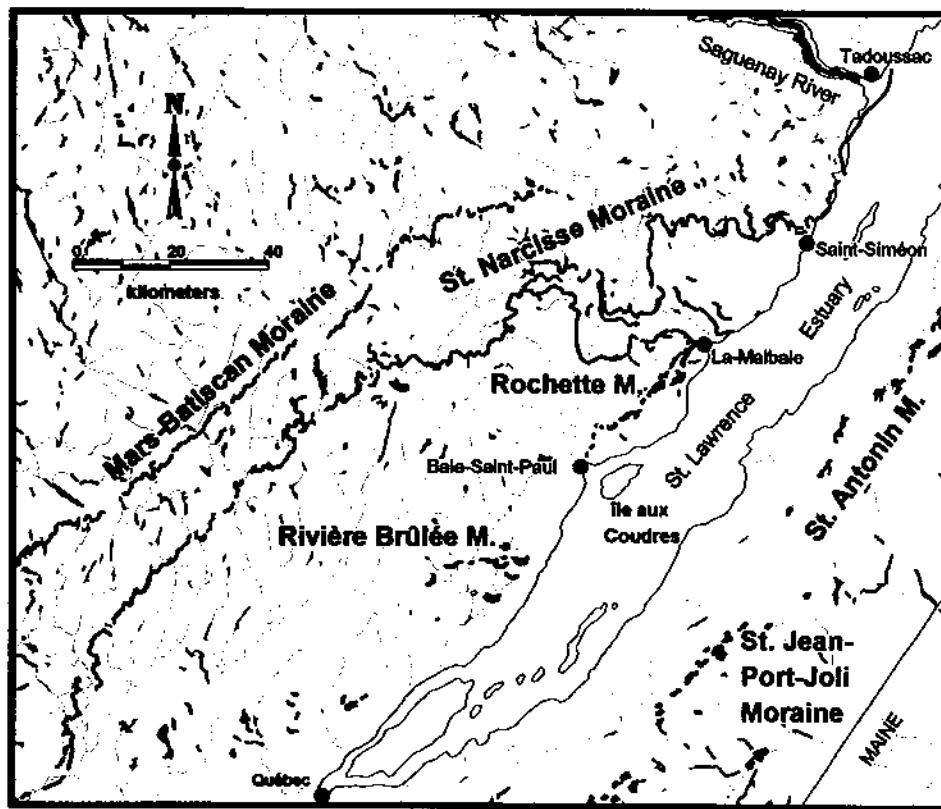


Stratigraphy of the Pleistocene units on land and below the St. Lawrence Estuary, and deglaciation pattern in Charlevoix



64th annual reunion of the

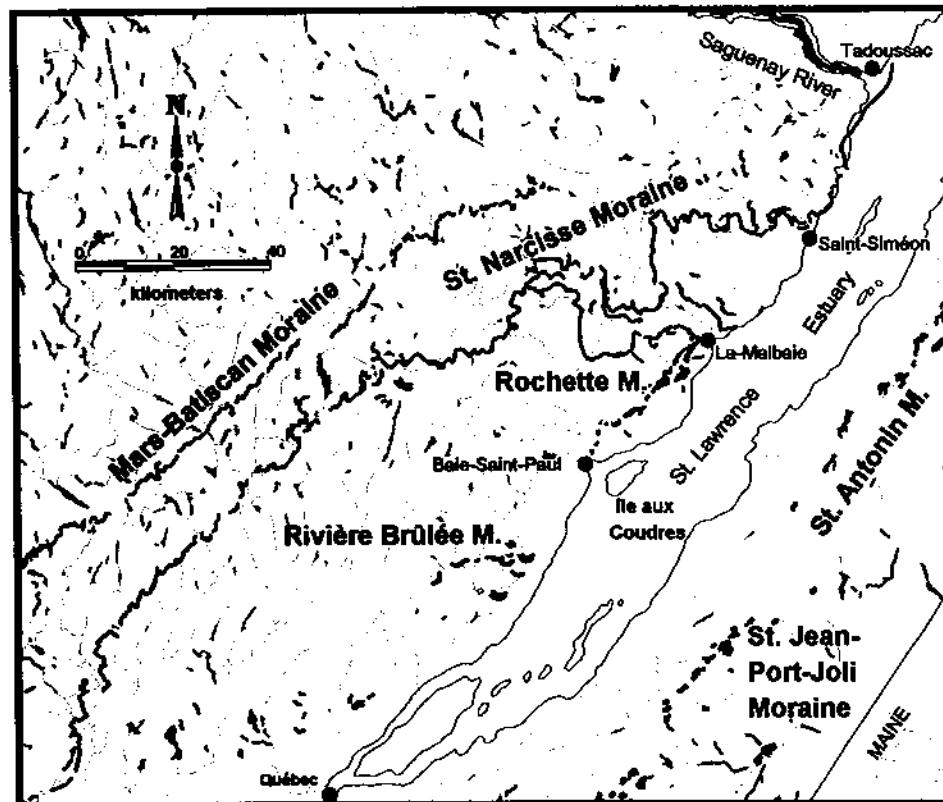
North East Friends of the Pleistocene

**1-3 june, 2001
Québec City, QC
Canada**

**Centre d'Études Nordiques, Université Laval
Geotop and Department of Geography, UQAM
Association québécoise pour l'étude du Quaternaire**

WOODROW THOMPSON
MAINE GEOLOGICAL SURVEY
22 STATE HOUSE STATION
AUGUSTA, ME 04333-0022

Stratigraphy of the Pleistocene units on land and below the St. Lawrence Estuary, and deglaciation pattern in Charlevoix



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Guidebook of the 64th annual reunion
of the
North Eastern Friends of the Pleistocene

**Stratigraphy of the Pleistocene units on land and below
the St. Lawrence Estuary, and deglaciation pattern in
Charlevoix**

June 1-3, 2001

Hotel Quartier, Québec City , Québec Canada

Trip leaders

Najat Bhiry and Jean-Claude Dionne (Centre d'Études Nordiques, Université Laval)
Martine Clet (M2C-CNRS, Caen, France)
Serge Occhietti (UQAM)
Jehan Rondot (Astroblème Exploration, Québec)

Hosts

GEOTOP and Département de géographie, Université du Québec à Montréal
Centre d'Études Nordiques, Université Laval
The FOP Field Conference is led jointly with an AQQUA (Association québécoise
pour l'étude du Quaternaire) informal field trip.

