THE LATE QUATERNARY STRATIGRAPHIC RECORD NORTHWEST OF MONTREAL: REGIONAL ICE SHEET DYNAMICS AND ICE STREAM ACTIVITY[1]

ROSS, MARTIN, PARENT, MICHEL, BENJUMEA, BEATRIZ, HUNTER, JAMES

M. Ross[2]. Institut National de la Recherche Scientifique (INRS-ETE), 490, rue de la Couronne, Québec, QC, G1K 9A9, Canada. maross@nrcan.gc.ca

M. Parent. Geological Survey of Canada, 490, rue de la Couronne, Québec, QC, G1K 9A9, Canada. miparent@nrcan.gc.ca

B. Benjumea[3]. Geological Survey of Canada, 601 Booth Street, Ottawa, ON, K1A 0E8, Canada

J. Hunter. Geological Survey of Canada, 601 Booth Street, Ottawa, ON, K1A 0E8, Canada.

jhunter@nrcan.gc.ca

[1] Geological Survey of Canada Contribution

[2] Corresponding author: **M. Ross**. Institut National de la Recherche Scientifique (INRS-ETE), 490, rue de la Couronne, Québec, QC, G1K 9A9, Canada.

E-mail : maross@nrcan.gc.ca

Phone: (418) 654-3161

Fax: (418) 654-2600

[3] Present address: Departament de Geodinàmica i Geofisica. Universitat de Barcelona. C/ Martí i Franquès s/n. 08028 Barcelona, Spain (e-mail: benjumea@geo.ub.es)

Abstract— The Quaternary sediments of previously unstudied buried valleys and sections near Montreal are analyzed and other sites are revisited to further develop the stratigraphic framework of the St. Lawrence Lowland and to provide new insights for the reconstruction of glacial and deglacial events. The southwest-trending buried valleys contain concealed bedrock ridges and overdeepened troughs whose sediment record and 2D architecture were investigated by stratigraphic drilling and high-resolution seismic profiling. The Quaternary succession consists, from base to top, of proximal glaciolacustrine sediments, two superposed and lithologically contrasting till sheets (Argenteuil and Oka tills) of inferred Late Wisconsinan age, and Champlain Sea sediments. The glacial sediments of this sequence record an ice advance toward south (Argenteuil Till) followed by an abrupt ice flow shift toward the southwest (Oka Till). Compositional and geomorphic data indicate that Oka Till is ubiquitous in the region and had a strong regional imprint in terms of glacial landform development. The analysis of a regional Digital Elevation Model (DEM) in combination with published ice-flow indicators shows convergent flow patterns from the Ottawa-Montreal-Adirondack regions toward the Lake Ontario basin. Landforms produced by the inferred ice stream are locally crosscut by southward-trending ice flow features, thus suggesting that fast southwestward flow within the Ontario Lobe was abruptly shut down and replaced briefly by southward ice flow. Hence southward flow in the upper St. Lawrence Valley seemingly took place in two distinct contexts: (1) during full glacial conditions, as ice margins stood at or near the LGM limits, and (2) during late deglaciation, as a post-ice stream re-equilibration mechanism. Deglacial events in the study area were also characterized by subglacial meltwater channelling and erosion along the valleys, subaquatic outwash deposition in glacial Lake Candona and rapid infill of the valleys during the early stages of the ensuing Champlain Sea.

Introduction

Quaternary stratigraphy and events in the Montreal region (Fig. 2.1) have received little attention during the last decades and, except for the Pointe-Fortune sequence (Veillette and Nixon 1984, Anderson *et al.* 1990), its stratigraphic record has been seldom used in regional correlations. Not only is the Montreal region lacking in organic-bearing interstadial or interglacial sediments but its glacial units have been characterized mainly on the basis of their engineering properties rather than on the basis of their age, provenance, or fabric (Prest and Hode-Keyser 1962, 1977). As a result, it is difficult to correlate these tills with regional ice flow phases or events; hence, their paleogeographic context cannot be readily discussed nor firmly established. In addition, the Quaternary successions that were reported subsequently from the vicinity of Montreal provided an apparently inconsistent record, including for instance a single Wisconsinan till in some reports (e.g. Lévesque 1982; Veillette and Nixon 1984) and two Wisconsinan tills in others (e.g. Prest and Hode-Keyser 1977; Prichonnet *et al.* 1987, Fig. 17). To further complicate our understanding of regional Quaternary events, ice flow sequences proposed by earlier workers are apparently contradictory: Prichonnet (1977) reported that a southwestward ice-flow event followed regional southward flow while Gadd (1980) and Delage (1997) reported just the reverse. The lack of a model integrating key available evidence has led to this somewhat confusing status. As a result, regional paleogeographic models are so poorly constrained that their relationships with Wisconsinan ice sheet dynamics cannot be made. Some of the recent concepts and models, particularly glacial streaming, have not been integrated in regional assessments or reconstructions although topographic and geologic settings, as well as subglacial conditions, are thought to be favorable to fast flow in such marginal areas of the Laurentide Ice Sheet (e.g. Denton and Hugues

1981; Boulton *et al.* 1985; Clayton *et al.* 1985; Hicock and Dreimanis 1992; Alley 1991; Marshall *et al.* 1996; Patterson 1998). Furthermore, only scant data regarding the deglacial events at the Lake Candona - Champlain Sea transition are available from the plain northwest of Montreal, thus resulting in a poorly constrained northern limit for the glaciolacustrine phase in this region (Rodrigues 1992; Parent and Occhietti 1988, 1999).

From a more local perspective, interest in the Quaternary geology of a large area northwest of Montreal (Fig. 2.1) was recently renewed as this region contains several buried valleys whose stratigraphic architecture was thought to exert a major role on regional groundwater resources (Savard *et al.* 2000, *in press*). New data on the nature and extent of the buried units were needed to determine their origin, stratigraphic placement and paleogeographic significance. The likelihood of finding unknown buried till sheets and other remnant sediment bodies suggested that careful subsurface investigations (e.g., seismic reflection, drilling) combined with new surface data would provide new insights on regional glacial and deglacial events and would contribute to the development of a well-constrained stratigraphic framework and paleogeographic model.

Hence this paper reports on an investigation of these buried valleys as well as of a few surface sections and landform assemblages and discusses implications for the regional Quaternary stratigraphy and paleogeography. More specifically, the objectives of this paper are (1) to develop a regional Quaternary stratigraphic framework, with emphasis on newly discovered till units and their correlations with regional ice-flow events, (2) to reconstruct the glacial dynamics of the upper St. Lawrence Valley by reinvestigating the published ice flow features together with regional landform assemblages and 3) to document deglacial events at the Lake Candona -

Champlain Sea transition. This paper also brings new insights into the stratigraphic architecture of Quaternary units which have been integrated in a computer-based regional 3D model of the study area. This model was used to define regional hydrogeologic settings (Ross *et al.* 2004a) and for mapping rock aquifer vulnerability to contamination (Ross *et al.* 2004b).

Physical setting and geology of the Lower Laurentians

The study area extends over about 1500 km^2 between the Laurentian Highlands, the Ottawa River and other St. Lawrence River tributaries in a region that is often referred to as the lower Laurentians (Fig. 1). At low elevations, between about 25 and 70 masl, the region mainly consists of a low-relief clay plain incised initially by paleochannels of the Ottawa River as it flowed into Lake Lampsilis, a successor basin of the Champlain Sea, and subsequently by modern rivers and streams. At higher elevations, from 70 masl to 95 masl, the region features a drumlinized till plain that was partly reworked by wave action on the shores of Champlain Sea and which acts as important recharge areas for regional aquifers. Both terrains mainly trend northeast-southwest, parallel to the nearby Shield margin (Laurentians). Elevations rise to 250 masl in a large Shield inlier, the Oka Hills.

The region is underlain by Paleozoic sedimentary rocks of the St. Lawrence Lowlands Platform which locally consists of a 1500 to 3000 meter-thick succession of sandstones and carbonates ranging from Cambrian to Middle Ordovician (Globensky 1987). These rocks are underlain by a Precambrian basement which crops out extensively in the Laurentian Highlands as well as in two inliers (Saint-André and Oka hills; cf. Fig. 3) which also contain Cretaceous alkaline intrusive rocks (carbonatites). This diverse bedrock is overlain by a discontinuous cover of Quaternary sediments reaching up to 150 m in thickness.

The current Quaternary stratigraphic framework (Fig. 2) includes several units, most of which were identified in the Bélanger pit near Pointe-Fortune (Richard 1978; Veillette and Nixon 1984; Anderson *et al.* 1990; cf. Fig. 3) and on excavations on Montreal Island (Prest and Hode-Keyser 1962, 1977). At Pointe-Fortune, the succession consists of an Illinoian till (Rigaud Till) and Sangamonian sediments (Pointe-Fortune sediments) which are unconformably overlain by a Wisconsinan unfossiliferous sand unit (Carillon sand), which is in turn overlain by a late Wisconsinan till. This till was regionally mapped and correlated with the Fort Covington Till (cf. Gwyn and Thibault 1975) originally defined in the Seaway excavations by MacClintock and Stewart (1965). Similarly, only one Wisconsinan till had been recognized in the lower Laurentians (Lévesque 1982). However, a threefold Wisconsinan glacial sequence, consisting of two tills with an intervening glaciolacustrine sediment complex, was identified on Montreal Island and correlated with the classical sequence defined in the Seaway excavations (Prest and Hode-Keyser 1962, 1977). Deglacial sediments in the study area (cf. Fig. 1) consist of ice-contact glaciofluvial and proximal proglacial sediment assemblages which are extensively covered by Champlain Sea silt and clay; these in turn locally grade into estuarine, fluvial and aeolian deposits which form the so-called Post-Champlain Sea sediments (Fig. 2). These Quaternary sediments had been previously mapped by Richard (1982) and Lévesque (1982).

Methodology

Extensive field work was carried out between 1999 and 2001, including surficial mapping, detailed geologic section analyses, stratigraphic drilling, and shallow seismic reflection surveys. Two maps of the Quaternary geology were completed at a scale of 1: 50 000 (Bolduc and Ross 2001*a*, 2001*b*). Prior to drilling, a total of about 5 line-km of high resolution shallow seismic data were acquired over two of the buried valleys (Fig. 3). The acquisition technique as well as the processing procedure are described in Benjumea *et al.* (2001). This tool is an effective means of delineating the stratigraphic architecture of buried Quaternary units, mapping bedrock topography and identifying drilling targets (e.g., Hunter *et al.* 1989; Slaine *et al.* 1990; Roberts *et al.* 1992; Boyce *et al.* 1995; Lanz *et al.* 1996; Pugin *et al.* 1999), especially where thick saturated and fine-grained sediments lie at the surface. Five stratigraphic boreholes, three of which are along the seismic profiles (Fig. 3), were diamond drilled in the main buried valleys. Continuous sampling of 4.5 cm diameter cores with high recovery rates was carried out in two boreholes (00_CHS_F2; 00_STJPH), whereas closely spaced but discontinuous samples were obtained using Shelby tubes for the upper marine clay and a standard split-spoon sampler for non-clayey material in the other boreholes (00_CHS_F1; 99_148; 99_RIV). PVC casings were installed in two boreholes to allow for geophysical profiling along the unconsolidated sequence. It must be noted, however, that only part of the boreholes and seismic lines are discussed in this paper. Additional stratigraphic information was retrieved from archival GSC borehole logs (St-Onge 1979) and from geotechnical logs drawn from the provincial database (Hydrogeologic Information System (HIS);

www.menv.gouv.qc.ca/eau/souterraines/sih/index.htm.). The lithofacies coding scheme used in this paper is detailed in Table A1.

Regional ice flow patterns and the sequence of ice flow phases were established on the basis of earlier and newly-acquired data such as glacial landforms, striations and crosscutting relations as well as by examining a regional Digital Elevation Model (DEM). The sequence of ice flow phases was also established through correlation with newly-discovered stacked till sheets and compositional changes within a single till sheet. Tills were characterized on the basis of their facies and lithic content as well as their geochemical signature; only results that are significant in terms of regional provenance are presented in this paper. Niobium (Nb) and *light rare-earth elements* (*LREE*) are used as the main indicators of glacial dispersal from known carbonatite intrusions. These rocks are characteristically enriched in *REE* (Van Wambeke 1960) and the minerals of the local Oka carbonatite are remarkably rich in *LREE* (Gold *et al.* 1986; Chakhmouradian 1996). Other elements were also used but to a lesser extent. The geochemical analyses were conducted at the INRS-ETE laboratory in Québec City using ICP-AES for major ions and trace metals and ICP-MS for Nb and *REE*. A few samples of proglacial rhythmites from boreholes and sections were submitted to Dr. J-P. Guilbault in Montreal for micropaleontological analyses in an effort to better discriminate between glaciolacustrine and glaciomarine depositional environments. Other samples of Champlain Sea sediments were also submitted. Finally, a few AMS radiocarbon ages were obtained on bivalves and wood fragments. These AMS analyses were conducted by Geochron Laboratories and by Beta Analytic Inc.

Regional stratigraphic record

The stratigraphy of the *Chemin des Sources* (CHS) buried valley

A subsurface study was carried out along a secondary road (*Chemin des Sources*) which crosses a southwest-trending buried valley north of the Saint_André Hills (Fig. 3) and which passes close to its deepest part. The CHS buried valley is characterized at the surface by a low-relief clay plain with a discontinuous post-Champlain Sea sand cover. Although a paleochannel of the ancestral Ottawa River lies above the buried valley, its boundaries extend some distance beyond the scarps of those paleoterraces. A seismic survey carried out across the buried valley revealed a large bedrock ridge which had no surface expression (Fig. 4). The cross-sectional profile of the valley shows that Quaternary units are discontinuous and highly variable in thickness over short distances, thus indicating a complex erosional and depositional history.

A stratigraphic borehole (00_CHS_F2) was drilled through the thick Quaternary sequence in the northern segment of the profile (Figs. 2.4b and 2.5a). At the borehole site, the Champlain Sea sediments are underlain by a 43.8 m thick succession of glacial sediments consisting of two very distinct till sheets which overlie ice-proximal stratified sediments (Fig. 5a). South of this site, at borehole 00_CHS_F1, part of the sequence is truncated by an erosional unconformity overlain by glaciofluvial sediments (Fig. 4b). Because the glacial sequence is different from that hitherto reported in the upper St. Lawrence Valley and because these till sheets are shown to have broad regional significance, two new lithostratigraphic units (Argenteuil Till and Oka Till) are introduced and a description of the unit boundaries, facies and content is provided herein.

Directions of ice movement associated with each of the two till units are inferred on the basis of provenance data.

The lowermost glaciolacustrine stratified sediments

The lowermost unit in the succession consists of diamictons interstratified with normally graded layers of coarse to very fine sand as well as rhythmically laminated silt and clay beds. The diamictons are remarkably similar to the overlying Argenteuil Till (see below). Facies assemblages collectively indicate deposition in an ice marginal subaqueous environment. The unit appears to be unfossiliferous. Infrared stimulated luminescence (IRSL) techniques were used on an exploratory basis on a few samples from layers of very fine sand; however, preliminary analyses indicate very poor zeroing (Lamothe 2003, *pers. comm.*), a conclusion that was somewhat expected given the proximal glaciolacustrine environment. The unit is therefore considered undatable by currently available techniques.

Argenteuil Till

The lower till is herein named Argenteuil Till from the name of the regional county municipality. At the borehole site, the Argenteuil Till is a dark olive gray (5Y 3/2) and dense matrix-supported diamicton (Fig. 5b) underlain by proximal glaciolacustrine sediments and overlain by a younger till sheet (Oka Till; Fig. 5a). The 9 m thick Argenteuil Till is remarkably consolidated and it has a low water content. It is characterized by a high content of Canadian Shield clasts and dolostone clasts and a low sandstone content (Fig. 5a). In addition, its Na_2O concentration is similar to most till samples from the Laurentian Highlands which is about 3.2%, whereas the Na_2O concentration of Lowland samples have a mean of only 1.6 ± 0.9% in the study area (Table 1). Since the boundary between the Lowland and the Canadian Shield lies 8.6 km to the north of the site and 9.5 km to the northwest (Fig. 3), the composition of the Argenteuil Till indicates provenance from either the north or the northwest. On the basis of available geological maps (Globensky 1987; Rocher *et al. in press*), the high content in dolostone clasts and low content in sandstone clasts seem most consistent with a northwestern provenance.

