of Canada
http://atlas.gc.ca

The Atlas of Canada provides authoritative, current and accessible geographic information products at a national level. Working with partners, the Atlas facilitates the integration and analysis of diverse data in order to increase overall knowledge about Canada.

GeoBase
http://www.geobase.ca

GeoBase is a federal, provincial and territorial government initiative that is overseen by the Canadian Council on Geomatics (CCOG). It is undertaken to ensure the provision of, and access to, a common, up-to-date and maintained base of quality geospatial data for all of Canada. Through the GeoBase portal, users with an interest in the field of geomatics have access to quality geospatial information at no cost and with unrestricted use.

GeoConnexions
http://www.geoconnections.org

GeoConnections helps decision-makers use online geospatial information, such as maps and satellite images, to tackle some of Canada's most pressing challenges. The program focuses on working with partners in public health, public safety and security, the environment and sustainable development, Aboriginal matters, and geomatics technology development.

Natural Resources Canada: http://www.nrcan-rncan.gc.ca
- **Earth Sciences Sector: http://ess.rncan.gc.ca**
- **Energy Policy Sector: http://www2.rncan.gc.ca/es**
- **Energy Technology and Programs Sector: http://www2.rncan.gc.ca/es**
- **Minerals and Metals Sector: http://www.rncan.gc.ca/mms**
- **Canadian Forestry Service: http://www.nrcan-rncan.gc.ca/cfs-scf**

Science and Technology at NRCan: http://www.rncan.gc.ca/dmo/scitech
NRCan kids' site: http://www.rncan.gc.ca/kids
Earth Sciences Sector Programs: http://sst.rncan.gc.ca/pri/index_e.php
Geological Survey of Canada: http://gsc.rncan.gc.ca
Geomatic Canada: http://sst.rncan.gc.ca/geocan/index_e.php
Network of Federal Research and Development Organizations in Québec: http://www.universadecouvrir.gc.ca/

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WATER, EARTH AND ENVIRONMENT

A global vision for sustainable environmental development

The Eau, Terre et Environnement research centre plays an important part in the sustainable development of natural resources.

Combining a multidisciplinary approach with extensive laboratory and field experience, the Centre's professor-researchers are well equipped to tackle such complex problems as global warming and environmental pollution hazards. They analyze the impact of climate change and extreme weather events on populations and ecosystems. In addition to being involved in resource management and land-use development, researchers at the Centre work to restore urban and natural environments.

They have earned a solid reputation for their investigations of geological phenomena, including mineral, gas, and oil resources and groundwater. Several teams are developing procedures for decontaminating sites, waste, and industrial residues, and for restoring natural landscapes and habitats. The Centre has also built a sound expertise in water management software, which is currently in high demand in Québec and worldwide.

Research

Sustainable use of the earth's resources, respect for the environment, and environmental risk assessment are matters that concern the entire world. Among the wide range of issues related to these matters, the Centre's professors have chosen to concentrate on four themes that are particularly crucial for the future of the planet: environmental and contamination risks; integrated management of water and mineral resources and land development; restorative technologies for urban and natural settings; and finally, impact and adaptability related to climate change and extreme weather event.

Some professors concentrate on surface water management and hydrology, studying the impact of climate change on water resources. They also develop integrated, user-friendly tools used for watershed management. Researchers also seek to understand and simulate water flow and the transport of dissolved substances, using a broad spectrum of statistical and numerical analyses, deterministic modelling and remote sensing.

Others focus on the contamination problems, a particularly crucial issue on both a scientific and socio-economic level. They also investigate the impact of pollutants on human fertility, a problem to which Canadian government has given high priority. Meanwhile, the biogeochemistry research team is working on identifying underlying processes so they can better predict the influence of environmental changes on aquatic ecosystems.

The Eau, Terre et Environnement research centre also acts as the main centre for the study of hydrocarbon resources in Eastern Canada. The geodynamic research group focuses on the characterization of surface geological processes and geological processes involved in the generation of natural resources. Finally, other researchers develop theoretical models and practical applications of hydrometallurgy and minerallurgy for use in decontamination and environmental restoration. Considerable research efforts have also been directed toward developing new procedures for the bio-transformation of waste, biomass, and industrial and urban waste into value-added products.