Guidebook available from:

Serge Occhietti

Département de géographie UQAM CP 8888 Centre-ville Montréal QC H3C 3P8 Canada
occhietti.serge@uqam.ca

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Schedule for FOP 2001 Events

June 1-3, 2001

Friday, June 1st

- 6:00-7:35 pm Registration and ice breaking at Hotel Quartier
2955 boul. Laurier, Sainte-Foy.
(from Pierre Laporte Bridge, turn right to Blvd. Laurier, the hotel faces the McDonald)
(cash bar-registration materials- plan to join the group for late arrivals)
- 7:45 pm Supper at La Tyrolienne
2486 rue Bois Gomin, close to the hotel
(car service available)(late people will get direction at the hotel)

Saturday, June 2nd

- 7:00-7:45 am Buffet breakfast available
Pick-up of registration materials
- 8:00 am Field trip leaves from the parking at the Hotel Quartier
Parking lots provided for cars by the Hotel Quartier
All participants are expected to ride on the bus
- 4:15 pm Arrival at Les Voitures D'Eau Hotel on Isle aux Coudres
Accompanying participants can rest at the hotel
Two more stops to be done on the island
- 6:30 pm Cash bar
- 7:30 pm Gastronomy dinner, cash bar
FOP informal meeting

Sunday, June 3rd

- 7:00-7:30 am Breakfast
- 7:35 am Field trip leaves Les Voitures d'Eau hotel
Bus on the ferry at 7:55
- 8:00-8:15 am Ferry from Isle aux Coudres to St. Joseph-de-la-Rive
before 10:00 am Arrival at the boarding point, at Baie-Ste-Catherine, for whale watchers
(guided sight-seeing cruise from 10:00 am to 13:15 pm)
Field trip bus takes the ferry to Tadoussac
- 2:30 pm Field trip leaves Baie-Ste-Catherine
3:30-4:00 pm Optional touristic stop at Baie-Saint-Paul
5:00 pm End of the FOP excursion
Arrival at the Hotel Quartier

**64th annual reunion of the Northeast Friends of the Pleistocene
June 1-3, 2001, along the north shore of the middle St. Lawrence Estuary**

**Stratigraphy of the Pleistocene units on land and below the St.
Lawrence Estuary, and deglaciation pattern in Charlevoix**

REGISTRATION (register by May 1st. After that date, rooms may not be available. The optional night on Sunday June 3d at the Hotel Quartier, after the fieldtrip, should be confirmed as soon as possible.)

Name(s):

Complete postal address - Institution or personal address:

- City
- State or province:
- Zip or code:
- email:

FEES

All included: registration, guidebook, breakfasts, lunches, snacks, banquet at Ile aux Coudres, bus, hotel and supper in Québec City (Friday night June 1) and at Ile aux Coudres (Saturday night June 2):

One person : 240 US\$ or 360 C\$.....

or

Two persons : 420 US\$ or 630 C\$

Optional Sunday night in Hotel Quartier (1 or 2 persons, continental breakfast)(as soon as possible): 75 US\$ or 105 C\$.....

Total payment enclosed (check payable to FOP2001): _____

Do you want to have a whale watching trip?

(about 30 US\$) Yes or No.....

Do you want to return to Québec City Sunday at 2:30 pm?....

Send the registration form and the payment to:

Najat Bhiry FOP
Centre d'Etudes Nordiques
Université Laval
STE FOY
QC
G1K 7P4
CANADA

NB: Cars can be parked at the University Laval (about 7\$ a day)

Weather is very variable (sun, rain, fog, snow, frost).

64th annual reunion of the North Eastern Friends of the Pleistocene
June 1-3, 2001, along the north shore of the middle St. Lawrence Estuary,
between Québec City and Tadoussac

**Stratigraphy of the Pleistocene units on land and below the St. Lawrence Estuary,
and deglaciation pattern in Charlevoix**

The trip conference will focus on the new glacial, marine, estuarine and fluvial units discovered in the middle estuary area, either on natural exposures, man made sections, or on drilling cores and by seismostratigraphy. These units record two pre-Illinoian major episodes, the Illinoian Glaciation, the marine invasion (Guettard Sea) related to the Illinoian-Sangamonian transition (6/5 transition), and the climatic optimum of the Sangamonian (substage 5e). An intermediate estuarine-fluvial-glaciolacustrine-glacial sequence indicates an early upper Pleistocene climatic deterioration and glaciation. Fluvial sediments and peat record an interstadial event (St. Pierre Sediments Event) followed by the classical Wisconsinan glaciation. The post-glacial sea-level regional curve will be presented. Laterally to the St. Lawrence main corridor, the small Saint-Tite basin record a detailed sequence of short lived glaciolacustrine and fluvial events intercalated between Wisconsinan glacial phases. We will look at the landscape related to the Charlevoix Astroblème inherited from the Devonian. We will examine the glacial striations pattern, the eastern extent of the Saint-Narcisse Moraine, ¹⁴C ages, units and forms related to the regional deglaciation. The calving bay ice retreat model will be challenged. Sequence analysis will be applied to the seismic units observed at the mouth of the Saguenay and at the head of the deep Laurentian Trough downstream Tadoussac. The St. Lawrence Estuary is the new frontier of Pleistocene stratigraphic studies in Québec.

The trip leaders include

Najat Bhiry [najat.bhiry@cen.ulaval.ca] and Jean-Claude Dionne: Centre d'Études Nordiques
Université Laval Ste Foy QC G1K 7P4 Canada

Martine Clet (M2C-CNRS, Caen, France)

Bernard Long (INRS-Géoressources)

Serge Occhietti [occhietti.serge@uqam.ca] (UQAM)

Jehan Rondot (Astroblème Exploration)

(site available by March www.geo.uqam.ca/fop2001/fop2001.htm)

Schedule

Friday, June 1st: 6:00-7:35 pm Registration and ice breaking Hotel Quartier
7:45 pm Supper at La Tyrolienne (close to the hotel)

Saturday, June 2d: 7:45 am Leaving hotel (8 am Université Laval)
7:45 am-6:00 pm Field trip

Banquet, meeting, night at Les Voitures d'Eau Hotel, Ile aux Coudres.