Oka Till

The upper till is herein named Oka Till after the Oka Hills located within the study area. It is an olive brown (2.5Y 4/4) stone-rich diamicton (Fig. 5b). At the borehole site, the unit is 14.8 m thick and is separated from the underlying Argenteuil Till by a sharp erosional contact. In contrast to Argenteuil Till, Oka Till is characterized by an abundance of sandstone clasts and a very low content of Precambrian clasts as well as by a Na_2O concentration of about 1.6% (Fig. 5a), which is typical of Lowland till samples (Table 1). The lithologic composition of Oka Till is consistent with a northeastern provenance since sandstones of the Potsdam Group are much more widespread toward northeast than in other directions. Somewhat unexpectedly, the till at the borehole site was found to be significantly anomalous in elements (Fig. 5a) such as Zn (222 ppm), La (73.2 ppm) and Cr (117 ppm), which are closely associated with the carbonatites of the region (Gleeson and Cormier 1971; Gold *et al.* 1986). A few small alkaline intrusive bodies lie about 22 km northeast of this locality (cf., Gold 1967; Globensky 1987), but other unmapped intrusive bodies may lie much closer along the northeast-trending buried valley.

Glaciofluvial and proglacial sediments

An erosional unconformity, which is distinctly recorded on the seismic profile between the 200 m and 1400 m distance markers, cuts partly through Oka Till (Fig. 4). This unconformity is interpreted as the result of channelized subglacial meltwater erosion, although some erosion may have occurred in ice-proximal environments. The bouldery layer on top of the Oka Till (Fig. 5a) may suggest that the unconformity extends across the whole profile. However, erosion may be due in this case to processes other than subglacial meltwater, such as glacial and glaciomarine processes. The channels are overlain by glaciofluvial and proglacial sediments. At other localities such as borehole 99_148 (Fig. 3), meltwater erosion reached bedrock and left only a bouldery lag between bedrock and the overlying marine clay (cf., Ross *et al.* 2001, Fig. 3). Similar coarse lags may also occur between the 800 m and 1200 m distance markers, as shown in Fig. 4b. Although a thin layer of Oka Till is shown in Fig. 4b, the unit may in fact have been completely eroded below that channel. Outwash fan sediments were intersected by another borehole (Fig. 6) drilled in the same glaciofluvial channel. Unfortunately, it was not possible to reach bedrock due to technical problems. Nevertheless, it is apparent from the log shown in Fig. 6 that the 13.7 m thick, sand and gravel outwash unit overlies a bouldery lag of inferred glaciofluvial origin. Several granules and isolated oversized angular clasts of distinctive pink igneous rock were found in the outwash sediments, indicating that the glaciofluvial channel was cut though at least part of Argenteuil Till, which is rich in Precambrian clasts. The top of the outwash is characterized by a fining-upward sequence consisting of interstratified sand and silty clay grading into massive silty clay. It can also be seen from the gamma log (Fig. 6) that the overlying marine unit is coarser between 3 and 24 meters. This facies is characterized by laminated silt and silty clay interlayered with closely-spaced very fine sand partings. This facies is also present in borehole 00_CHS_F2 (Fig. 5a).

Microfaunal assemblages (Fig. 6) observed in a sample (R039A) from the coarsening-upward sequence indicate a salinity ranging between 10 and 25 ‰. This assemblage is similar to Zone B assemblages (Guilbault 1989) which are thought to record declining salinity following the salinity maximum (Zone A). An AMS radiocarbon age of 11 140 ± 40 years BP (GX-28862-AMS) on shell fragments extracted from borehole 00_CHS_F2 (Fig. 5a) at an elevation of 24.5 m suggests that almost half of the fine-grained proglacial sedimentation occurred in the early stages of marine sedimentation in this valley (Fig. 4b). Lastly, the base of the fine-grained sediment sequence in the deeper parts of the valley shows a distinct seismic facies reaching up to 15 m in thickness (Fig. 4b) and which is characteristic of turbidite successions in acoustic depositional models (Piper *et al.*, 1990).

Saint-Joseph-du-Lac (SJL) buried depression

The SJL buried depression is a somewhat isolated trough located below the village of Saint-Joseph-du-Lac just on the eastern flank of the Oka Hills (Figs. 3). It is the largest through whose orientation differs from the northeast-southwest axis. Prior to this study, the only available subsurface information regarding this depression was from a few geotechnical boreholes aligned along Highway 640 and which had not reached bedrock. The deepest ones indicate that the marine clay is at least 27 m thick and reaches 53 m at one site.

A few samples were collected during the drilling of a residential well (MR-1999-0001) and a stratigraphic borehole with continuous sampling (00_STJPH) was subsequently drilled nearby. A cross section integrating the two logs (Figure 7) presents the local subsurface context while the detailed stratigraphic log (Fig. 8) shows compositional and microfaunal data. A piece of wood was recovered from the first meter of the sandy unit underlying thick till at the well site (Fig. 7). AMS dating yielded a non-finite radiocarbon age for this sample (> 48.32 ka BP; Beta-176905). This subtill sandy unit pinches out over a short distance to the east and does not seem to extend much beyond the limit of the village. Since only reworked samples could be recovered during well drilling, we suggest that this unit be simply referred to as "SJL sediments", at least until samples allowing a more detailed description of the unit become available.

At the borehole site (00_STJPH), the depression contains a single, 28 m thick, till sheet characterized by few facies changes and buried under 55 m of sediments consisting mainly of Champlain Sea silt and clay. The till is a light olive brown (2.5Y 5/4) matrix-supported, yet stone-rich, diamicton with few sandy interbeds. There is no evidence of a significant glacial dynamics shift, although minor vertical compositional changes can be detected (Fig. 8). Given the high content of dolostone clasts, ice flow was probably toward SSW and/or SW (cf., Globensky 1987 for geological map). The low content of Canadian Shield clasts seems more consistent with a northeastern provenance. Moreover, Sr concentrations of two till samples (Fig. 8) , among the highest ones obtained for till over the study area, are in the range of those obtained for till overlying limestone rocks (Table 1) and also for tills located close down-ice from carbonatite bodies. The till is underlain by sandstone (Fig. 8) and since the average Sr abundance in sandstone is about 30 times less than that of limestone (610 ppm in limestone; cf., Turekian 1977), much of the Sr likely originates from the widespread limestone strata about 15 km northeast of the site (cf., Globensky 1987). Conversely, other elements such as La and Cr are slightly anomalous indicating a contribution from carbonatite rocks. One plausible source may be the small alkaline intrusive body located about 5 km to the northeast (cf., Globensky 1987). A palimpsest glacial dispersion signal (*sensu* Parent *et al.* 1996) from the Oka carbonatite located 5.3 km west of the site is plausible but cannot explain on its own the strong Sr anomaly and the much less significant La and Cr anomalies. The composition of the till at the borehole requires the mixing of a large quantity of fine-grained material from a limestone source with a small quantity originating from an alkaline intrusion. This till is thus thought to have been deposited during a southwest ice flow phase, and is considered equivalent to Oka Till, as defined in the CHS buried valley.

As mentioned above, the till is overlain by thick Champlain Sea silt and clay (Figs. 7 and 8). Microfaunal assemblages were found to be poor in many samples, but in spite of this limitation, they suggest deposition in a low salinity environment for most of the unit, except for the upper meter or so, where the presence of *Islandiella helenae* requires a higher paleosalinity, probably close to 25 ‰ (Fig. 8). However, the number of observed specimens is too small to confidently assign that sample to Zone A of Guilbault (1989), which corresponds to the marine maximum, but it is close to it. It is thus likely that most of the silty clay below that sample was deposited during the early phase of the Champlain Sea, again suggesting high sedimentation rates.

Saint-Benoît buried valley

This buried valley is the deepest trough in the study area (Fig. 3). The seismic survey revealed a buried bedrock ridge separating the valley into two sub-valleys (Fig. 9a, b). The seismic data suggest that up to 34 m of stratified sediments are present in the deepest part and up to 21 m in the northern segment of the profile (Fig. 9). Till thickness ranges between 16 and 50 m in both sub-valleys. Evidence of truncated beds close to the 1000 m (Fig. 9) suggests that the till sheet may be more discontinuous than shown along the bedrock ridge and that the till surface was eroded by either glacial or glaciofluvial processes. The seismic facies analysis also suggests that the till sheet may in fact consist of two till units (Fig. 9b), but this remains to be confirmed by stratigraphic drilling. Nevertheless, it is likely that Argenteuil Till is present in that valley, as suggested in Fig. 9b, because it was encountered in a nearby borehole (99_VIN_F-1; cf. Fig. 3) on a till ridge between *Saint-Benoit* and CHS valleys. The stratigraphy of the *Saint-Benoît* buried valley appears to be quite similar to that of the CHS buried valley.

Furthermore, the seismic profile suggests up to 35 m of interstratified sand and silt sediments between the till and the more homogenous and thick Champlain Sea clay unit (Fig. 9b). Two seismic facies are recognized and interpreted as intermediate (facies 1) and distal (facies 2) subaqueous fan facies assemblages (Fig. 9b). It is inferred that subglacial meltwater conduit(s) developed along the valley down to about 30 m below present sea level forming a system which may have been connected to the channel that formed the *Sainte-Thérèse* esker. The latter lies upglacier about 21 km northeast of the seismic line at the narrower end of this valley (Bolduc and Ross 2001*b*). Lastly, it is worth noting the discrepancy in the depth to bedrock between the seismic data and an archival GSC borehole log (092P; cf. St-Onge 1979) located about 20 m NE of the survey line (Fig. 9b). However, there is an almost perfect match between the log and the seismic profile for the contact separating Champlain Sea sediments from the underlying till. Since the location of the borehole was validated from the original field notebook and maps, the problem with bedrock elevation may be due to the presence of a large boulder lodged in the till and misinterpreted as bedrock. The lithologic log confirms that at least 36 m of till underlie Champlain Sea sediments in the *Saint-Benoît* buried valley. Other GSC borehole data within the valley but away from the seismic profile also indicate a thick till sheet.

Pointe-au-Sable section

A rare exposure showing thick stratified sand below laminated silt and clay occurs in a sand pit near the north shore of the Ottawa River (Fig. 3). The detailed stratigraphic log shown in Figure 10 was supplemented by detailed sedimentological and micropaleontological analyses to determine depositional environments.

The base of the sandy unit was investigated using a portable drill and was encountered at 1.5 m below the pit floor. It is underlain by an undifferentiated massive, matrix-supported olive grey till. East and west of the sand pit, poorly sorted but generally coarse sediments as well as reworked till were found along the road at higher elevation than the base of the sandy sequence suggesting that channelized erosion into the till took place prior to deposition of the sandy sequence. At the base of the pit, the first meter of exposed sand is characterized by planar cross-beds dipping towards SSW and overlain by massive medium to coarse sand. One erosive channelized scour filled by such massive sand was observed, suggesting deposition by cohesionless debris flow. This facies is capped by laminated sand partly deformed by dewatering structures and overlain by laminated fine sand (Sh). The rest of the sandy unit shows a fining-upward sequence with abundant primary sedimentary structures typical of lower flow regime such as ripple cross-laminations (Sr). The unit displays a vertical gradation from type A to type B ripple cross-lamination and, in some cases to sinusoidal (Jopling and Walker 1968) or draped lamination (Gustavson *et al.* 1975) (Fig. 10). It is mainly characterized by an upward increase in both the angle of climb and preservation of stoss-side laminae. Such gradation is common in glaciolacustrine outwash fans (e.g., Jopling and McDonald 1975) and, according to Jopling and Walker (1968), it suggests both a reduction in underflow velocity and an increase in deposition from suspension. Paleocurrents have a fan-shaped distribution ranging from 150° to 240°. This assemblage grades upward into a thin turbidite sequence made of a series of normally graded fine sand and silt laminae forming a rhythmic succession. This is overlain by slightly diamictic silt and clay laminae containing isolated larger striated dropstones. No microfaunal specimens were found in samples from the base of this facies but *Candona subtriangulata*-only assemblages were found just below an erosive contact marked by a thin diamictic layer (Fig. 10).

The diamictic layer marking the unconformity at the top of the fan is fossiliferous and shell fragments consist almost exclusively of *Hiatella arctica*, probably reworked from higher elevations in the *Saint-André* Hills. This layer is overlain by laminated grey and reddish brown Champlain Sea clay sometimes separated by very fine sand partings. A *Hiatella arctica* valve collected in the diamictic layer at the base of the marine unit yielded an AMS radiocarbon age of

10 450 ± 40 years BP (GX-28861-AMS). More details on the paleoecology of the marine unit at this site are reported in Bolduc and Ross (2000).

The top of the sequence consists of fluviatile sand which lie unconformably over the clay and form the upper part of the 60 m terrace which extends west of the sand pit. Ripple lamination at the base of the unit indicates paleocurrent towards the east, which is consistent with the general direction of flow for the ancestral Ottawa River.

Provenance of the upper till at Pointe-Fortune

The Bélanger pit at Pointe-Fortune (Fig. 3) is located northwest of several features which were interpreted to be the result of a late southeastward ice flow phase, such as drumlins and Rogen moraines south of Rigaud Mountain (Richard 1982, Corbeil 1984). Southeastward striae were also found on a few outcrops northwest of the site (Bolduc and Ross 2001a). This combined evidence suggests that the southwestward flow phase was not the last ice flow event in the westernmost part of the region as opposed to elsewhere in the study area. Indeed east of Pointe-Fortune, glacial landforms, striations, and crosscutting relations as well as provenance data from the Oka Till indicate that the last ice flow event was toward SW. Therefore, because of its location and key stratigraphic position, the upper till exposed in the Bélanger pit, sometimes referred to as the Border Till (cf., Anderson *et al.* 1990), may contain important clues to unravel the complex Wisconsinan glacial events of this region and to evaluate the relative importance of the different flow phases on till deposition. Gwyn and Thibault (1975) carried out 2D till fabric analyses in the upper till at the Bélanger pit and the results suggest several ice flow directions ranging from SSE to SW. They mapped this till unit regionally and correlated it with the Fort Covington Till defined by MacClintock and Stewart (1965). On the basis of a single pebble count (n=100), Veillette and Nixon (1984) concluded that the upper till was deposited by ice flowing toward SSW. To further constrain this interpretation and to check for a possible ice-flow shift, geochemical analyses were carried out on three stacked samples (Table 2). All three samples yielded values which appear to be above background for Nb and *LREE* and there is a significant increase in the uppermost sample (Table 2). For instance, the Nb concentration of the uppermost sample is twice that of the middle sample. The most probable source of this anomaly is the large niobium-bearing carbonatite intrusion located about 7 km northeast of the site in the *Saint-André* Hills (Gleeson and Cormier 1971; Gold *et al.* 1986; Globensky 1987).

Pebble counts were also carried out on these three samples and the results differ from those reported by Veillette and Nixon (1984). This may be due to differences in both the number and size class of the counted pebbles. Nevertheless, Shield erratics and Potsdam Group sandstone were found in significant numbers (Table 3). Sandstone and dolostone contents increase from base to top while Shield erratics decrease. Most sandstone clasts found at the base of the till are confidently assigned to the Potsdam Group. Clasts of the dolomitic sandstone of the Theresa Formation (Beekmantown Group) were counted as dolostone. According to available geological maps (Globensky 1982, 1987; Rocher *et al. in press*), Potsdam Group sandstones and known Nb sources are located northeast and east of the Bélanger pit but are absent to the north and northwest, an area where the geological map is well constrained by numerous outcrops and over 20 years of active exploration for niobium-bearing rocks. The lithologic content of the till and the Nb and *LREE* concentrations thus suggests that the southeastward and southward flow phases which deposited the Argenteuil Till and left some "old" erosional marks (cf., Prichonnet 1977, Bolduc and Ross 2001a,b) were not involved in the deposition of the upper till in the Bélanger pit. Moreover, the significant increase in Nb and *LREE* as well as the increase in sandstone clasts near the top combined with a decrease in Shield erratics suggest that the upper till was already deposited when the late southeastward ice flow phase (e.g., Terasmae, 1965; Gadd, 1980; Richard, 1982) took place at that location. It is possible that this last phase only created a few internal shear planes and other structures. This would explain the few reported measurements of south-southeastward flow in the upper till (e.g., Prichonnet 1984; Fig. 17). Considering the above results, the vertical compositional change in the upper till could be the result of increasing incorporation of distant debris with time without any change in ice flow direction, as shown in the glacial sediment transport model of Boulton (1996). If a change in ice flow direction did occur, it was only from a south-southwestward to a more southwestward direction.

Paleogeographic interpretation and regional stratigraphic implications

The stratigraphic record outlined above leads to a reappraisal of some of the regional geologic events. Although the age control on the Pleistocene units in the St. Lawrence Valley remains weak, relative time constraints are proposed. The discussion provided in this section pertains to the units which are stratigraphically below Champlain Sea sediments.