Expertise

The Centre's professors have perfected new, high-performance data analysis methods for hydraulic, hydrological, limnological, and hydrogeological phenomena. They have a long-standing reputation for their in-depth knowledge of the geological processes of eastern Canada. Their sound body of expertise has earned the Centre a Canada Research Chair in Metal Ecotoxicology, a Canada Research Chair in Environmental Decontamination, a Canada Research Chair in Hydrological Variable Assessment and a Canada Research Chair on the bioconversion of wastewater water and wastewater sludge into value added products. In addition to overseeing the CRSNG/Hydro-Québec Industrial Research Chair in Statistical Hydrology, the Centre is widely acknowledged for its expertise in the following fields:

- Integrated watershed management;
- Hydrology, hydraulics and ecohydraulics;
- Biogeochemistry and ecotoxicology of metals and organic contaminants;
- Determination of snow coverage by remote sensing;
- Environmental hydrometallurgy and minerallurgy;
- Biomass and residue recycling;
- Regional hydrogeology;
- Geomorphology (glacial, periglacial, fluvial, and coastal);
- Mineral and organic diagenesis;
- Geology of the Appalachians and Grenville;
- Geology of the quaternary period and glacial-sedimentary exploration;
- Geological risk prevention.

Research training

Research training at the Centre puts students in direct contact with real and concrete tasks such as flow modelling, decontamination technologies, chemical and biological dynamics of aquatic environments, geodynamics, and geochemistry of mineral, oil, and gas resources. The Centre offers six graduate and postgraduate study programs:

- MSc in Water Sciences;
- Professional MSc in Water Sciences;
- PhD in Water Sciences;
- MSc in Earth Sciences (offered in conjunction with Université Laval);
- Professional MSc in Earth Sciences (offered in conjunction with Université Laval);
- PhD in Earth Sciences (offered in conjunction with Université Laval).

Partnerships and alliances

The Eau, Terre et Environnement research centre participates in numerous strategic partnerships. To date, the Centre has sustained a close collaboration with the Geological Survey of Canada (Québec section) for research and training. The Centre also maintains solid partnerships with Hydro-Québec, concretized by the CRSNG/Hydro-Québec Industrial Chair in Statistical Hydrology.

The Centre is actively involved in the management of a Canadian research network on metals in the environment (aquatic sector), with support from the Natural Sciences and Engineering Research Council of Canada, a group of scientists as well as government and industrial representatives.

The Centre's professors also collaborate with researchers from all continents. Projects are underway in Latin America with the Federal University of Parana in Brazil and the National University of the North-East in Argentina. In Africa, agreements have been made with various institutions in the Ivory Coast, Egypt, Tunisia, Morocco and Algeria. Researchers of the Chair in Statistical Hydrology also take part in SPHERE, a project financed by the European Community.

The Centre's professors also participate in joint projects with government ministries and public organizations. They regularly collaborate with Québec departments: ministère du Développement durable, de l'Environnement et des Parcs; de l'Agriculture, des Pêcheries et de l'Alimentation; des Affaires municipales et des Régions; and des Ressources naturelles. Other governmental and municipal bodies rely on the Centre's know-how, including Environment Canada, Parks Canada, the Department of National Defence, and numerous ministries from the Maritime provinces as well as Québec City, Montréal and other cities. Finally, several local and international corporations have benefited from the INRS expertise: Breuvages Nora, BPR Groupe-conseil, Roche, Cambior, Gaz de France, Mines Gaspé, Shell and SOQUIP.

Services

While the laboratory services are geared to support the Centre's research projects, they are equally useful for external clients. The following are some of the many laboratories at the Centre:

- Tomography;
- Geology and geochemistry;
- Hydrogeology and environmental characterization;
- Biogeochemistry;
- Trace metals;
- Pesticides;
- Decontamination;
- Digital and software methods;
- Microscopics;
- Dendrochronology;
- Isotopic geochemistry;
- Digital cartography and photogrammetry;
- Remote sensing and image analysis;
- Paleoclimatology.

The Centre also has access to a wide range of resources for natural phenomena hazards site characterization and *in situ* prototype testing.