Sunday, June 3d: 7:45 am Leaving hotel

12:00 am Arrival at Tadoussac

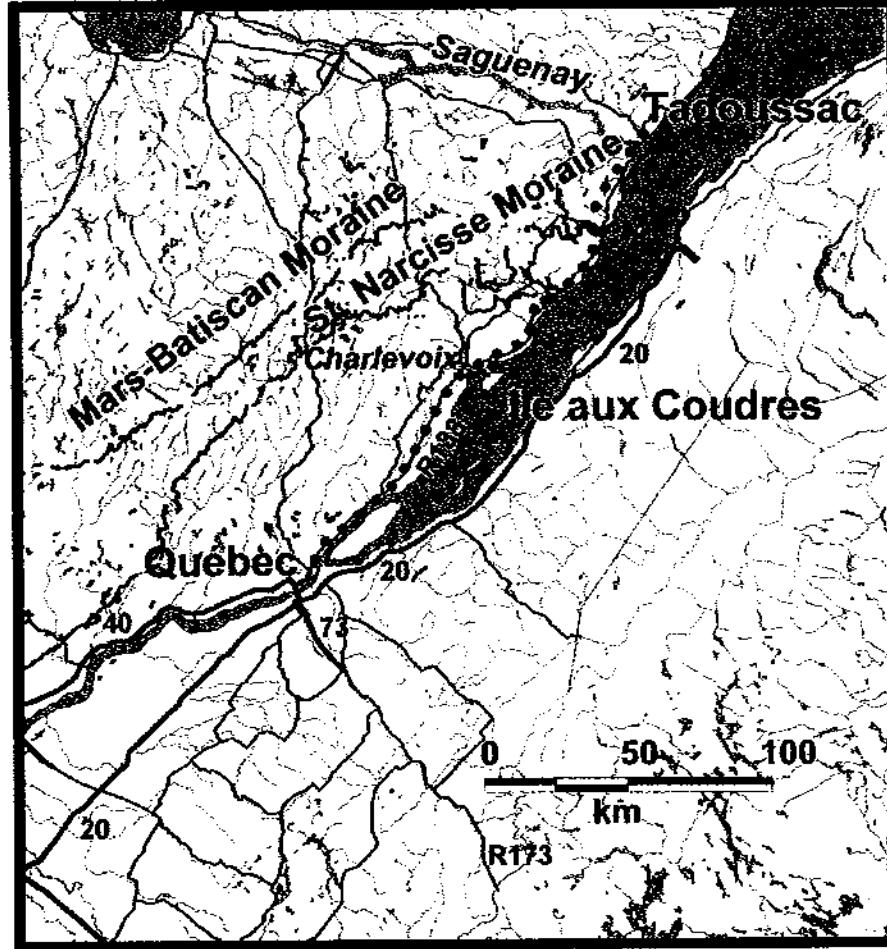
12:00 am- 2:30 pm Field trip or whale watching

5:00 pm Back at Québec City (Vehicles with limited number of seats may leave at 12:00 am and arrive at 2:30 pm)

The GEOTOP and the Département de géographie of Université du Québec à Montréal (UQAM), and the Centre d'Études Nordiques of the Université Laval are the hosts of the 64th annual reunion of the North eastern FOP.

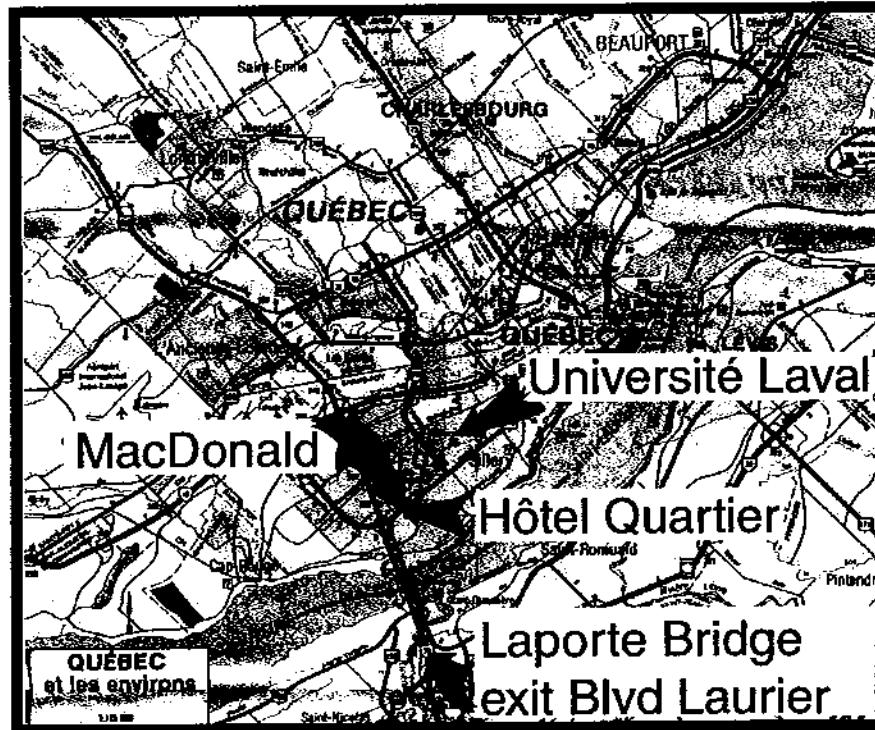
The FOP Field Conference is led jointly with an AQQUA (Association québécoise pour l'étude du Quaternaire) informal field trip.

64th annual reunion of the Northeast Friends of the Pleistocene



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Hôtel Quartier
2955 Blvd Laurier
Sainte-Foy
1-888-818-5863
1-418-650-1616