Pre-Wisconsinan events

SJL sediments

The sandy unit containing wood fragments at the base of the sequence below Oka Till in the SJL buried depression lies at elevations between about -31 and -37 m (cf., Fig. 7). This may suggest that relative sea level was below that of today, thus indicating greater continental ice volume and colder climate. Correlation with the Lotbinière Sand of inferred late Sangamonian age (Lamothe 1989) is tempting, although the latter has yet to be identified below about -10 m. Alternatively, these wood fragments may have been simply deposited in a subaqueous environment such as a prodeltaic depositional setting. In that case, the elevation of the unit would have little or no implications in terms of relative sea level. Another alternative could be that organic material was reworked and flushed into place by subsequent meltwater flow, which seems to be often the case in other areas such as in the Oak Ridges Moraine area (Sharpe 2005, *pers. comm.*). In spite of these uncertainties, the SJL sediments are preliminarily assigned to the late Sangamonian; further investigations are needed to adequately define the origin, age and significance of this unit.

The Wisconsinan ice advance and the southward ice flow phase

Unnamed glaciolacustrine sediments and Argenteuil Till

The proximal glaciolacustrine sediments and overlying Argenteuil Till identified in the CHS valley record a glacial advance across the study area. The facies and composition of Argenteuil Till suggest that it was a major ice advance toward the south (Fig. 5a). This event may correspond to the onset of stage 2 (Late Wisconsinan), implying that a glacial lake extended over the study area some time prior to stage 2. The glacial lake may be coeval or coalescent with the glacial lake recorded by the Gray Varves and the Saint-Maurice Rhythmites near Trois-Rivières whose age is known by the IRSL relative depositional dates of 25 and 34 ka ± 20% (Hardy and Lamothe 1997). The Argenteuil Till recording southward ice flow is thus assigned to a period which may have spanned from early stage 2 to the Late Glacial Maximum (LGM). An alternative interpretation would be to assign an Early Wisconsinan age to the Argenteuil Till (cf., Fig. 2). However, there is no evidence to suggest that the unconformity at the top of the Argenteuil Till represents a long temporal gap. This unconformity is currently interpreted as a short hiatus created by a rapid glacial dynamics shift (see below).

Subsurface investigations and observations made during fieldwork and mapping (Bolduc and Ross 2001a, b) suggest that occurrences of Argenteuil Till are rare in the study area. Most compositional data also suggest that it was mostly reworked by the subsequent southwestward flow leaving only a palimpsest geochemical signal in the younger Oka Till (cf. Ross 2004). However, the latter can be quite apparent. For example, the distribution of Nb and *LREE* in the surface till clearly shows fan-shaped dispersal trains from the known carbonatites of the region (cf. Ross 2004). Therefore, the southward ice flow phase represents a significant glacial event and future investigations may reveal a greater extension of Argenteuil Till in the subsurface, especially where till thickness exceeds 20-30 m such as in the *Saint-Benoît* buried valley (cf., Fig. 9). Finally, a few south to southeast-trending striae cut by southwestward striae were identified during mapping (cf., Bolduc and Ross 2001b) and are inferred to be contemporaneous with the Argenteuil Till.

Abrupt ice flow shifts and inferred ice stream activity

The Oka Till

The Oka Till is widespread in the study area and although its composition may vary from that described at the borehole site, it characteristically reflects a northeastern provenance. Even at sites located just 2 or 3 km south of the Canadian Shield margin, Oka Till has a very low content of Shield clasts, generally on the order of 5 % to 10 %. At a few sites, the concentration of lithic components derived from a local source is near 100 % suggesting high bedrock erosion rates. Such erosion rates are expected in the initial stage of a glacial advance over fresh bedrock (Parent *et al.* 1996) or following an abrupt glacial dynamics shift because glacier bed roughness is greater along the new ice flow direction. Since no evidence of significant glacial retreat has been identified between the Argenteuil Till and the Oka Till, it is infered that a major glacial dynamics shift occurred during the gap between deposition of the Argenteuil and Oka tills. The Oka Till was deposited during a southwestward ice flow phase that is assumed to have quickly followed the southward flow phase which had previously emplaced the Argenteuil Till. The Oka Till is thought to have been deposited in the late stages of the last glaciation, most likely between about 15 ka and 12 ka.

Regional evidence

Glacial flow indicators compiled for the upper St. Lawrence Valley show evidence of a regional southwestward ice flow phase which was apparently both preceded and followed by southward and southeastward ice flow phases (Fig. 11). Many of these features are apparent on a regional DEM (Fig. 12a). Of particular interest is the widespread occurrence of streamlined landforms that clearly converge toward the Lake Ontario basin. Such a convergent pattern is consistent with a pervasive regional southwestward ice flow phase. Furthermore, an abundant record of glacial striae as well as till provenance data (cf. Fig. 11) are also consistent with the convergent pattern suggesting that it was essentially produced by glacial processes. Indeed, abundant striae indicate 1) ice flow toward south in the area south of Ottawa; 2) ice flow toward southwest in the Montreal region and; 3) ice flow toward the west between Montreal and the Adirondacks. The latter are known since at least 25 years (e.g. Gadd 1980) and such striae have been observed during recent work in the region south of Montreal (Lamothe, Tremblay 2005, *pers. comm.*). In addition, several southwest-trending striae were reported between Lake Ontario and Montreal (e.g., MacClintock and Stewart 1965; Prest and Hode-Keyser 1977; Prichonnet 1977; Gadd 1980; Lévesque 1982; Corbeil 1984; Bolduc and Ross 2001a,b), anorthosite erratics from *Sainte-Adèle* were found near Cornwall (Gadd 1980) and Paleozoic erratics and carbonate-rich till over the Frontenac arch were reported by Kettles and Shilts (1987). Other evidence such as clasts of Appalachian provenance (e.g., slates of the Granby Formation) were more recently reported in the till forming the southwest-trending ridges in the Huntingdon area (Delage 1997) and glaciotectonic structures affecting limestone strata and indicating southwestward flow have been reported on Montreal Island (Durand and Ballivy 1974; Prichonnet *et al.* 1987, Fig. 32). In light of these observations, in addition to those reported herein, the southwestward ice flow phase clearly appears as a regional event which left a widespread landform and sediment record throughout the upper St. Lawrence Valley and which obliterated much of the record left by the earlier southward phase (Argenteuil Till).

A glacial dynamics model for the upper St. Lawrence Valley

In light of the above results and interpretation, a glacial dynamics model is proposed for the upper St. Lawrence Valley whereby a "switching mechanism" operates between a "normal" southward flow mode, and an ice stream mode (Fig. 13). Argenteuil Till was deposited during "normal" flow (Figs. 13a and 13b), a situation which corresponds to early and full glacial conditions and which is characterized by southward ice-flow across the valley and into the Adirondacks. This full glacial mode was followed by an abrupt shift in ice flow direction due to extensive glacial streaming in the upper St. Lawrence valley (Fig. 13c). During this episode, as recorded by deposition of Oka Till as well as by many landforms, the Ontario lobe was in a general state of fast southwestward ice flow (ice stream mode) and its catchment area migrated toward the northeast along the St. Lawrence Valley and into the study area (Fig. 13c). Ice flow remained regionally toward the southwest almost until final deglaciation, as suggested by the development of subglacial meltwater features, such as tunnel valleys and eskers. Ice stream activity was apparently shut down and replaced by southward ice flow. The termination of the ice stream flow mode was presumably triggered by a change in subglacial conditions as the ice margin retreated from the Ontario Basin. At that point, the ice margin must have been anchored atop the Frontenac arch (cf. Fig. 11) and subglacial conditions no longer favored fast southwestward flow in the upper St. Lawrence Valley. The reduction of sliding velocities is thought to have caused re-equilibration of the ice sheet surface profile, hence the observed brief return to conditions of southward ice flow (Fig. 13d). This late-glacial phase is especially apparent from landforms and striae southwest of the study area where such features clearly crosscut the older southwest-trending features (Fig. 11 and 12).

The glaciofluvial system

The regional distribution of glaciofluvial sediments and landforms (Bolduc and Ross 2001a,b; Ross *et al.* 2004c) suggests that a channelized subglacial meltwater system developed in the late stages of deglaciation and was focused along the southwest-trending buried valleys of the region. There is no clear evidence of widespread glaciofluvial activity outside the channels identified in the buried valleys and along the St. Thérèse esker. Evidence of erosion (e.g. truncated beds and pinch-outs) on till ridges (e.g. Fig. 9, close to 1000 m mark) could well be the product of glacial processes. The lack of deposits of unequivocal glaciofluvial origin outside the channels must be considered as significant, given the extensive surveys that were carried out in the region. In summary, meltwater erosion was clearly significant in the buried valleys and was mainly focused along channels in which much of the pre-existing sediments were removed.

A comparison between the CHS seismic profile (Fig. 4) and the *Saint-Benoît* profile (Fig. 9) as well as borehole data from the *Rivière du Nord* Valley (St-Onge 1979; Ross *et al.* 2001, Fig. 3) suggests that the channelized meltwater system did not erode into its till substrate below elevations of about 0 to -30 m. This is deduced from the fact that a thick and almost ubiquitous till sheet (mainly Oka Till) is present at sites below that elevation range (e.g., Fig. 9), while it has been locally dissected or eroded away above it (e.g., Fig 4). The presence of thick glacial sediments in the buried valleys, including the > 48 ka old SJL sediments, clearly indicates that the bedrock depressions are older than late Wisconsinan and were thus overdeepened during multiple glacial episodes.

Early proglacial environments

The results of this study, particularly the presence of the freshwater ostracode Candona at the Pointe-au-Sable section, indicate that glaciolacustrine sediments are present below Champlain Sea sediments at least in the southern part of the study area. At the Pointe-au-Sable section, facies assemblages of the stratified sediments underlying the erosive contact are also consistent with a glaciolacustrine setting (cf., Fig. 10). These stratified sediments are thus interpreted to have been deposited from sediment-laden meltwater discharging into Glacial Lake Candona (cf., Parent and Occhietti 1988; Rodrigues 1992) from a subglacial conduit, predominantly in the form of quasi-continuous hyperpycnal underflows (cf., Bates 1953). Secondarily, the facies assemblages at the top of the sequence are indicative of pulsating turbidity currents. These processes resulted in the construction of a small subaqueous outwash fan. The age (10 450 ± 40 ka BP) obtained for the *Hiatella arctica* just above the unconformity overlying the outwash (cf., Fig. 10) indicates that the unconformity represents a hiatus separating Lake Candona sediments from the overlying Champlain Sea sediments and that the latter were deposited sometime after the marine maximum.

Other less forceful observations suggest that Lake Candona may have extended further north such as in the CHS valley and even near Sainte-Anne-des-Plaines (cf., Fig. 3), but available data do not allow confirmation of glaciolacustrine sedimentation north of Pointe-au-Sable.

Glaciomarine sediments, sometimes several meters thick, are mainly concentrated in buried valleys. The CHS and perhaps SJL buried valleys were already partly filled by proglacial sediments at 11.1 ka BP (cf. Fig. 4) indicating high sedimentation rates in the early stages of Champlain Sea.

Discussion

The data presented in this paper have been supplemented with data reported elsewhere in the upper St. Lawrence Valley to propose a regional model which include abrupt glacial dynamics shifts, the development of a large ice stream in the upper St. Lawrence Valley during the last deglaciation, significant glaciofluvial activity in the buried valleys, and the brief extension of glacial Lake Candona in the southern part of the lower Laurentians. While this model most likely provides a more integrated and regionally consistent framework, a few elements remain problematic and new questions arise. Some of the criteria used in this study and taken from other paleo-ice stream studies are thus examined along with alternative interpretations for some of the reported features.

An ice stream in the upper St. Lawrence Valley?

Topographic and geologic settings as well as subglacial conditions are important factors controlling ice flow direction and velocity in ice streams (e.g., Anandakrishnan *et al.* 1998; Bell *et al.* 1998) and large valleys and troughs are generally thought to have favored fast flow and streaming in marginal areas of the Laurentide Ice Sheet (e.g. Denton and Hugues 1981; Boulton *et al.* 1985; Clayton *et al.* 1985; Hicock and Dreimanis 1992; Alley 1991; Marshall *et al.* 1996;

Patterson 1998). At least three of the criteria generally considered for identifying former terrestrial ice streams (e.g. Hart 1999; Stokes and Clark 1999, 2001) can be readily recognized in the upper St. Lawrence Valley: (1) the convergence of flow lines toward the Lake Ontario basin (cf., Figs. 11 and 12); (2) the occurrence of abrupt lateral margins such as that shown by contrasting drumlin fields west of Kingston (Chapman and Putnam 1984; Gadd 1987: his Fig. 5; Barnett et al. 1991) and; (3) the similarity in form and dimension of the proposed ice stream (Fig. 12b) with those of well known Antarctic ice streams (e.g. Alley and Bindschadler, 2001; Joughin et al., 2004; Lang et al., 2004).

Interestingly, the second criterion was used to postulate two almost perpendicular major subglacial floods by Shaw and Gilbert (1990). In the vicinity of Kingston, some of the southwest-trending streamlined features visible on the DEM (Fig. 12) are apparently related to intense glaciofluvial activity (e.g., Gilbert 1990, 1994; Gilbert and Shaw 1992; Brennand and Shaw 1994) and this raises the question of whether or not the regional convergent pattern (cf. Fig. 12b) could be the product of a large subglacial flood. Shoemaker (1992) proposed a theoretical explanation for subglacial meltwater floods of such magnitude and others have proposed models in which regional meltwater processes play a significant role in landscape development (e.g. Sharpe et al., 2004.). However, no evidence to support such a flood event was observed in the study area. Evidence of meltwater erosion at the till surface is by and large restricted to narrow corridors generally located in the southwest-trending buried valleys, save for perhaps a few truncated reflectors of uncertain origin along the Côte Rouge seismic profile (e.g. Fig. 9; near 1000 m mark). Furthermore, other evidence of unequivocally glacial processes, such as glacial striae and glacial dispersal trains, are quite consistent with the convergent pattern (cf. Fig. 11). The observed large-scale convergent pattern of ice-flow indicators is best explained as the product of glacier flow in the catchment area of an ice stream rather than by a widespread glaciofluvial event such as the so-called "Ontario event" of Shaw and Gilbert (1990).

Yet, it could also be argued that many southwest-trending landforms that have been identified on the DEM and used to generate the flow lines on Fig. 12b have in fact been interpreted as Rogen moraines (Fig. 11) by Carl (1978) and Corbeil (1984) suggesting ice flow toward the southeast. However, Delage (1997) showed that in the Huntingdon area (cf. Fig. 11), these ridges were initially formed by southwestward ice flow and were later reworked by a southeastward ice flow phase, a conclusion that closely resembles that reached earlier by MacClintock and Dreimanis (1964) during their investigation of the St. Lawrence Seaway excavations. This interpretation is in accord with Boulton's model (Boulton 1987) in which Rogen moraines can develop from transverse ridges following a shift in ice flow direction. Several south-trending drumlin fields which had been mapped by several workers (e.g., Terasmae 1965; Corbeil 1984) are also apparent on the DEM (Fig. 12a). Some of these drumlins are superimposed on the crest of the southwest-trending till ridges (e.g. Terasmae 1965; Fig 1) and Carl (1978) suggested that the Rogen moraines and drumlins on the northern flank of the Adirondacks form a typical transition belt. These contrasting ice flow features record an abrupt shift in regional flow patterns which was presumably caused by the shutdown of a southwest-trending ice stream (Fig. 12b).

This body of evidence clearly indicates that there was at least one, and probably several, phase of regional southwestward ice flow in the upper St. Lawrence Valley during the Wisconsinan Stage. Otherwise, several significant features could not be explained satisfactorily, e.g. the abundant SW-trending striae across the whole region and the carbonate-rich till on the Frontenac arch (cf. Fig 11), the Niobium anomaly at Pointe-Fortune (cf. Table 2) and the presence of Appalachian clasts in the till south of Montreal (Delage 1997) just to name a few. The convergent pattern of ice-flow features as well as the general geologic/physiographic setting strongly further suggest that this phase of southwestward ice-flow was related to the development of a regional ice stream.