Statistics

Human resources

- 38 professor-researchers
- 48 visiting professors and researchers
- 21 associate professors
- 66 professionals, technicians and support staff

Research trainees

- 163 students, including:
  79 MSc students
  62 PhD students
  9 postdoctoral fellows
  13 internship students

Funding

- total budget of 17,5 million dollars including external research funds (grants and research contracts) of 8,6 million dollars

Université du Québec
Institut national de la recherche scientifique
Eau, Terre et Environnement

Yves Bégin, director

490, rue de la Couronne
Québec (Québec) G1K 9A9
CANADA
Telephone : 418 654-2524
Fax : 418 654-2600
yves.begin@ete.inrs.ca

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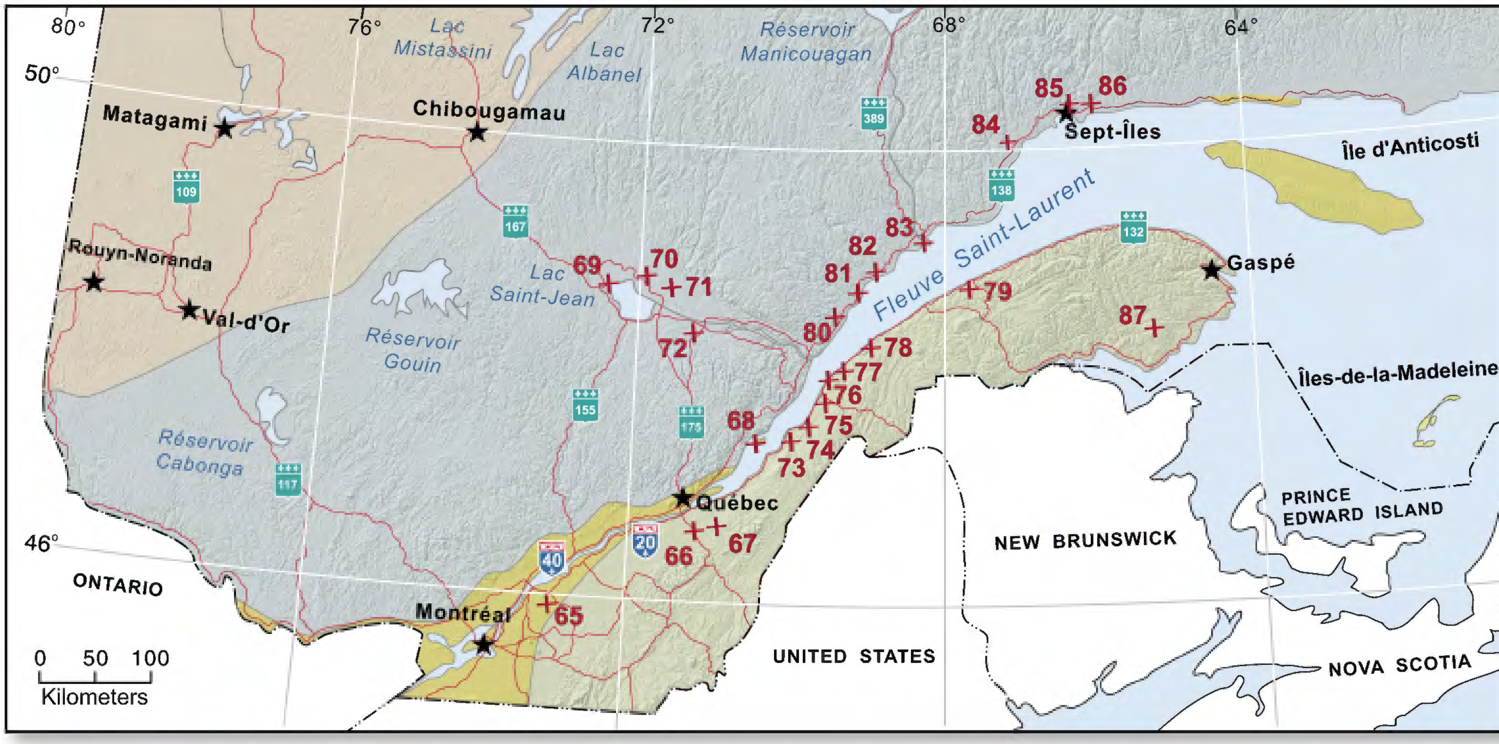
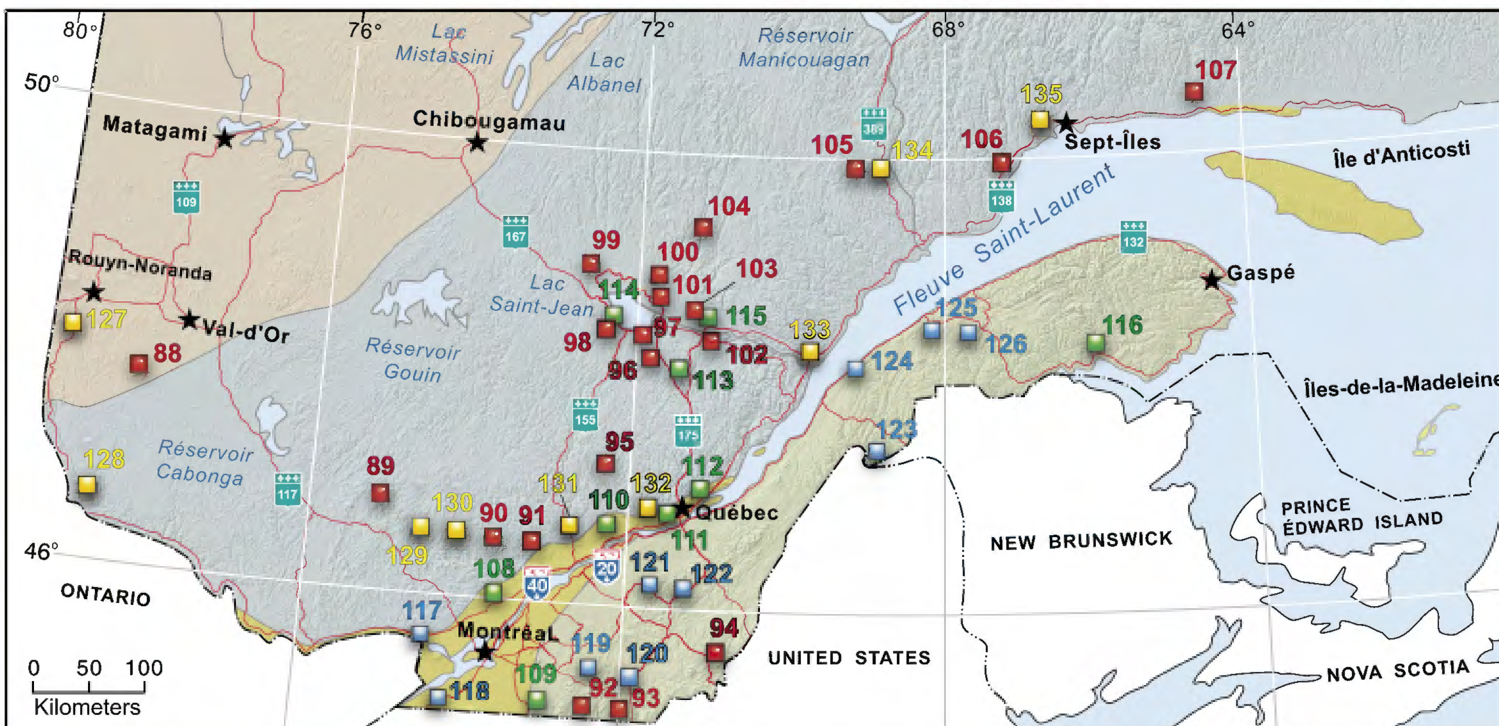
PEAT +



ARCHITECTURAL STONE ■



PEAT +	ARCHITECTURAL STONE ■	GEOLOGICAL PROVINCES
+ Peat	Granite	Appalachians
	Limestone, dolomite, marble	St. Lawrence Lowlands
	Sanstone, siltstone, slate, steatite	Grenville
	Gneiss, schist, quartzite	Superior
		Churchill

Ressources naturelles et Faune

Québec

MINES AND MAIN MINERAL DEPOSITS OF QUÉBEC

MINES

- Gold
- Nickel, copper, cobalt, PGE
- Gold, silver, zinc, copper
- Iron
- Ilmenite
- Niobium
- Asbestos
- Graphite
- Mica
- Salt, brine

MAIN DEPOSITS

- Gold
- Nickel, copper, cobalt, PGE
- Gold, silver, zinc, copper
- Zinc
- Iron
- Niobium
- Diamond

GEOLOGICAL PROVINCES

- Appalachians
- St. Lawrence Lowlands
- Grenville
- Superior
- Churchill

the mines — Online Products and Services

Geoscience maps, databases and reports are available at:
www.mrnf.gouv.qc.ca/english/products-services/mines.jsp

Ressources naturelles et Faune Québec