Restaurant La Tyrolienne
2486 rue Bois Gomin
Sainte-Foy
1-418-651-6905

Hôtel Les Voitures d'Eau
(Île aux Coudres)
1-800-463-2118
1-418-438-2208

FOREWORD TO THE NE FOP 2001

Serge Occhietti, trip leader

This year, the annual field reunion occurs in a new area for the Friends: Charlevoix, a World Biosphere Reserve. This region is located north of the St. Lawrence middle Estuary, between Mont Sainte-Anne and the Saguenay River, from the shore to the Parc des Laurentides Precambrian Highlands. In the southern border of Charlevoix, contrasted and unforgettable landscapes attract thousands of tourists every year. Moreover, a large structure, 56 km wide, due to a Devonian impact brings another original feature which was discovered by Rondot (1970). The field trip focuses on two major themes: the complex deglaciation history of the area and the Pleistocene stratigraphy extended to pre-Illinoian units. An update on deglaciation will be presented, from some papers (Rondot, 1974), an impressive PhD thesis (Govare, 1995) and several MSc theses (Hardy, 1970; Poulin, 1977; Bonenfant, 1993; Lanoie, 1995; Fournier, 1998). Striation sets indicate powerful changes in the ice flow: main glaciation to the SSE, ice convergence towards the St. Lawrence Estuary (E and NE), northward inversion on the south margin, local ice flows and St. Narcisse readvance. Despite the strong local influence of the topography, the deglaciation pattern in Charlevoix is directly linked to the deglaciation in the Estuary. The major St. Lawrence Ice Stream drained converging ices from the Appalachians and the Charlevoix regions towards a calving bay in the Gulf. This feature explains the faster deglaciation in Charlevoix than in more southerly areas. The field trip goes through the first deglaciated area in the southwest part of Charlevoix (St. Léon Delta), local recession moraines, the Rochette Moraine which is related to a major halt of west to east flowing ice during the Dryas II cold episode, and the St. Narcisse Moraine complex related to an early Younger Dryas readvance. This complex can be now followed from Tadoussac to the Algonquin Highlands in Ontario, on a distance of 850 km.

The Pleistocene stratigraphy of the St. Lawrence Estuary and Charlevoix is established from natural and excavated sections, drilling cores, and seismostratigraphy. The area is a present frontier for the study of continental Pleistocene stratigraphy. Seismic data reveal tunnel valleys below the bottom of the Estuary. Some of these valleys are incised as deep as 500 meters in the Appalachian bedrock. The seismostratigraphy of the upper 250 m is validated by two cores (Ile aux Coudres, Occhietti et al., 1995, and Petite-Rivière). At least two units are recognized below the Illinoian marker unit (the Baie-Saint-Paul Glacial Complex). From numerous field observations by Dionne (1996), it is now established that several large tidal flats on the north shore of the Estuary are incised into pre-Wisconsinan marine, estuarine and prodeltaic stratified units. For example, the pollen and foraminifera content of the drilled Ile aux Coudres Formation characterises a late-Illinoian-early-Sangamonian (6/5 transition and 5e) marine invasion named Guettard Sea (from the first geologist who compared rocks of Canada to rocks of Switzerland in 1752). The stratigraphy of visible units is the result of three sedimentary modes: the general system of the St. Lawrence Valley and Estuary, systems in lateral basins, and tributary and slope systems. The field trip visits a key section of the St. Tite basin (Lombrette beds), sections with marine units dated at 35 ka and 10.1 ka B.P., and glacial and estuarine units of upper Pleistocene. Five marine invasions are now recognized in the St. Lawrence Valley and Estuary.

I would like to thank the faithful Friends who accepted to drive long distances to discover Charlevoix. We hope they will be charmed by the landscapes, the food and the people of Charlevoix. I take this opportunity to thank all the organisers, especially Francine Robert and Simon Laliberté for their contribution to the field guide. I would like to dedicate this Friends meeting to our tireless colleagues Jehan Rondot (presently in Europe) and Jean-Claude Dionne who have worked for several decades on the geology and geomorphology of the Charlevoix region.



CHAPTER 1

DEGLACIATION OF THE MIDDLE ESTUARY AND CHARLEVOIX: AN OVERVIEW by Serge Occhietti

Introduction

The studied region can be subdivided into very distinct areas (Fig. 1.1): southern, central (**Astrobleme**) and northern Charlevoix, lower Saguenay area, and the middle St. Lawrence Estuary. (The upper Estuary is the fresh water part of the St. Lawrence River with tides, from Québec City to Lake St. Pierre). This paper presents a synthesis of data (bedrock striations, glacial landforms and sedimentologic/stratigraphic data) gathered over the past thirty years from various parts of the region (Ph.D. thesis of Étienne Govare (1995), original data from recent MSc theses (Bonenfant, 1993; Lanoie, 1995; Fournier, 1998; Robert, MSc current research), papers (e.g. Rondot, 1974, Govare and Gangloff, 1991; Dionne, 1996 a, b, c; Dionne and Occhietti, 1996), original work in collaboration with Najat Bhiry, Jean-Claude Dionne, and Jehan Rondot). In an attempt to reconstruct the deglacial story, Charlevoix data will be compared and contrasted with data collected from surrounding regions throughout the paper.

As suggested by the historical ice dynamics and retreat in Alaska (Syverson, 1995), short-lived events occur frequently during deglaciation of areas with a contrasted topography. This highly changing ice dynamics has been applied recently to the deglaciation pattern of southern Québec (Parent and Occhietti, 1999; Occhietti et al., 2001; Occhietti et al., INQUA Commission Report) and applies to the Charlevoix region. Another characteristics of deglaciation must be noted. Short-lived late ice flow events occurred, as evidenced by local ice front features, but seldomly deposited till sheets or striated bedrock surfaces. This lack of ultimate ice flows data have been due to the warm based nature of the ice during late deglaciation.

The Late Pleistocene glacial history of the Charlevoix and middle St. Lawrence Estuary regions can be divided into the following: ice flow prior to deglaciation, early deglacial ice flow events, deglaciation of the south shore of the middle estuary, and deglaciation of Charlevoix.

Ice-flow patterns before deglaciation in Charlevoix and the St. Lawrence middle Estuary

Southward and SSE glacier flows

Southward and SSE glacial striations (Phase A, Fig. 1.2) are usually the oldest ice flow features observed in Charlevoix (Rondot, 1974; Govare, 1995; Lanoie, 1995; Fournier, 1998). S/SSE bedrock striations are also present throughout the middle St. Lawrence Estuary and Appalachian Mountains of Québec and Maine. They are typically interpreted as recording generalized southward flow of the Laurentide Ice Sheet during the Last Glacial Maximum. The LIS profile was domelike, similar to modern Antarctica, and ice flow was largely unconfined by topography. Some S/SSE striations are related to local late lobes in southern Charlevoix, and to the St. Narcisse readvance in central Charlevoix.