Such ice stream activity probably occurred repeatedly over the region during the Wisconsinan, as suggested by evidence of ductile deformation in the Sunny Point or Sunnybrook Till and the Catfish Creek Till in the Ontario-Erie basins (cf., Hicock and Dreimanis 1992; Lian *et al.* 2003). It has also been demonstrated numerically that an ice sheet will be characterized by similar patterns during successive stadial periods in a glacial cycle (Boulton *et al.* 2003). As suggested by Clark (1994, 1995), the lobes of the southern margin of the Laurentide Ice Sheet were dynamic entities adapting their configuration to climate, proglacial water bodies, and subglacial conditions and undergoing rapid advance and retreat cycles indicative of oscillatory unstable behavior in time and in space. Results from this study are consistent with this interpretation and although additionnal work is needed to better understand this complex behavior and to further constrain the model presented in this paper, our interpretation encompasses the key observations made by earlier studies in the upper St. Lawrence Valley (e.g., Prichonnet 1977, Gadd 1987; Delage 1997) and improves regional paleogeographic reconstructions of Late Wisconsinan events (e.g. Hugues et al. 1985; Dyke and Prest 1987; Karrow and Occhietti 1989; Barnett 1992). The episodic development of a large ice stream offers a consistent explanation for both the apparent abrupt changes in ice flow direction and the observed flow patterns. The ice stream model presented in this paper may also provide an explanation for the relative abundance of Precambrian clasts in tills over sandstone bedrock along the northern flank of the Adirondacks, an observation which was previously considered "anomalous" as it could not be readily fitted into regional frameworks available then without invoking pre-glacial processes or geological map inaccuracies (cf., Denny 1974; Clark and Karrow 1983). Finally, the proposed ice stream model may at last provide an explanation for the unequivocal northward-trending glacial striae reported by Clark (1937) near Bedford, a locality situated in Quebec about 10 km northeast of Lake Champlain (cf. Fig 11).

Stratigraphic correlations

Most mappers in the upper St. Lawrence Valley have correlated the surface till with the Fort Covington Till (e.g. Gwyn and Thibault 1975). This raises the question as to why should the surface till in the lower Laurentians be called differently, e.g. the Oka Till?

The Fort Covington Till was first identified in the Seaway excavations and then mapped as the surface till south of the St. Lawrence River by MacClintock and Stewart (1965). This till was originally associated to a limited SE ice flow phase with a terminus along the northern flank of the Adirondacks. Outside that limit, the surface till was correlated with the Malone Till (which records a SW ice flow phase). This limit was disputed by Clark and Karrow (1983) who proposed a model in which a single till sheet covers the whole region (Fort Covington Till). They also suggested that this till may be representative of at least the late Wisconsinan glaciation and that the major physiographic elements of the region were responsible for the different ice flow movements. Therefore, all reported ice flow phases were linked to that till and continuous flow lines were proposed. In the ensuing discussion, Dreimanis (1985) pointed out the abundant evidence of cross-cutting glacial striae and questioned the validity of Clark and Karrow's regional flow lines. The work presented in this paper seems to confirm that: continuous flow lines cannot be reasonably drawn from the available data indicating that glacial dynamics in the upper St. Lawrence Valley were affected by significant changes in ice flow directions during the Late Wisconsinan.

An important point worth mentioning is that the Oka Till, which is the surface till in the lower Laurentians, has more to share in terms of glacial dynamics with the Malone Till than with the Fort Covington Till, although the Malone Till may actually record an older ice stream episode. Not only are abrupt shifts in ice flow directions clearly demonstrated, but the ice-flow phases recorded thus far by till sheets in the upper St. Lawrence Valley were apparently in the reverse order. This is a clear indication that correlation between the different till units cannot be made readily over the entire region and these apparent ambiguities justify the introduction of a new name (Oka Till) for the surface till in the lower Laurentians, at least until further studies clarify the links between the till sequences. However, evidence for a southwestward ice flow phase is so ubiquitous in the lower Laurentians that it is more realistic to assign a Late Wisconsinan age to the Oka Till. Furthermore, evidence of southwestward ice flow appears to extend throughout the upper St. Lawrence Valley. If the Fort Covington Till has to be related to a regional SE ice flow phase, which seems to be the case (MacClintock and Dreimanis 1964), it most likely represents a late phase (corresponding to the re-equilibration phase; Fig. 13d) and would thus be slightly younger than the Oka Till. This brings back the idea that the Fort Covington Till may represent a relatively short-lived and late event (cf. Dreimanis 1977: his Fig. 2).

Extension of Lake Candona

Evidence suggesting that a short-lived glacial lake covered the central St. Lawrence Lowlands prior to the incursion of the Champlain Sea have been reported by several researchers (LaSalle 1981; Anderson *et al.* 1985; Parent 1987; Naldrett 1988; Rodrigues 1992) and were integrated in regional paleogeographic models (e.g., Parent and Occhietti 1988, 1999; Pair and Rodrigues 1993; Occhietti *et al.* 2001). Assemblages made exclusively of the freshwater ostracode *Candona cf. C. subtriangulata* in rhythmites overlying the regional till and underlying Champlain Sea sediments is definitely the most convincing evidence of the existence of such a lake. Parent and Occhietti (1988) presented a reconstruction of the glaciolacustrine phases prior to the marine invasion and named the most extensive coalescent phase Lake Candona. Based on the work of Anderson *et al.* (1985), Naldrett (1988) and Rodrigues (1992), it is clear that this freshwater lake extended into the Ottawa and upper St. Lawrence valleys. Evidence presented in this paper helps to constrain the extension of this glacial lake east of Ottawa and north of the Ottawa River.

As suggested by Rodrigues (1992), many of the formely interpreted proximal glaciomarine outwash fans in the Ottawa Valley (e.g., Burbidge and Rust 1988; Sharpe 1987, 1988) must have been deposited in Lake Candona, not in early Champlain Sea.

Conclusion

The Quaternary successions in buried valleys of the Plain northwest of Montreal contain evidence of pre-Late Wisconsinan non-glacial sedimentation (SJL sediments), glaciolacustrine deposition prior to a major ice advance, and two till sheets (Argenteuil Till and Oka Till) with contrasting characteristics which provide a clear record of the last two major ice flow phases that occurred in this region. Both till sheets are assigned a Late Wisconsinan age. The oldest phase was toward the south, but much of its record was obliterated by a subsequent and major southwestward flow phase. The latter was in turn followed by a short-lived late glacial southeastward flow phase. This late glacial reorientation is more apparent southwest of the study area. Therefore, ice flow direction clearly shifted several times during the last glacial cycle and was not necessarily dominated by southward ice flow. In spite of uncertainties regarding its timing and magnitude, the southwestward ice flow phase was definitely much more than a minor late glacial reorientation. Abrupt changes in ice flow direction and convergent flow patterns suggest that ice stream activity was a key process in the Late Wisconsinan record of the upper St. Lawrence Valley. A glacial dynamics model is thus proposed whereby a "switching mechanism" operated between an ice stream mode and a "normal" SE ice flow mode. The ice stream was initiated southwest of the study area, but its catchment area episodically migrated northeastward into the study area and perhaps beyond. Full glacial conditions were seemingly more favorable for southward flow in the upper St. Lawrence Valley. In the late stages of deglaciation, a channelized meltwater system developed subglacially and was focused along the southwest-trending buried valleys of the study area. Lastly, it is now confirmed that Lake Candona briefly extended in the study area prior to marine incursion and that exceptionally elevated sedimentation rates were recorded in buried valleys during the early phase of Champlain Sea.

Acknowledgments

This paper is part of a Ph.D. dissertation at INRS Eau, Terre et Environnement. The work was mainly supported by Natural Resources Canada. Drilling of borehole 00_CHS_F1 was supported by the Québec Ministry of Transportation and the residential well (MR-1999-0001; cf., Fig. 7) was drilled by *Les Puits Deux-Montagnes Inc.* Partial financial support to the first author was provided through scholarships from the Fonds Québécois de la Recherche sur la Nature et les Technologies. The authors would like to thank Andrée M. Bolduc, J.P. Guilbault and all the teammates of both the NATMAP and AFSOQ projects for their invaluable help. Denis Lavoie (NATMAP project leader) and Martine M. Savard (AFSOQ project leader) are acknowledged for generous project support. The authors would also like to thank Michel Lamothe and other colleagues at UQAM for the IRSL tests and for numerous discussions. D. Sharpe provided stimulating internal GSC review.

References

Alley, R.B. 1991. Deforming-bed origin for southern Laurentide till sheets? Journal of Glaciology, **37**: 67-76.

Alley, R.B., and Bindschadler, R.A. 2001. The West Antarctic ice sheet and sea-level change. *In* The West Antarctic ice sheet: behavior and environment. *Edited by* R.B. Alley and R.A. Bindschadler, American Geophysical Union, 1-11 (Antarctic Research Series 77).

Anandakrishnan, S., Blankenship, D.D., Alley, R.B., and Stoffa P.L. 1998. Influence of subglacial geology on the position of a West Antarctic ice stream from seismic observations. Nature, **394**: 62-65.

Anderson, T.W., Mott, R.J., and Delorme, L.D. 1985. Evidence for a pre-Champlain Sea Glacial Lake phase in Ottawa Valley, Ontario and its implications. *In* Current research, part A, Geological Survey of Canada, Paper 85-1A, pp. 239-245

Anderson, T.W., Matthews, J.V., Jr., Mott, R.J., and Richard, S.H. 1990. The Sangamonian Pointe-Fortune site, Ontario-Québec border. Géographie physique et Quaternaire, **44**(3): 271-287.

Barnett, P.J. 1992. Quaternary geology of Ontario. *In* Geology of Ontario. *Edited by* P.C. Thurston, H.R., Williams, R.H., Sutcliffe, and G.M. Stott. Ontario Geological Survey, Special Vol. 4, Part 2, Toronto, Ont., pp. 1011–1088.

Barnett, P.J., Cowan, W.R., and Henry A.P. 1991. Quaternary geology of Ontario, southern sheet. Ontario Geological Survey, Map 2556, scale 1:1 000 000.

Bates, C.C. 1953. Rational theory of delta formation. American Association of Petroleum Geologists Bulletin, **37**: 2119-2162.

Bell, R.E., Blankenship, D.D., Finn, C.A., Morse, D.L., Scambos, T.A., Brozena, J.M., and

Hodge, S.M. 1998. Influence of subglacial geology on the onset of a West Antarctic ice stream from aerogeophysical observations. Nature, **394**: 58-61.

Benjumea, B., Hunter, J.A., Good, R.L., Burns, R.A., and Ross, M. 2001. Application of high-resolution seismic reflection techniques in Champlain Sea sediments near Lachute-Saint-Benoît, Québec. Geological Survey of Canada, Current research 2001-D6.

Bolduc, A.M., and Ross, M. 2000. La géologie et la géomorphologie quaternaire des basses Laurentides (ouest de Montréal). Field guide, AQQUA-CGRG.

Bolduc, A.M., and Ross, M. 2001*a*. Géologie des formations superficielles, Lachute-Oka, Québec. Geological Survey of Canada, Open-file 3520, 1/50 000.

Bolduc, A.M., and Ross, M. 2001*b*. Géologie des formations superficielles, Laval, Québec. Geological Survey of Canada, Open-file 3878, 1/50 000.

Boulton, G.S. 1987. A theory of drumlin formation by subglacial sediment deformation. *In* Drumlin Symposium. *Edited by* J. Menzies and J. Rose, Balkema, Rotterdam, pp. 25-80.

Boulton, G.S. 1996. The origin of till sequences by sub-glacial sediment deformation beneath mid-latitude ice sheets. Annals of Glaciology, **22**: 75-84.

Boulton, G.S., Smith G.D., Jones, A.S., and Newsome, J. 1985. Glacial geology and glaciology of the last mid-latitude ice sheets. Journal of the Geological Society of London, **142**: 447-474.

Boulton, G.S., Hagdorn, M., and Hulton, R.J. 2003. Streaming flow in an ice sheet through a glacial cycle. Annals of Glaciology, **36**: 117-128.

Boyce, J.I., Eyles, N., and Pugin, A. 1995. Seismic reflection, borehole and outcrop geometry of Late Wisconsin tills at a proposed landfill near Toronto, Ontario. Canadian Journal of Earth Sciences, **32**: 1331-1349.

Brennand, T.A., Shaw, J. 1994. Tunnel channels and associated landforms, south-central Ontario:

their implications for ice-sheet hydrology. Canadian Journal of Earth Sciences, **31**: 505-522.

Brooks, R.R. 1972. Geobotany and Biogeochemistry in Mineral Exploration. Harper and Row, New York.

Burbidge, G.H., and Rust, B.R. 1988. A Champlain Sea subwash fan at St. Lazare, Québec. *In* The Late Quaternary Development of the Champlain Sea Basin. *Edited by* N.R. Gadd. Geological Association of Canada, Special Paper 35, pp. 47-61.

Carl, J.D. 1978. Ribbed moraine-drumlin transition belt, St. Lawrence Valley, New York. Geology, **6**: 562-566.

Chakhmouradian, A.R. 1996. On the development of niobium and rare-earth minerals in monticellite - calcite carbonatite of the Oka complex, Québec. The Canadian Mineralogist, **34**: 479-484.

Chapman, L.J., and Putnam, D.F. 1984. The Physiography of Southern Ontario. Third edition, Ontario Geological Survey, Special Volume 2, Ministry of Natural Resources, Ontario.

Clark, P.U. 1994. Unstable behavior of the Laurentide ice sheet over deforming sediment and its implications for climate change. Quaternary Research, **41**: 19-25.

Clark, P.U. 1995. Fast glacier flow over soft beds. Science, **267**: 43-44.

Clark, P.U., and Karrow P.F. 1983. Till stratigraphy in the St. Lawrence Valley near Malone, New York: Revised glacial history and stratigraphic nomenclature. Geological Society of America Bulletin, 94: 1308-1318.

Clark, T.H. 1937. Northward moving ice in southern Quebec. American Journal of Science, **34**(201): 215-220

Clayton, L., Teller, J.T., and Attig, J.W. 1985. Surging of the southwestern part of the Laurentide Ice Sheet. Boreas, **14**: 235-241.

Connor, J.J., and Shacklette, H.T., 1975. Background geochemistry of some soils, plants, and vegetables in the conterminous United States. U.S. Geological Survey, Professional Paper 574-F.

Corbeil, P. 1984. Géologie du Quaternaire de la région de Rigaud/Rivière-Beaudette (Québec): quelques applications à l'environnement. Unpublished M.Sc. thesis, Université du Québec à Montréal, Québec.

Delage, M. 1997. Façonnement et métamorphose du modelé drumlinoïde par deux écoulements glaciaires successifs dans la région de Huntingdon (sud du Québec). Unpublished Ph.D. thesis, Université de Montréal, Québec.

Denton, G.H., and Hugues, T.J. 1981. The Last Great Ice Sheets. Wiley, New York.

Dreimanis, A. 1977. Correlation of Wisconsin glacial events between the eastern Great Lakes and St. Lawrence Lowlands. Géographie physique et Quaternaire, **31**(1-2): 37-51.

Dreimanis, A. 1985. Till stratigraphy in the St. Lawrence Valley near Malone, New York : Revised glacial history and stratigraphic nomenclature : Discussion. Geological Society of America Bulletin, **96**: 155-156.

Durand, M., and Ballivy, G. 1974. Particularités rencontrées dans la région de Montréal résultant de l'arrachement d'écailles de roc par la glaciation. Canadian Geotechnical Journal, **11**: 302-306.

Dyke, A.S., and Prest, V.K. 1987. Late Wisconsinan and Holocene history of the Laurentide ice sheet. Géographie physique et Quaternaire. **41**(2): 237-263.

Gadd, N.R. 1980. Ice flow patterns, Montreal-Ottawa lowland areas. *In* Current Research, Part A, Geological Survey of Canada, Paper 80-1A, pp. 375-376.

Gilbert, R. 1990. Evidence for the subglacial meltwater origin and late Quaternary lacustrine environment of Bateau Channel, eastern Lake Ontario. Canadian Journal of Earth Sciences, **27**: 939-945.

Gilbert, R., and Shaw, J. 1992. Glacial and early postglacial lacustrine environment of a portion of northeastern Lake Ontario. Canadian Journal of Earth Sciences, **29**: 63-75.

Gleeson, C.F., and Cormier R. 1971. Evaluation by geochemistry of geophysical anomalies and geological targets using overburden sampling at depth. *In* Geochemical Exploration. *Edited by* R.W. Boyle and J.I. McGerrigle. Canadian Institute of Mining and Metallurgy, Third International Geochemical Exploration Symposium, Toronto, Special Volume 11, pp. 159-165.

Globensky, Y. 1982. Région de Lachute. Ministère de l'Énergie et des Ressources, Québec, RG-200.

Globensky, Y. 1987. Géologie des Basses-Terres du Saint-Laurent. Ministère de l'Énergie et des Ressources, Québec, MM 85-02.

Gold, D.P. 1967. Alkaline ultrabasic rocks in the Montreal area, Quebec. In Ultramafic and related rocks. P.J. Wyllie, John Wiley & Sons, New York, pp. 288-302.

Gold, D.P., Eby, G.N., Bell, K., and Vallée, M. 1986. Carbonatites, diatremes, and ultra-alkaline rocks in the Oka area. Quebec. Geological Association of Canada - Mineralogical Association of Canada - Canadian Geophysical Union, Field Trip Guidebook 21.

Guilbault, J-P. 1989. Foraminiferal distribution in the central and western parts of the Late Pleistocene Champlain Sea Basin, Eastern Canada. Géographie physique et Quaternaire, **43**(1): 3-26.

Gustavson, T.C., Ashley, G.M., and Boothroyd, J.C. 1975. Depositional sequences in glaciolacustrine deltas. *In* Glaciofluvial and Glaciolacustrine Sedimentation. *Edited by* A.V. Jopling, and B.C. McDonald, Society for Sedimentary Geology, Special Publication 23, pp. 264-280.

Gwyn, Q.H.J., and Thibault, J.J.L. 1975. Quaternary geology of the Hawkesbury-Lachute area, southern Ontario, Ontario Division of Mines, map P1010, Geological Series.

Hardy, F., and Lamothe, M. 1997. Quaternary basin analysis using infrared stimulated luminescence on borehole cores and cuttings. Quaternary Science Reviews (Quaternary Geochronology), **16**: 417-426.

Hart, J.K. 1999. Identifying fast ice flow from landform assemblages in the geological record: a discussion. Annals of Glaciology, **28**: 59-66.

Hicock, S.R., and Dreimanis, A. 1992. Deformation till in the Great Lakes region: implications for rapid flow along the south-central margin of the Laurentide Ice Sheet. Canadian Journal of Earth Sciences, **29**: 1565-1579.

Hughes, T., Borns, H.W., Fastook, J.L., Hyland, M.R., Kite, J.S., and Lowell, T.V. 1985. Models of glacial reconstruction and deglaciation applied to Maritime Canada and New England. *In* Late Pleistocene History of Northeastern New England and Adjacent Quebec. *Edited by* H.W. Borns, Jr., LaSalle, P., and W.B. Thompson. Geological Society of America, Special Paper 197, pp. 139-150.

Hunter, J.A., Pullan, S.E., Burns, R.A., Gagné, R.M., and Good, R.L. 1989. Applications of a shallow seismic reflection method to groundwater and engineering studies. In Proceedings of Exploration '87, Third Decennial International Conference on Geophysical and Geochemical Exploration for Minerals and Groundwater. Edited by G.D. Garland. Ontario Geological Survey, Special Volume 3, pp. 704-715.

Jopling, A.V., and Walker, R.G., 1968. Morphology and origin of ripple-drift cross lamination, with examples from the Pleistocene of Massachusetts. Journal of Sedimentary Petrology, **38**: 971-984.

Jopling, A.V., and McDonald, B.C., Editors. 1975. Glaciofluvial and Glaciolacustrine Sedimentation. Society of Economic Paleontology and Mineralogy, Special Publication 23.

Joughin, I., Tulaczyk, S., MacAyeal, D.R., Engelhardt, H. 2004. Melting and freezing beneath the Ross ice streams, Antarctica. Journal of Glaciology, **50**(168): 96-108

Karrow, P.F., Dreimanis, A., and Barnett, P.J. 2000. A proposed diachronic revision of Late Quaternary time-stratigraphic classification in the eastern and northern Great Lakes area. Quaternary Research, **54**: 1-12.

Karrow, P.F., and Occhietti, S. 1989. Quaternary geology of the St. Lawrence Lowlands of Canada. *In* Quaternary geology of Canada and Greenland. *Edited by* R.J. Fulton. Geological Survey of Canada, Geology of Canada, no. 1, pp. 321-389.

Kettles, I.M., and Shilts, W.W. 1987. Tills of the Ottawa region. *In* Quaternary geology of the Ottawa region, Ontario and Quebec. *Edited by* R.J. Fulton. Geological Survey of Canada, Paper 86-23, pp. 10-13.

Lamothe, M. 1989. A new framework for the Pleistocene stratigraphy of the central St. Lawrence Lowland, Southern Québec. Géographie physique et Quaternaire, **43**(2): 119-129.

Lang, O., Rabus, B.T., Dech, S.W. 2004. Velocity map of the Thwaites glacier catchment, West Antarctica. Journal of Glaciology, **50**(168): 46-56

Lanz, E., Pugin, A., Green, A., and Horstmeyer, H. 1996. Results of 2- and 3-D high-resolution seismic reflection surveying of surficial sediments. Geophysical Research Letters, **23**: 491-494.

LaSalle, P. 1981. Géologie des dépôts meubles de la région Saint-Jean-Lachine. Ministère de l'Énergie et des Ressources, Québec, DPV-780.

Lévesque, G. 1982. Géologie des dépôts quaternaires de la région de Oka - Ste-Scholastique, Québec. Unpublished M.Sc. thesis, Université du Québec à Montréal.

Lian, O.B., Hicock, S.R., and Dreimanis, A. 2003. Laurentide and Cordilleran fast ice flow; some sedimentological evidence from Wisconsinan subglacial till and its substrate. *In* Paleo-ice streams. *Edited by* J.A. Piotrowski, K.L. Knudsen, C.D. Clark, and D.J.A. Evans. Boreas, **32**, pp. 102-113.

MacClintock P, Dreimanis A (1964) Reorientation of till fabric by overriding glacier in the St. Lawrence Valley. American Journal of Science, **262**: 133-142

MacClintock, P., and Stewart, D.P. 1965. Pleistocene Geology of the St. Lawrence Lowland. New York State Museum and Science Service, Bulletin 394.

Marshall, S.J., Clarke, G.K.C., Dyke, A.S., and Fisher, D.A. 1996. Geologic and topographic controls on fast flow in the Laurentide and Cordilleran Ice Sheets. Journal of Geophysical Research, **101**(B8): 17 827-17 839.

Naldrett, D.L. 1988. The late glacial-early glaciomarine transition in the Ottawa Valley: evidence for a glacial lake? Géographie physique et Quaternaire, **42**(2): 171-179.

North American Commission on Stratigraphic Nomenclature (1983) North American stratigraphic code. American association of petroleum geologists Bulletin, **67**:841-875

Occhietti, S., Parent, M., Shilts, W.W., Dionne, J-C., Govare, É., and Harmand, D. 2001. Late Wisconsinan glacial dynamics, deglaciation, and marine invasion in southern Québec. *In* Deglacial History and Relative Sea-Level Changes, Northern New England and Adjacent Canada. *Edited by* T.K. Weddle, and M.J. Retelle. Geological Society of America, Boulder, Colorado, Special Paper 351, pp. 243-270.

Pair, D.L., and Rodrigues, C.G. 1993. Late Quaternary deglaciation of the southwestern St.

Lawrence Lowland, New York and Ontario. Geological Society of America Bulletin, **105**: 1151-1164.

Parent, M. 1987. Late Pleistocene stratigraphy and events in the Asbestos - Valcourt region, southeastern Québec. Unpublished Ph.D. thesis, University of Western Ontario.

Parent, M., and Occhietti, S. 1988. Late Wisconsinan deglaciation and Champlain Sea invasion in the St. Lawrence Valley, Québec. Géographie physique et Quaternaire, **42**(3): 215-246.

Parent, M., and Occhietti, S. 1999. Late Wisconsinan deglaciation and glacial lake development in the Appalachians of southeastern Québec. **53**(1): 117-135.

Parent, M., Paradis, S.J., and Doiron, A. 1996. Palimpsest glacial dispersal trains and their significance for drift prospecting. Journal of Geochemical Exploration, **56**: 123-140.

Patterson, C.J. 1998. Laurentide glacial landscapes: The role of ice streams. Geology, **26**(7): 643-646.

Piper, D.J.W., Mudie, P.J., Fader, G.B., Josenhans, H.W., Maclean, B., and Vilks, G. 1990. Quaternary Geology. *In* Geology of the continental margin of eastern Canada. *Edited by* Keen, M.J., and Williams, G.L., Geological Survey of Canada, Geology of Canada, no. 2, pp. 513-652.

Prest, V.K., and Hode-Keyser, J. 1962. Surficial Geology and Soils, Montreal Area, Quebec. Department of Public Works, Montreal.

Prest, V.K., and Hode-Keyser, J. 1977. Geology and Engineering Characteristics of Surficial Deposits, Montreal Island and Vicinity, Quebec. Geological Survey of Canada, Paper 75-27.

Prichonnet, G. 1977. La déglaciation de la vallée du Saint-Laurent et l'invasion marine contemporaine. Géographie physique et Quaternaire, **21**(3-4): 323-345.

Prichonnet, G. 1984. Glaciations d'inlandsis: séquences glaciaires, proglaciaires et non glaciaires du Quaternaire de l'est canadien. Centres de Recherche en Exploration-Production Elf-Aquitaine Bulletin, **8**(1): 105-133.

Prichonnet, G., Durand, M., Elson, J.A., Gagnon, P., Schroeder, J., and Veillette, J. 1987. Glaciations et déglaciations du Wisconsien dans le sud du Québec (région de Montréal). INQUA, XIIth INQUA Congress, Field guide A-7/C-7.

Pugin, A., Pullan, S.E., and Sharpe, D.R. 1999. Seismic facies and regional architecture of the Oak Ridges Moraine area, southern Ontario. Canadian Journal of Earth Sciences, **36**: 409-432.

Rayburn, J.A., Knuepfer, P.L.K., and Franzi, D.A. 2003. Why a higher resolution Champlain Sea age determination is needed for meltwater flood discharge routing models? *In* 2003 CANQUA-CGRG Program and Abstracts, June 8-12 2003, Halifax, p. A94.

Richard, P.J.H., and Occhietti, S. 2005. ^{14}C chronology for ice retreat and inception of Champlain Sea in the St. Lawrence Lowlands, Canada. Quternary Research, 63: 353-358.

Richard, S.H. 1978. Surficial geology: Lachute-Montebello area, Quebec. *In* Current Research, Part B, Geological Survey of Canada, Paper 78-1C, pp. 23-28.

Richard, S.H. 1982. Surficial geology, Vaudreuil, Québec-Ontario. Geological Survey of Canada, Map 1488A, 1/50 000

Ridge, J.C., Besonen, M.R., Brochu, M., et al. 1999. Varve, paleomagnetic, and ^{14}C chronologies for Late Pleistocene events in New Hampshire and Vermont (U.S.A.). Géographie physique et Quaternaire, **53**(1): 79-106

Rocher, M., Salad-Hersi, O., and Castonguay, S. *in press*. Geologic map of St. Lawrence Lowlands – Sector west of Montreal (update). *In* Regional hydrogeologic characterization of the fractured aquifer system in south-western Quebec: Part III-Hydrogeologic atlas, CD-ROM, Fig. 4. Geological Survey of Canada, Bulletin.

Roberts, M.C., Pullan, S.E., and Hunter, J.A. 1992. Applications of land-based high resolution seismic reflection analysis to Quaternary and geomorphic research. Quaternary Science Reviews, 11: 557-568. et al. 1992

Rodrigues, C.G. 1992. Successions of invertebrate microfossils and the Late Quaternary deglaciation of the central St. Lawrence Lowland, Canada and United States. Quaternary Science Reviews, **11**: 503-534.

Ross, M. 2004. Stratigraphie et architecture des formations quaternaires au nord-ouest de Montréal – Applications en hydrogéologie régionale. Unpublished Ph.D. thesis, Université du Québec, Institut nationale de la recherche scientifique, Eau, Terre et Environnement, Québec, Qc.

Ross, M., Parent, M., Bolduc, A.M., Hunter, J.A., and Benjumea, B. 2001. .Étude préliminaire des formations quaternaires comblant les vallées des basses Laurentides, nord-ouest de Montréal, Québec. *In* Current Research, 2001-D5, Geological Survey of Canada.

Ross, M., Parent, M., and Lefebvre, R. 2004*a*. 3D geologic framework models for regional hydrogeology: a case study from a Quaternary basin of southwestern Quebec, Canada. Hydrogeology Journal. DOI:10.1007/s10040-004-0364-x; available online: http://link.springer.de/journals/hydrogeo/

Ross, M., Martel, R., Parent, M., Lefebvre, R., and Savard, M.M. 2004*b*. Assessing rock aquifer vulnerability using downward advective times from a 3D model of surficial geology: a case study from the St. Lawrence Lowlands, Canada. Geofisica Internacional, special issue on aquifer vulnerability and risk, **43**(4): 591-602

Savard, M.M., Nastev, M., Lefebvre, R., Martel, R., *et al.* 2000. Regional hydrogeology of fractured rock aquifers in southwestern Québec (St. Lawrence Lowlands). *In* Groundwater Specialty Proceedings, 53rd Canadian Geotechnical Conference, First Joint IAH-CNC and GSC Conference, pp. 247-253.

Savard, MM, Nastev, M, Paradis, et al., *in press*. Partie I - Hydrogéologie régionale du système aquifère; *In* - Caractérisation hydrogéologique, intégrée et régionale du système aquifère fracturé du sud-ouest du Québec, GSC Bulletin, pp. 1-42.

Sharpe, D.R 1987. Excursion G - Glaciomarine fans built within and marginal to the Champlain Sea. *In* Quaternary Geology of the Ottawa Region and Guides for Day Excursions. *Edited by* R.J. Fulton. XIIth INQUA Congress, pp. 71-84.

Sharpe, D.R. 1988. Glaciomarine Fan Deposition in the Champlain Sea. *In* The Late Quaternary Development of the Champlain Sea Basin. *Edited by* N.R. Gadd. Geological Association of Canada, Special Paper 35, pp. 63-82.

Shaw, J., Gilbert, R. 1990. Evidence for large-scale subglacial meltwater flood events in southern Ontario and northern New York State. Geology, **18**: 1169-1172

Shoemaker, E.M. 1992. Water sheet outburst floods from the Laurentide Ice Sheet. Canadian Journal of Earth Sciences, **29**: 1250-1264

Slaine, D.D., Pehme, P.E., Hunter, J.A., Pullan, S.E., and Greenhouse, J.P. 1990. Mapping overburden stratigraphy at a proposed hazardous waste facility using shallow seismic reflection methods. *In* Geotechnical and environmental geophysics. Vol. II. Environmental and groundwater. *Edited by* S.H. Ward. Society of Exploration Geophysicists, Tulsa, Okla., pp. 273-280.

Stokes, C.R., and Clark, C.D. 1999. Geomorphological criteria for identifying Pleistocene ice streams. Annals of Glaciology, **28**: 67-74.

Stokes, C.R., and Clark, C.D. 2001. Palaeo-ice streams. Quaternary Science Reviews, **20**: 1437-

1457.

St-Onge, D.A. 1979. Forages au roc, région nord de Montréal. Ottawa University, Research note 22.

Terasmae, J. 1965. Surficial geology of the Cornwall and St. Lwrence Seaway Project areas, Ontario. Geological Survey of Canada, Bulletin 121.

Turekian, K.K. 1977. Geochemical distribution of elements. In Encyclopedia of Science and Technology. 4th edition, McGraw Hill, New York, 627-630.

Van Wambeke, L. 1960. Geochemical prospecting and appraisal of Niobium-bearing carbonatites by X-Ray methods. Economic Geology, **55**: 732-758.

Veillette, J.J., and Nixon, F.M. 1984. Sequence of Quaternary sediments in the Bélanger sand pit, Pointe-Fortune, Québec-Ontario. Géographie et Quaternaire, **38**(1): 59-68.

http://www.menv.gouv.qc.ca/eau/souterraines/sih/index.htm (consulted June 2004)

List of tables

Table 1: Average Na_2O and Sr concentrations in till samples overlying different substrates in the study area.

	Lowlands	**Laurentians**
Na_2O (%)	1.6 ± 0.9 (n = 26)	3.2 ± 0.2 (n = 11)

	Till/Limestone	**Till/Sandstone**
Sr (ppm)	412 ± 117 (n = 5)	257 ± 80 (n = 6)

Table 2: Concentration of Nb (ppm) and *LREE* (ppm) in the upper till at the Bélanger pit (Pointe-Fortune) as well as typical background values.

Concentration in ppm

UPPER TILL SAMPLES	**Nb***	**La****	***LREE*** †	**Sr**
R011C (Top)	40.32	59.97	250.08	413.50
R011B (Middle)	20.60	40.81	183.04	354.92
R011A (Base)	22.94	43.28	198.08	379.83
Samples outside expected dispersal trains				
AH-99-16	18.67	32.95	151.69	328.78
R001	13.18	N/A	N/A	N/A
R006	12.82	N/A	N/A	N/A
R016	14.90	N/A	N/A	N/A
R019	10.16	27.70	118.26	254.37

* Average abundance in soils is 15 ppm (Brooks 1972)

**Median abundance in soils is 33 ppm (Connor and Shacklette 1975)

† Includes Ce, La, Nd and Pr

Table 3: Pebble counts in the upper till at the Bélanger pit (Pointe-Fortune).