SE ice flow

A set of SSE to ESE striations (Phase B, Fig. 1.3) observed mainly in southern Charlevoix is related to the progressive deflexion of the ice flow from south to east (Lanoie, 1995; Fournier, 1998). Some

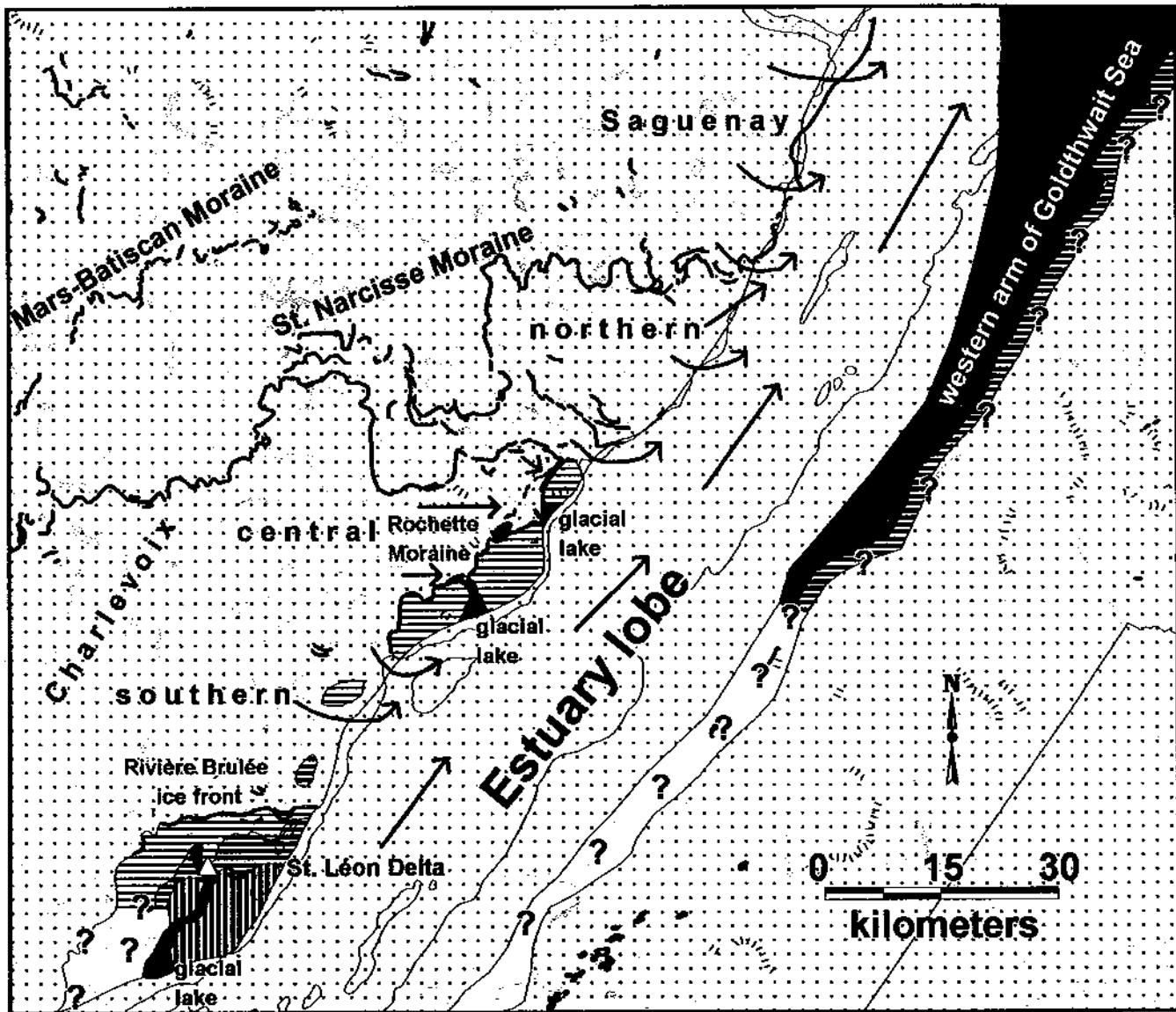


Figure 1.1: Charlevoix early deglaciated areas (vertical and horizontal bars).

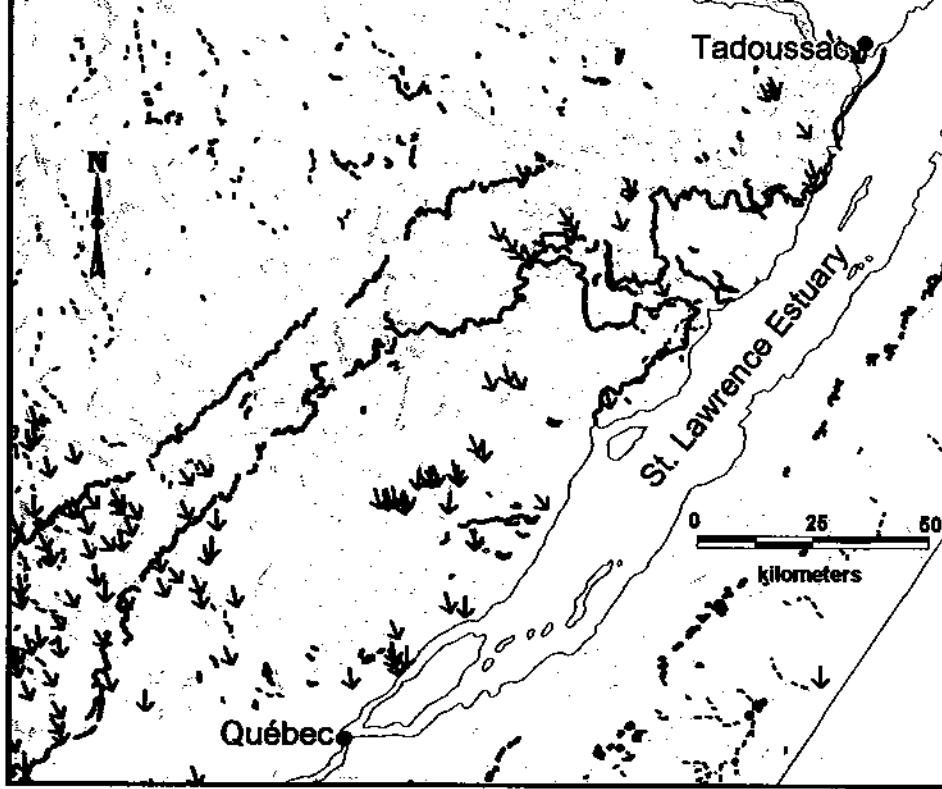


Figure 1.2: S and SSE group of striations (phase A and late St. Narcisse phase in Charlevoix).