Till section

	Pebble counts (%) on 4-2mm Ø fraction		
	Base (n = 1128)	**Middle** (n = 862)	**Top** (n = 1753)
Dolostone	38.6	35.0	46.5
Sandstone	16.3	20.8	22.8
Metamorphic (Shield)	44.7	43.7	30.4
Others	0.4	0.5	0.3

Figure captions

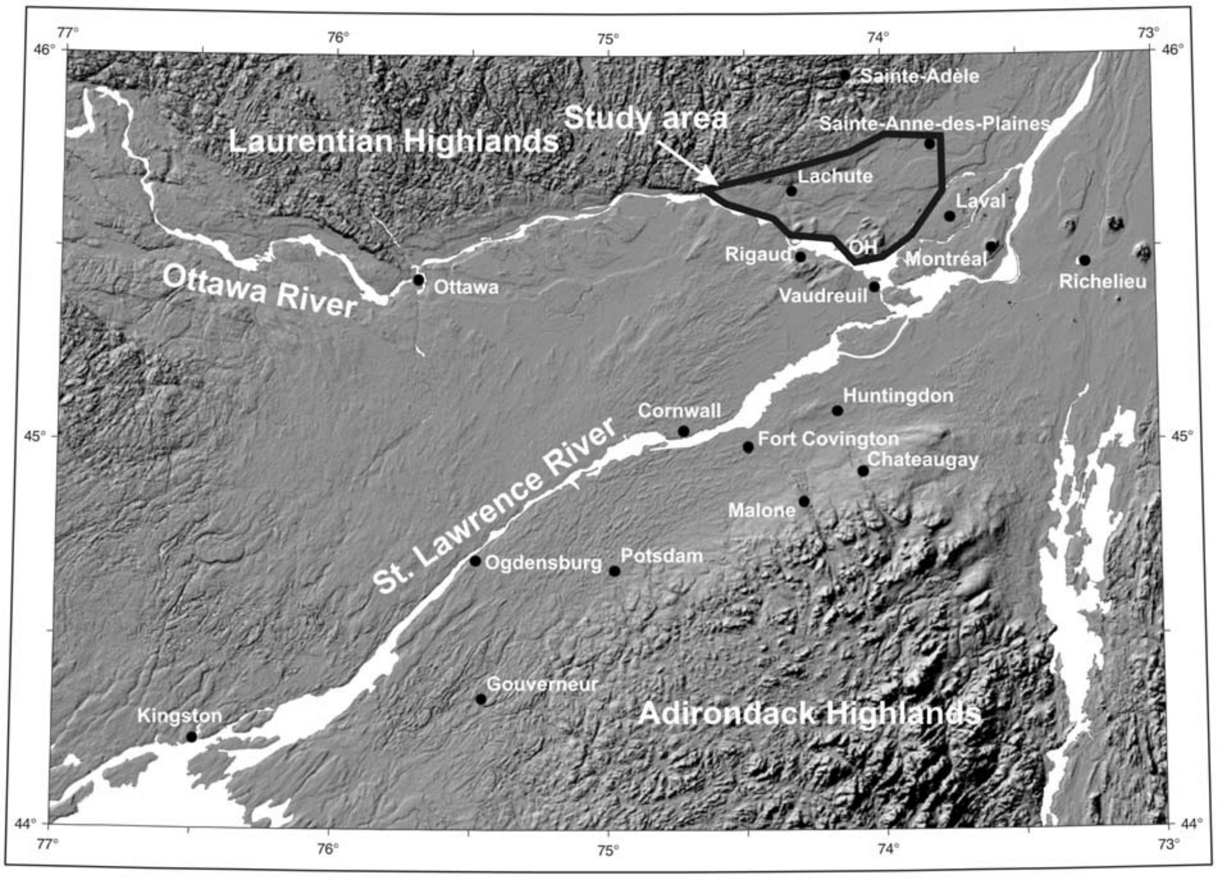

Figure 1: General location of the study area with a regional Digital Elevation Model (DEM) as background. (OH) Oka Hills.

Age	Bélanger pit (Pointe-Fortune)	Montreal Island	Northwest of Montreal	
	Veillette and Nixon (1984) Anderson et al. (1990)	Prest and Hode-Keyser (1962, 1977)	Lévesque (1982)	This study
Holocene		Post-Champlain Sea sediments	Post-Champlain Sea sediments	Post-Champlain Sea sediments
10 ka		Champlain Sea Glacial lake seds	Champlain Sea	Champlain Sea Lake Candona[b]
11.3 ka[a] Late Wisconsinan	Fort Covington, Border Till Carillon sand	Fort Covington Till	Glaciofluvial seds. upper till	Oka Till Argenteuil Till
35-25 ka Mid-Wisconsinan	↓	Middle Till Complex (glaciolacustrine)		Glaciolacustrine seds.
65-53 ka Early Wisconsinan	?	Malone Till		↓? ?↓
80-75 ka Sangamonian	Pointe-Fortune sediments (units 2, 3, 4)			Sand with wood fragments > 48 ka BP
130-128 ka Illinoian 300 ka	Rigaud Till			

[a] Extrapolated from data from Ridge (1999), Rayburn et al. (2003), as well as Richard and Occhietti (2005)
[b] The name "Lake Candona" is after Parent and Occhietti (1988)

Figure 2: Stratigraphic framework and correlation chart of Quaternary units in the Montreal region after authors cited.

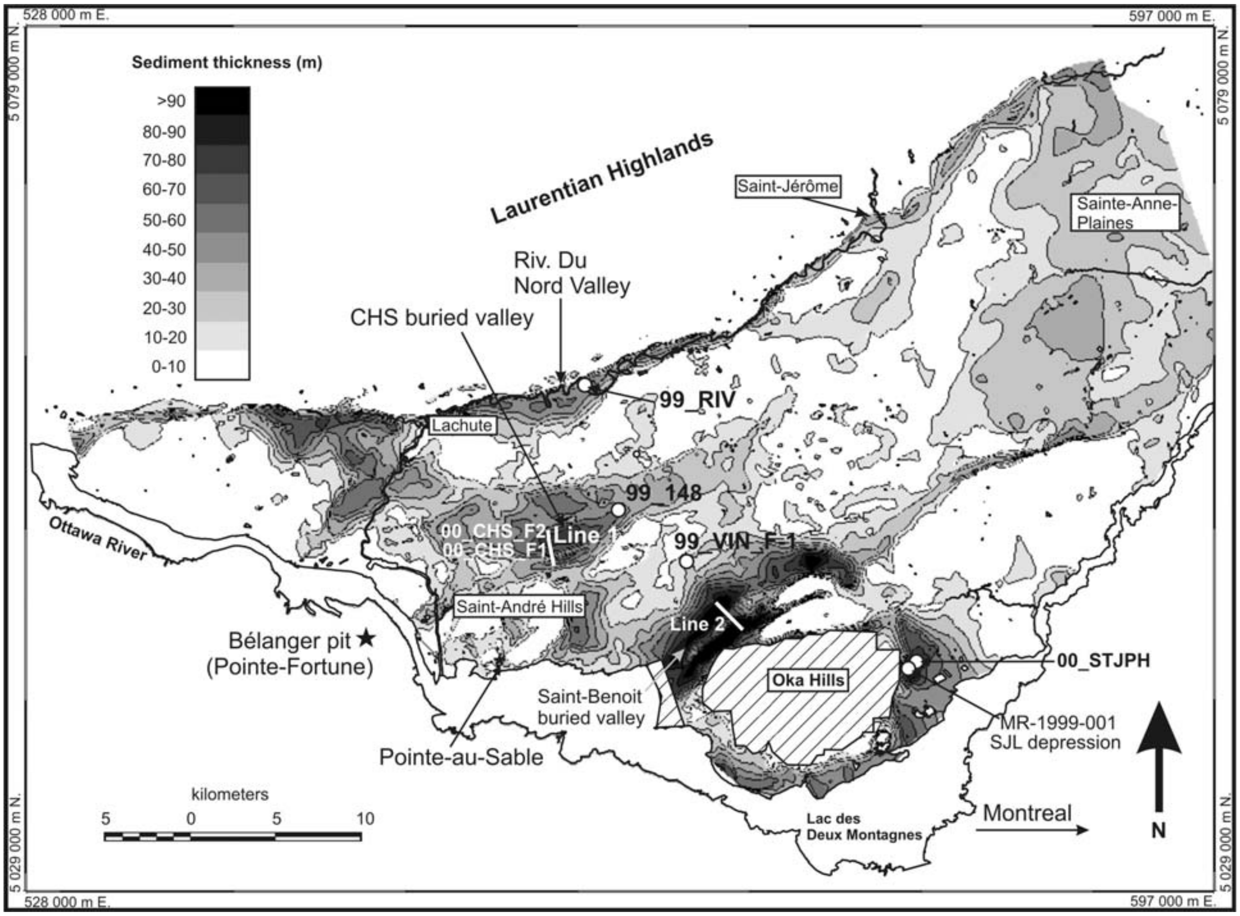

Figure 3: Location of seismic lines, boreholes and sections discussed in the text with an isopach map of Quaternary sediments as background showing the main buried valleys (after Ross *et al.* 2004a).

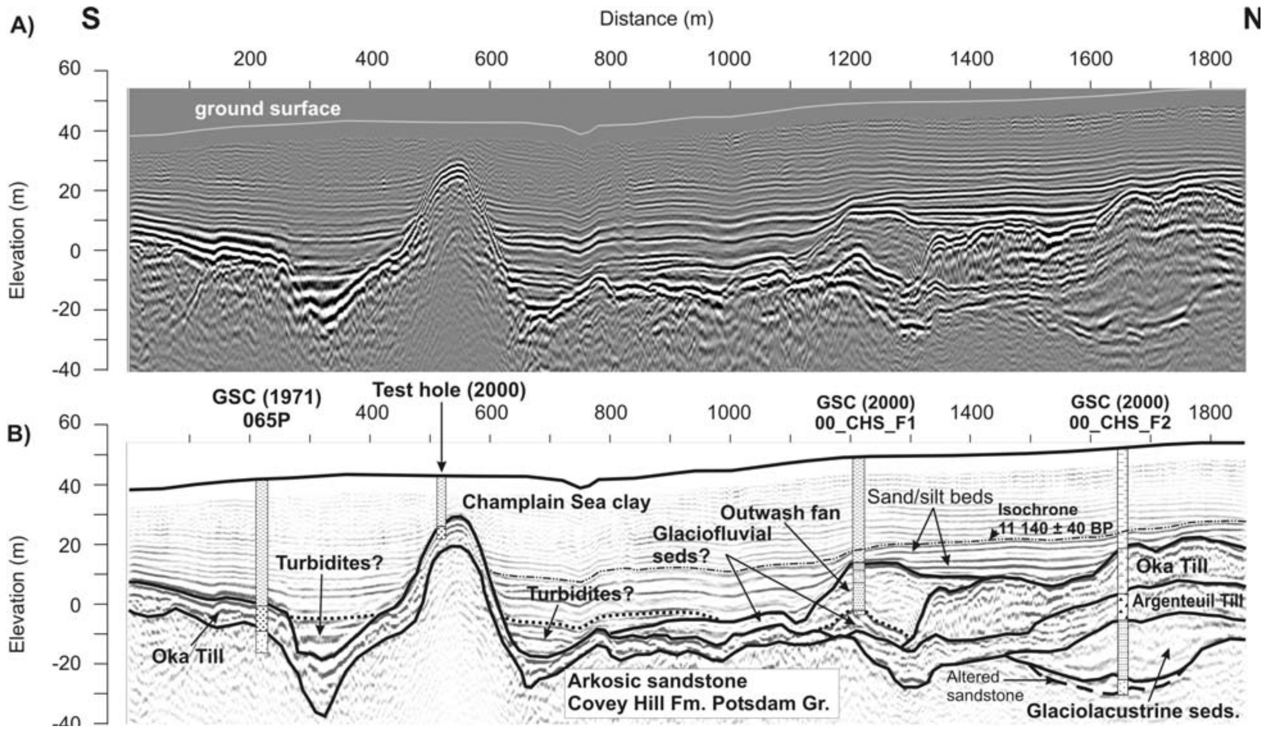

Figure 4: Line 1. **a**) Seismic reflection section recorded along *Chemin des Sources* (CHS): processed section in variable amplitude; and **b**) interpreted section. Two-way travel times are converted to depth and are displayed as elevations relative to sea level. Schematic representation of the lithological logs of three boreholes and one test hole drilled using a portable drill (Pionjär) along this seismic line are superimposed on the interpreted profile. Log 00_CHS_F1 and log 00_CHS_F2 are shown in more detail in Fig. 6 and Fig. 5, respectively.

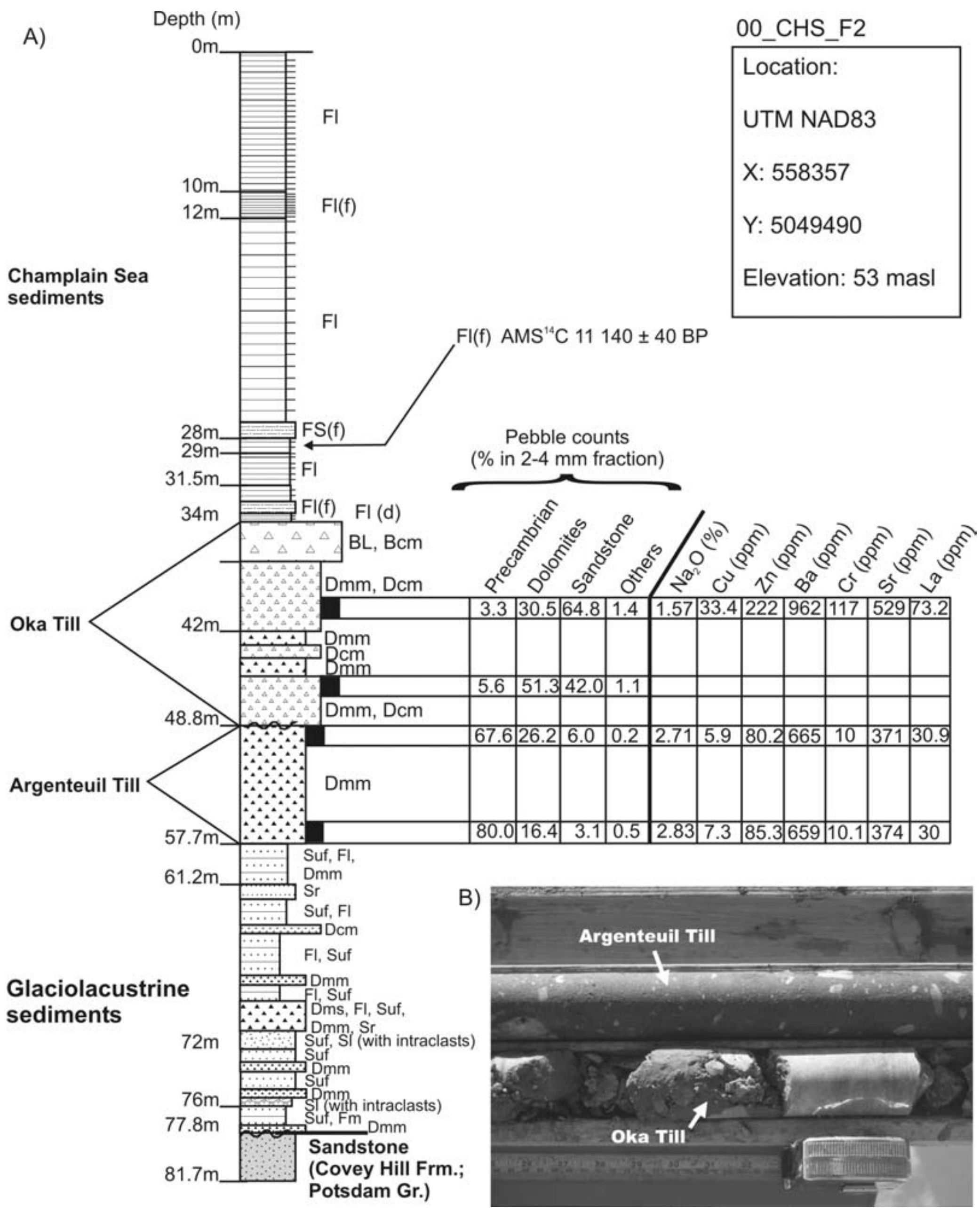

Figure 5: **a**) Stratigraphic log of borehole 00_CHS_F2. Two superposed tills overlying proximal glaciolacustrine sediments are recognized. **b**) Close-up view of the Argenteuil and Oka tills showing contrasting facies. Lithologic and geochemical results indicate that Argenteuil Till was deposited by ice flowing toward the south over its own proglacial suite of glaciolacustrine sediments, while Oka Till was clearly deposited by ice flowing toward the SW (See text for explanation on provenance).

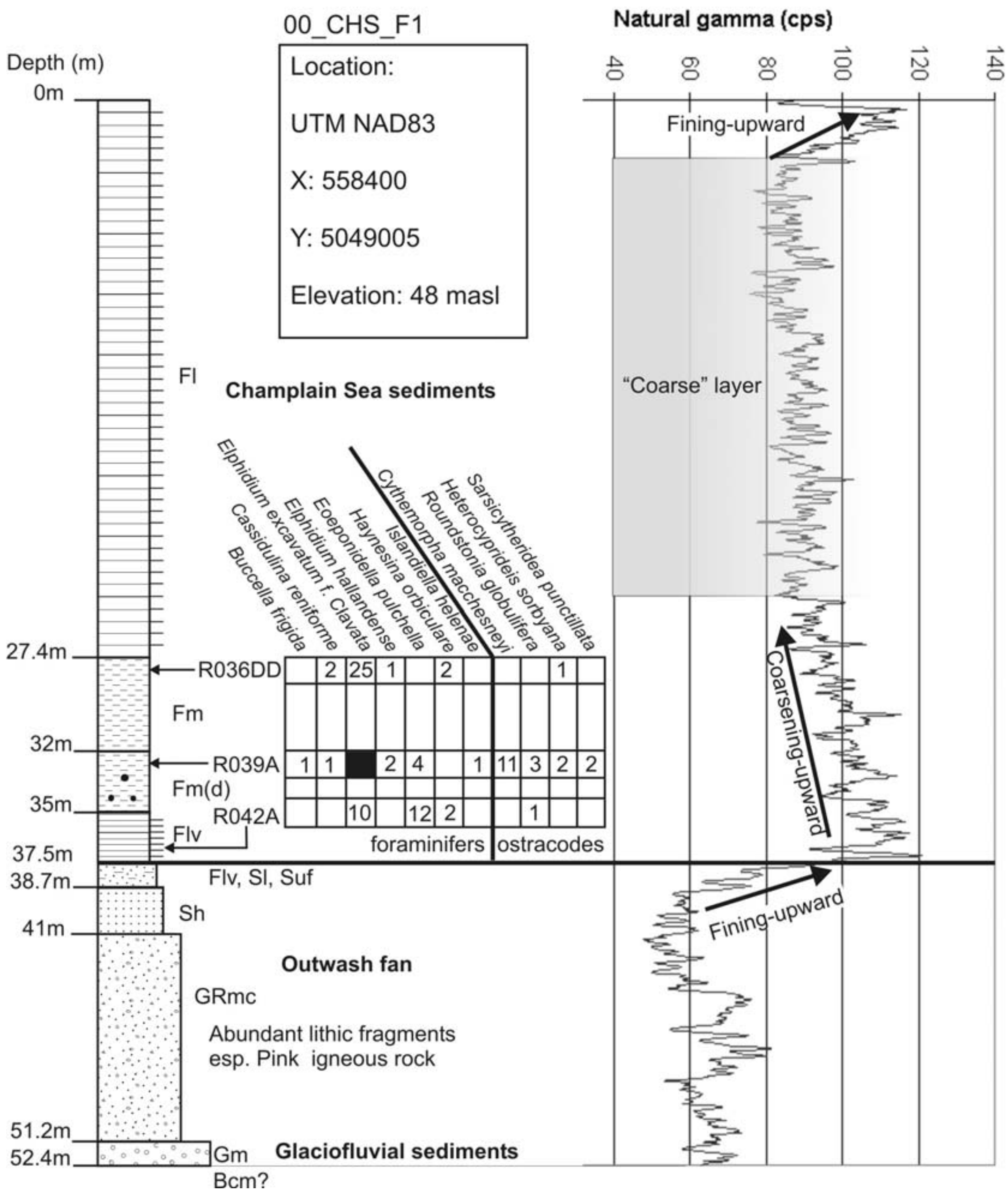

Figure 6: Stratigraphic and gamma logs of borehole 00_CHS_F1. The outwash sediments conformably overlie boulders of assumed glaciofluvial origin. The "coarse" layer within the marine unit is composed of laminated silt and silty clay interlayered with closely-spaced very fine sand partings. The microfaunal assemblage of sample R039A requires a salinity between 10 and 25‰. Distinction between glaciolacustrine and glaciomarine settings for the outwash fan sediments cannot be clearly established.

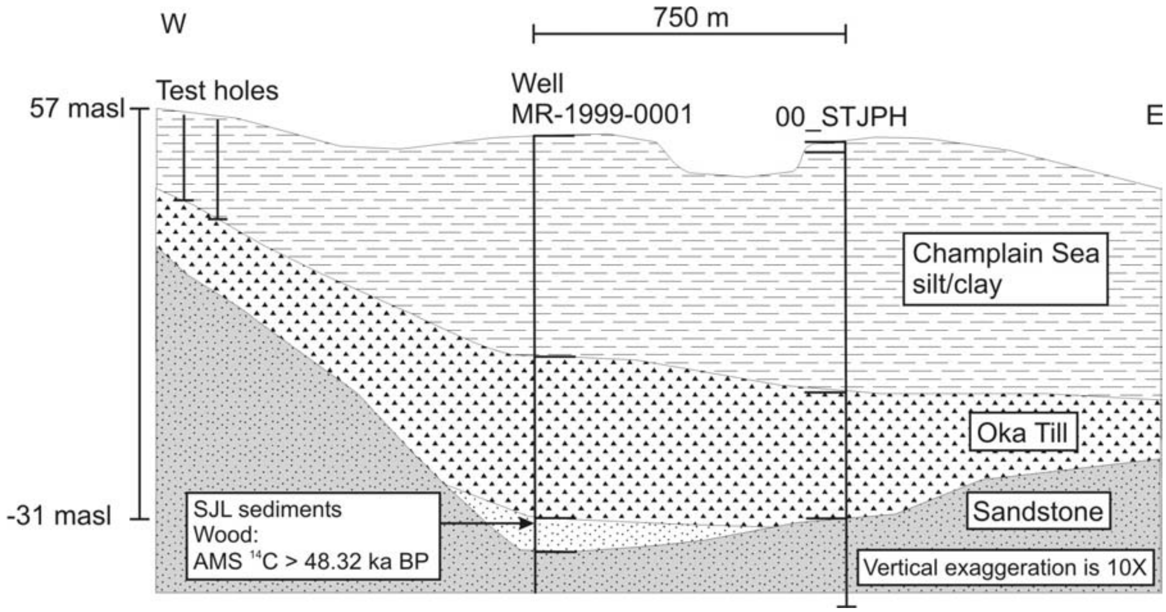

Figure 7: Schematic cross section linking borehole and well logs drilled during this study in *Saint-Joseph-du-Lac* (cf. Fig. 3). Wood from the sandy unit underlying the thick Oka Till yielded a non-finite radiocarbon age. The unit is thus at least older than late Wisconsinan and could be late Sangamonian in age. Details of borehole log 00_STJPH are shown on Figure 8.

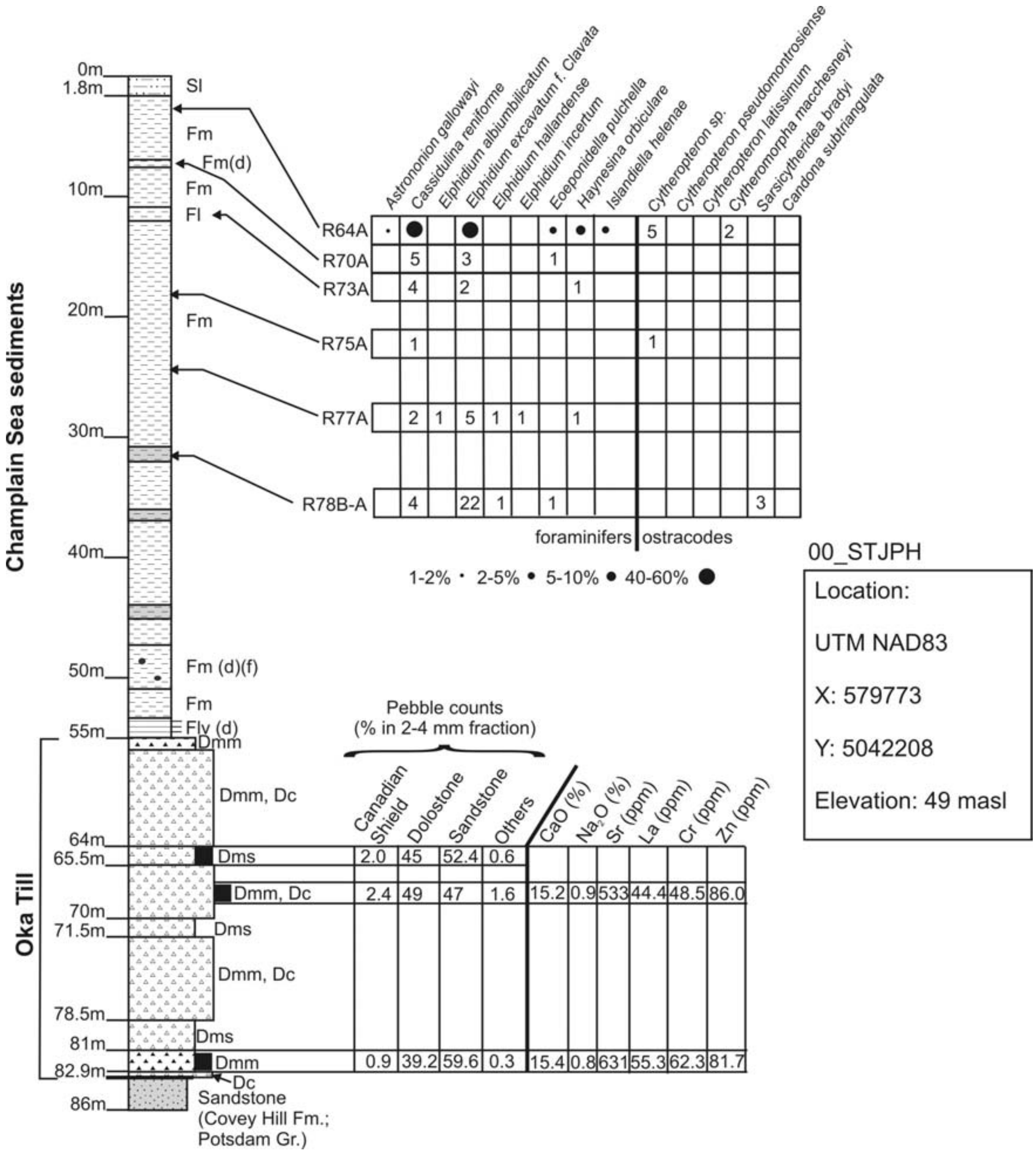

Figure 8: Stratigraphic borehole log 00_STJPH. The thick till sheet does not show evidence of a significant glacial dynamics shift. The < 63 µm fraction reveals a Sr anomaly. Geochemical carbonatite indicators are only slightly anomalous. Mixed contributions from both the widespread limestone and a small alkaline intrusion to the northeast best explain the geochemical signature of the till. Finally, most of the overlying Champlain Sea sediments appear to have been deposited prior to the maximum salinity phase.

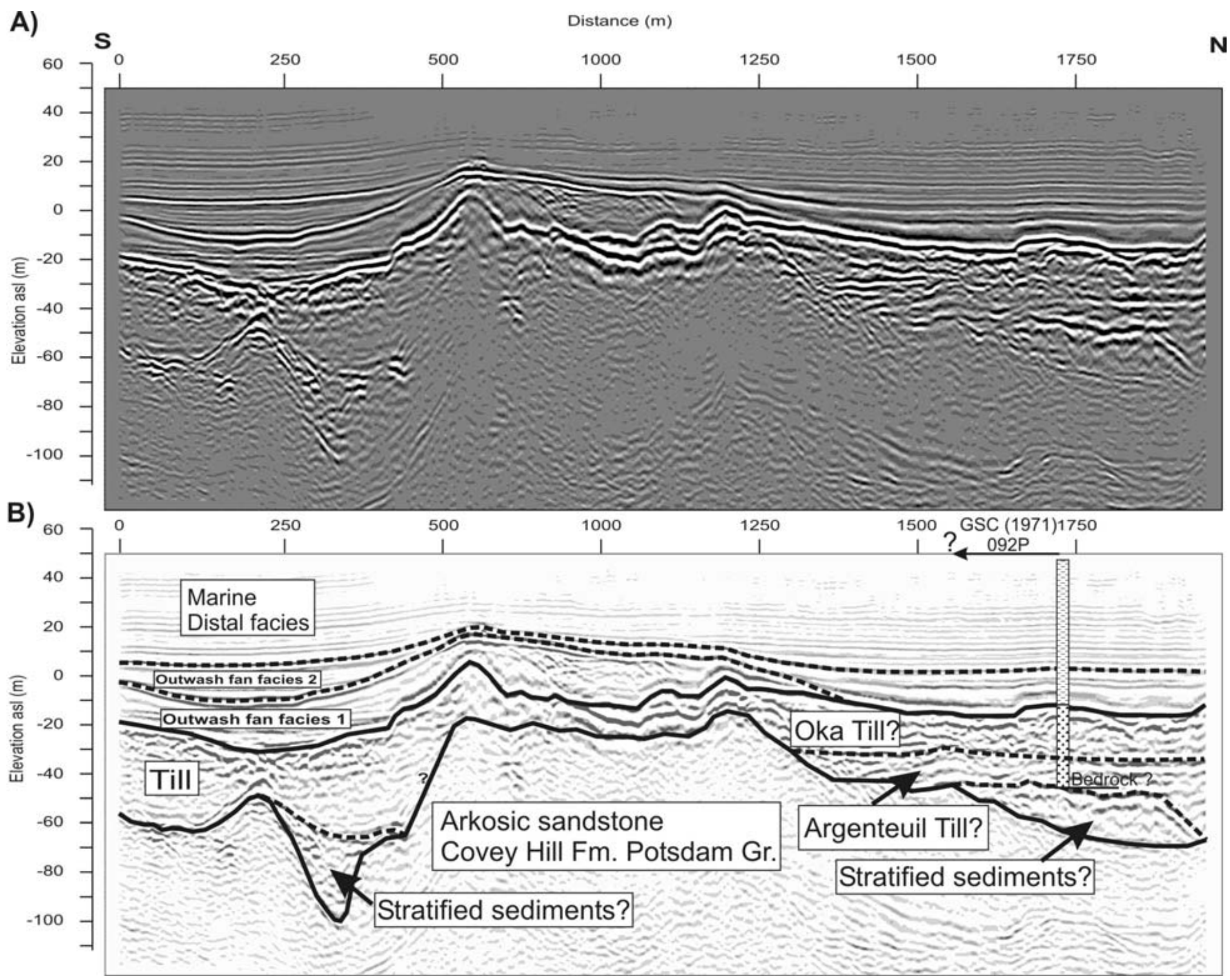

Figure 9: Line 2. **a**) Seismic reflection section recorded along *Côte Rouge* road and; **b**) interpreted section. Two-way travel times have been converted to depth and are displayed as elevations. Schematic representation of a GSC archival borehole log located about 22 m to this seismic line has been superimposed on the interpreted profile. Note the apparent discrepancy between the borehole log and seismic data due to the imprecise borehole location and/or large boulder misinterpreted as bedrock.