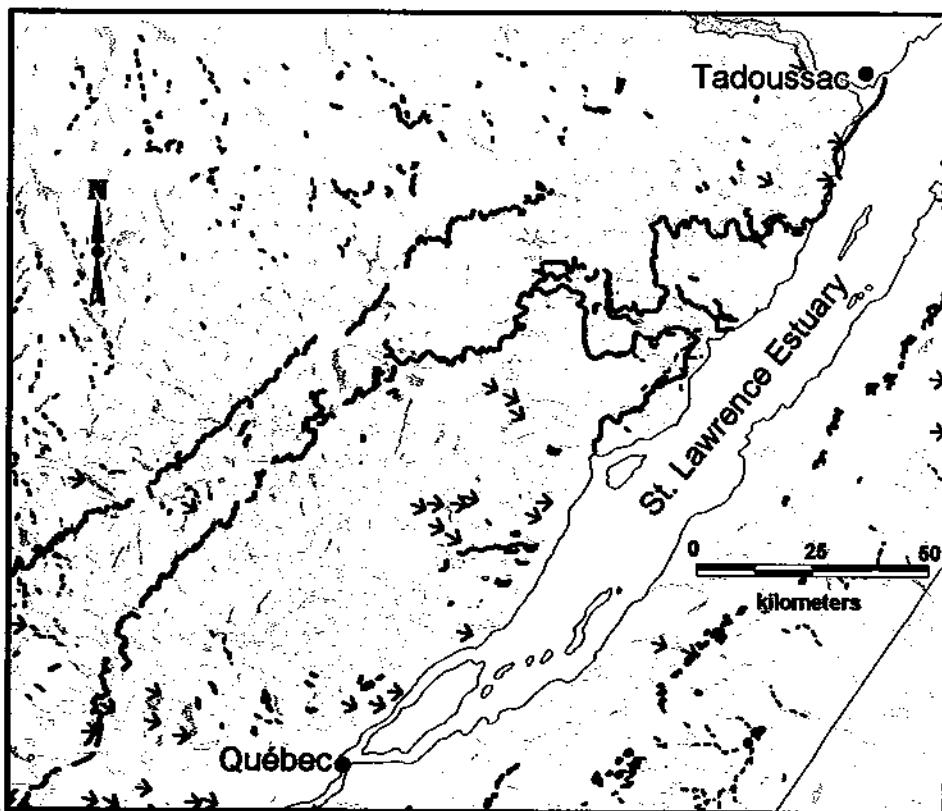


Figure 1.3: SE group of striations (phase B in Charlevoix).

SE striations observed locally in northern Charlevoix and Saguenay areas (Hardy, 1970) are associated with post-St. Narcisse ice flows.

Eastward ice flow

A set of eastward striations (Phase C, Fig. 1.4) is observed inland of Charlevoix, and at Baie des Rochers in the Saguenay area. Similar eastward striations are observed on the south shore of the St. Lawrence Estuary (Rappol, 1993), and mostly in Maine (Lowell, 1985; Lowell et al., 1990). Eastward striations and anorthosite dispersal in central Charlevoix (Rondot, 1974), west of the Rochette Moraine, indicate that the eastward ice flow remained later in Charlevoix than in Maine. In inland Charlevoix, the ice converged eastward to the St. Lawrence Ice Stream but the ice was not deflected. The striation at Baie des Rochers is related to the St. Narcisse episode.

Early deglacial ice flows events in Charlevoix and the middle estuary

Influence of the St. Lawrence Ice Stream

The mode of deglaciation in the southern Québec part (including the Charlevoix and middle estuary) of the Laurentide Ice Sheet was controlled by a series of semi-independent climatic and non-climatic factors. The generally negative mass balance conditions for the LIS resulted in the gradual transition from a multidome-shaped ice sheet, such as the Antarctic ice sheet (Lliboutry, 1965), to a much flatter plateau-like ice sheet, mostly in the marginal areas, much like modern-day Greenland ice sheet (Lliboutry, 1965). This thinning of the ice sheet had several consequences in its marginal areas including: 1) increasing topographic control on ice-flow patterns, 2) development of ice streams, as in the Greenland and Antarctic ice sheets, 3) migration of ice divides and ice mass centers and 4) several secondary glacio-dynamic readjustments.

Below a certain ice thickness and in conjunction with accelerated calving in the Gulf of St. Lawrence, a major northeast-trending ice stream formed within the ice sheet (Rappol, 1993; Occhietti et al., 1996; Parent and Occhietti, 1999). This major feature of the Laurentide Ice Sheet was characterized by flow rates that were at least one order of magnitude higher than in adjacent ice masses, similar to present flow rates in Greenland (Lliboutry, 1965). This accelerated ablation regime (ice stream and iceberg calving) caused substantial thinning within the catchment area of the ice stream, particularly on the northwest flank of the Appalachian Uplands (Genes et al., 1981; Lowell, 1985) and along the southern margin of the Laurentian Highlands (Fournier, 1998). The St. Lawrence Ice Stream favored the progressive isolation of Appalachian ice masses in New Brunswick and northern Maine, in the Gaspé Peninsula and in the Notre Dame Mountains of southern Québec (Stea et al., 1998). Instability in the ice masses generated by the St. Lawrence Ice Stream strengthened the role of regional topographic control on regional glacial dynamics and increased the sensitivity of ice margins to climatic fluctuations (Occhietti et al., INQUA report). The northward pattern of glacial retreat implies that glacial isostatic rebound began earlier along the Appalachian piedmont than along the southern edge of the Laurentians. Glacial thinning generated by the St. Lawrence Ice Stream also caused early crustal unloading along the axis of the St. Lawrence Corridor and a delayed response from east to west (Dionne, 1977; Locat, 1977; Lebuis and David, 1977; Parent, 1987; Dionne, 1988; Dionne and Coll, 1995).

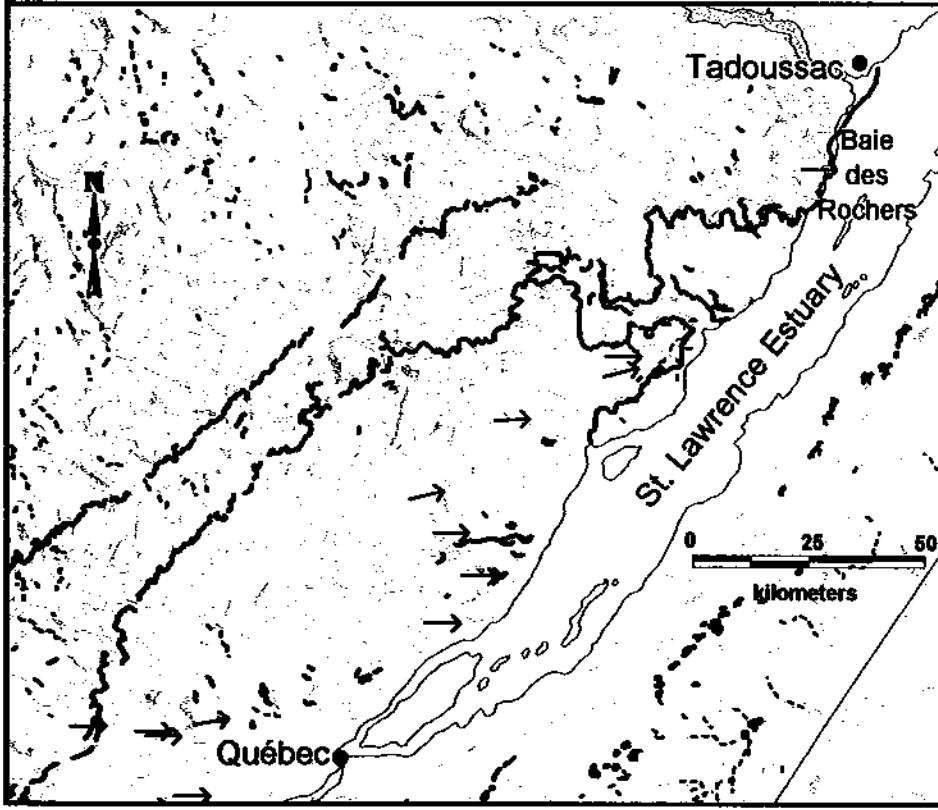


Figure 1.4: W to E group of striations (phase C in Charlevoix).

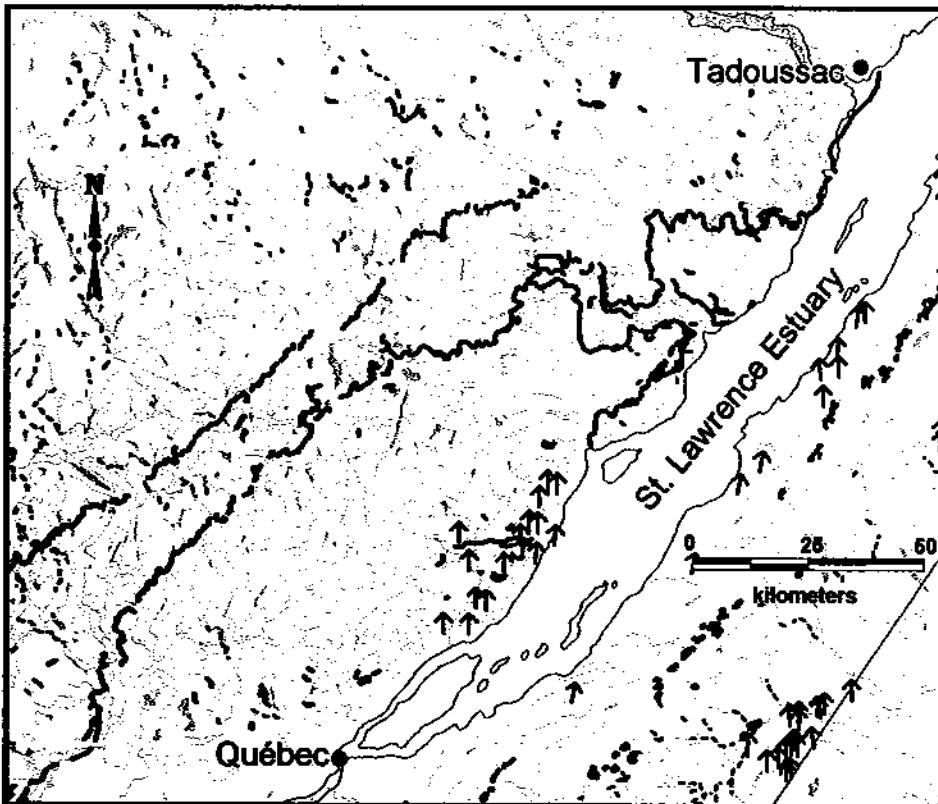


Figure 1.5: N group of striations (phase D in Charlevoix; ice flow reversal from the Appalachians).

Calving bay in the lower estuary

Between 15 and 12 ka (^{14}C y. BP), a calving bay formed at the terminus of the St. Lawrence Ice Stream and migrated 1000 km up the axis of the St. Lawrence Gulf and Estuary. As a result, the southern shore of the lower St. Lawrence Estuary was progressively deglaciated from the Gulf to the Saguenay. The calving bay reached the southern shore in front of the Saguenay mouth by about 12.4 ka BP (^{14}C years) (Rappol, 1993). There is no evidence whether a true calving bay existed farther up the St. Lawrence past the head of the Laurentian Channel, close to the mouth of the Saguenay River.

Northward ice flow in southern Charlevoix

Thinning of ice in the St. Lawrence Valley and Estuary, resulting from the St. Lawrence Ice Stream and the extensive calving bay in the lower Estuary, and isolation of ice masses over the Appalachians (Quebec Ice Divide, Shilts, 1981) resulted in a major regional ice flow reversal to the north (Phase D, Fig. 1.5). The northward reversal is observed from Rimouski to the Bois Francs area. The ice overrode the southern part of Charlevoix (Occhietti et al., 1996, 1997), Fournier, 1998) and the Québec City area (Paradis and Bolduc, 1999).

Northeast ice stream in the middle estuary

Convergence of ice towards the ice stream is observed upstream from Québec City. In central Charlevoix, the ice flow remained eastward (Fig. 1.6). A set of NE and NNE striations belongs to a strong deflected ice flow over southern Charlevoix (Phase E, Fig. 1.7). The same indicators are observed on both sides of and on islands within the middle estuary (Dionne, unpublished data). This event is related to a late phase of the St. Lawrence Ice Stream.

Deglaciation of the south shore of the middle estuary

The middle estuary and Charlevoix were deglaciated within a short period of time (between about 12.4 ka BP (^{14}C years) and 10.6 ka BP.

Early deglaciation of the south shore of the St. Lawrence Estuary

Early marine clay dated at 12.7 ka BP (^{14}C years) is overlain by a younger Appalachian till in the Trois-Pistoles area, downstream of the middle estuary limit. We suppose that the calving bay reached the head of the St. Lawrence Channel by this time and that a small part of the middle estuary may have been deglaciated close to the Appalachian piedmont slightly later (Rappol, 1993).