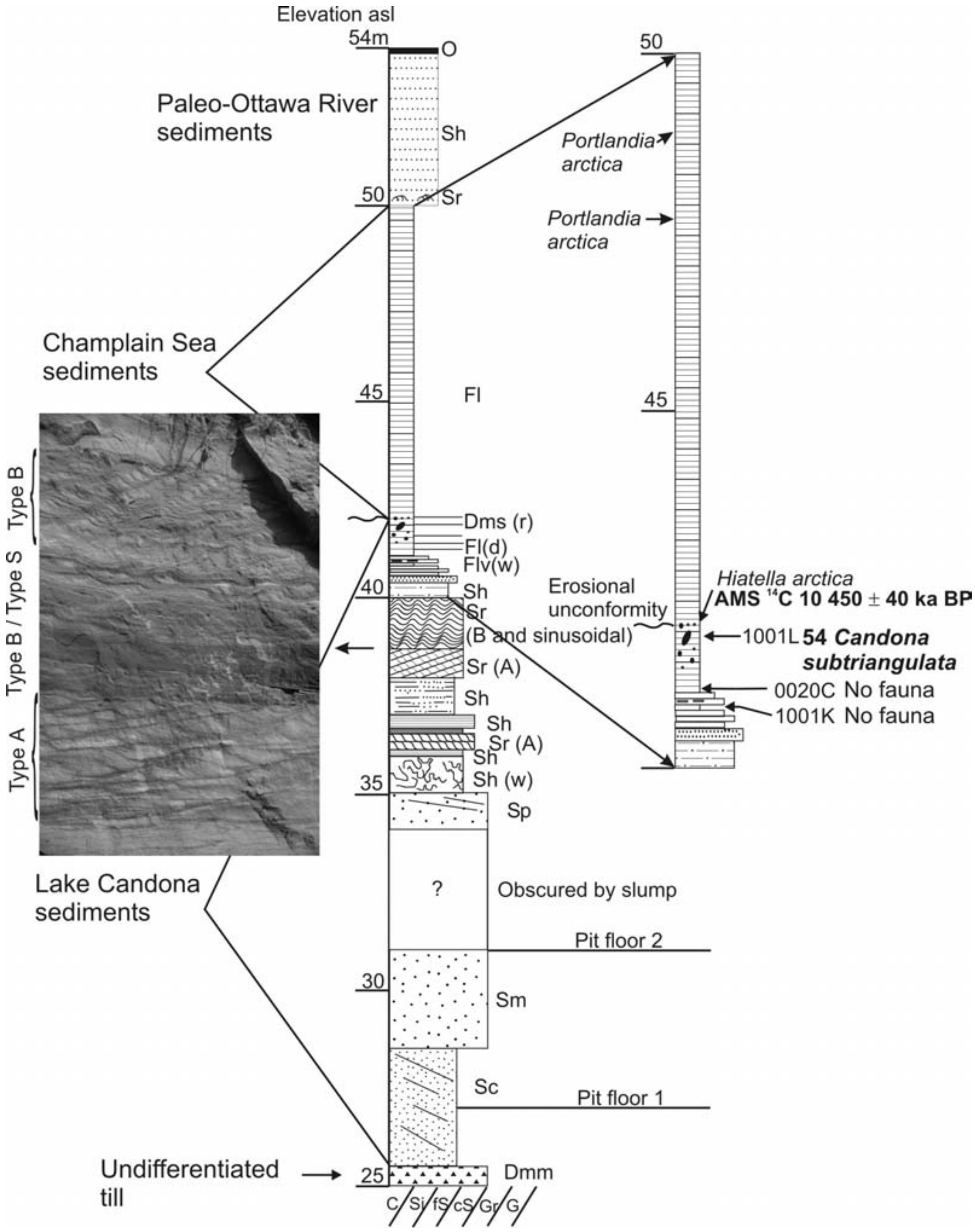

Figure 10: The Pointe-au-Sable section. The sequence between the undifferentiated till and the erosional unconformity represents a small subaqueous outwash fan deposited in a glaciolacustrine setting. The unconformity represents a hiatus separating glaciolacustrine sediments deposited into Lake Candona and sediments deposited later in the Champlain Sea, probably after the marine maximum. The top of the sequence is made of fluviatile sand related to the paleo-Ottawa River.

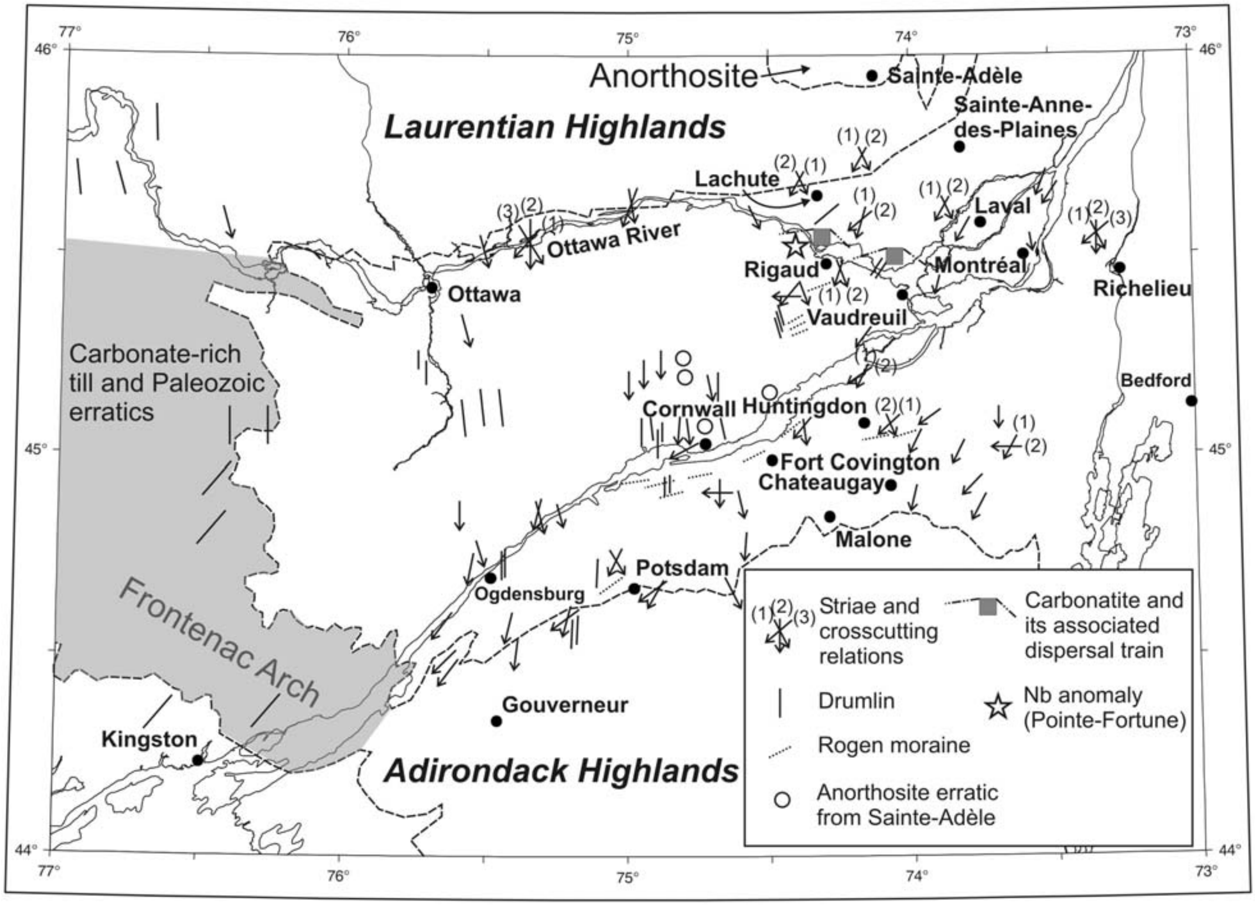

Figure 11: Selected glacial striae, streamlined landforms, and other ice flow indicators in the upper St. Lawrence Lowlands (compiled from multiple sources; references in text). These features clearly indicate that several changes in ice flow direction occurred in the upper St. Lawrence Valley during the last glacial cycle. Early southward ice flow shifted clockwise and was followed by a significant southwestward flow phase which was in turn followed by a late glacial counterclockwise shift between Ogdensburg and Vaudreuil.

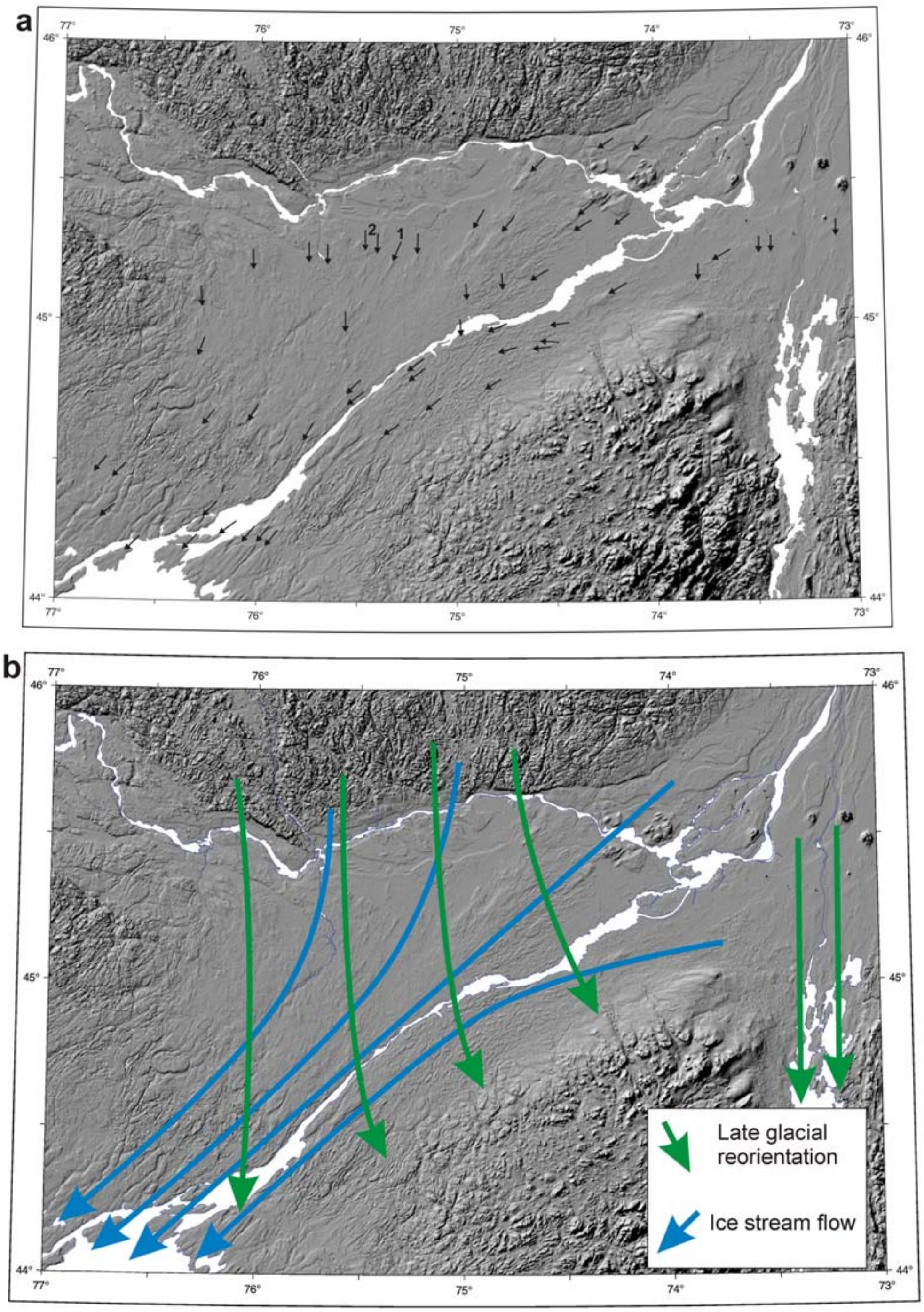

Figure 12. **a**) Abundant streamlined landforms of assumed glacial origin observed on the DEM converge toward the southwest into the Kingston area. Some south-trending drumlin fields are also apparent. A relative chronology is proposed (1, 2) for the different landform assemblages. **b**) Proposed ice flow lines. The older SE ice flow phase (Argenteuil Till) is not shown.

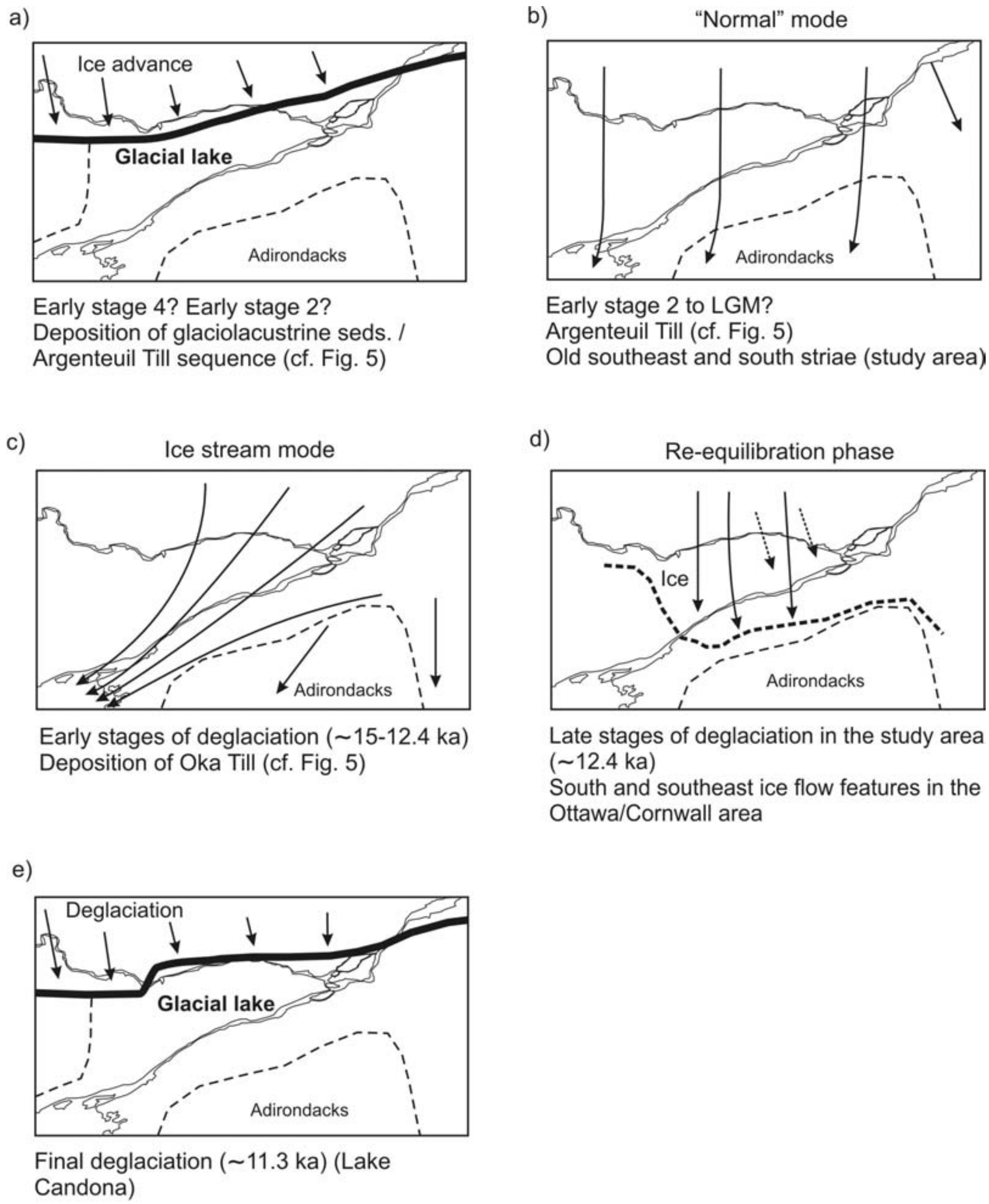

Figure 13: Glacial dynamics shifts in the upper St. Lawrence Valley during the last glacial cycle. It is postulated that ice flow was generally toward the south or southeast across the region at times of (**a-b**) ice advances and probably until full glacial conditions; **c**) Ice flow shifted toward the southwest when the Ontario Lobe was in a state of fast flow; **d**) Ice sheet profile re-equilibrates after retreat of the Ontario Lobe from the Lake Ontario basin; **e)** Final deglaciation of the study area with brief glaciolacustrine conditions prior to Champlain Sea incursion.

Appendix

Table A1: Lithofacies coding scheme (cf. Benn and Evans (1998) for a more complete scheme).

Code	Description
Diamictons	Very poorly sorted admixture of wide grain size range
Dmm	Matrix-supported, massive
Dcm	Clast-supported, massive
Dms	Matrix-supported, stratified
Boulders	Particules > 256 mm (b-axis)
Bcm	Clast-supported, massive
BL	Boulder lag or pavement
Gravels	Particules of 8-256 mm
Gm	Clast-supported, massive
Granules	Particules of 2-8 mm
GRmc	Massive with isolated outsized clasts
Sands	Particules of 0.063 – 2 mm
Sp	Medium to very coarse and planar cross-bedded
Sr(A)	Ripple cross-laminated (type A)
Sr(B)	Ripple cross-laminated (type B)
Sh	Very fine to very coarse and horizontally/plane Bedded or low angle cross-laminated
Sl	Horizontal and draped lamination
Sm	Massive
Sc	Steeply dipping planar cross-bedding (non-deltaic foresets)
Suf	Upward-fining
___ (w)	With dewatering structures

Silts & Clays	Particules of < 0.063 mm
Fl	Fine lamination often with minor fine sand and very small ripples
Flv	Fine lamination with rhythmites or varves
Fm	Massive
___ (d)	With dropstones
___ (f)	With macrofossils

Benn, D.I., and Evans, D.J.A., 1998. Glaciers and Glaciation. Arnold and Oxford University Press, London, New York.