St. Antonin Moraine and northeastward readvance

The St. Antonin Moraine (Fig. 1.8) was deposited along the Appalachian piedmont, east of Rivière du Loup. It has been interpreted as an ice-marginal position of the retreating Laurentide ice front (Lee, 1962), an interlobate moraine (Lasalle et. al., 1977; Rappol, 1993), or as an end moraine deposited by Appalachian ice (Chauvin et al., 1985). Overriding till and glaciomarine fossiliferous stony clay (Lee, 1962; Dionne, 1972) indicate a northeast-east readvance over a part of the moraine. Ice was still active in Charlevoix and at least covered most of the middle estuary by about 11.7 ka (age of shell fragments of *Portlandia arctica*). It is tempting to correlate this readvance with the Beauce Event, the ice readvance or reactivation observed in the Etchemin and Chaudière valleys by

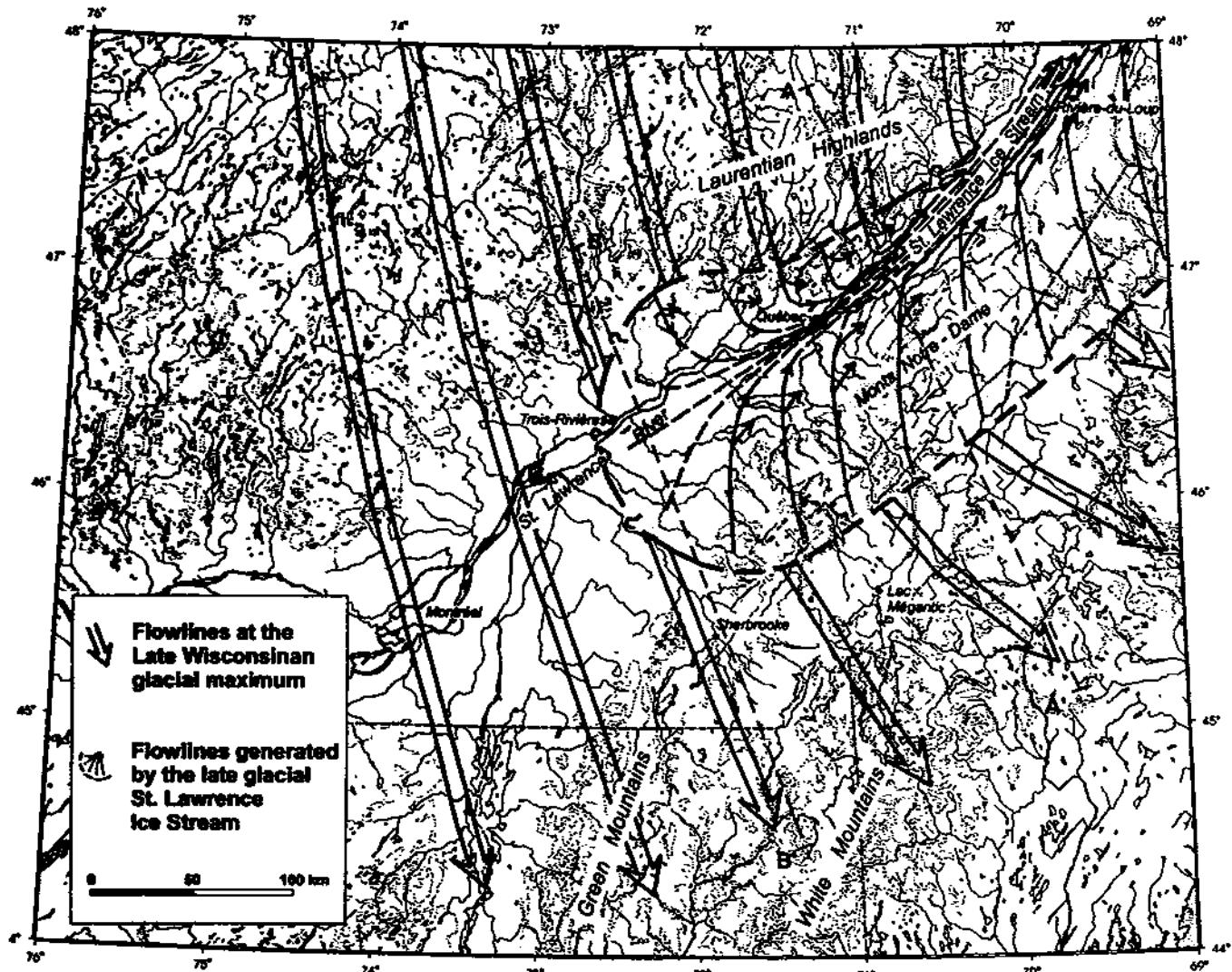


Figure 1.6: Reorientation of Late Wisconsinan flowlines generated by the St. Lawrence Ice stream (Parent and Occhietti, 1999).

This map was prepared before the works of Fournier (1998), and Robert (2001). The reorientation in Charlevoix was underestimated.

Gadd et al.(1972), Blais (1989), and Blais and Shilts (1989)(Occhietti et al., 2001).

Deglaciation along the Appalachian piedmont: the western arm of Goldthwait Sea

We assume that the deglaciation was more effective along the Appalachian piedmont, due to the thermal effect along the piedmont and the diverted Laurentide ice to the NE in the middle estuary. The model proposed by Rappol (1993) -downstream Rivière du Loup- of a no symmetrical development of the calving bay across the St. Lawrence estuary can be applied to the middle estuary. A button-hole model (Fig. 1.1) proposed by Occhietti et al. (2001) would explain the rapid deglaciation along the Appalachian piedmont and the early Champlain Sea invasion in the southern and western part of the St. Lawrence fluvial valley. The opening of Champlain Sea occurred by about 11,650 - 11,500 y BP (corrected ^{14}C years , Rodrigues, 1992; Occhietti et al., 2001) or about 11.3 ka (Ridge et al., 1999). This deglaciation model precludes deglaciation by a transversal calving bay, at least upstream the Ile aux Coudres area.

Deglaciation of Charlevoix

Early deglaciated areas of Charlevoix

In southern Charlevoix, the raised St. Léon Delta is a key site (Fig. 1.1). The elevation of the delta (360 m a.s.l.), northwestward outwash from the Ligori Ridge toward the St. Tite basin, and sedimentary clasts in outwash deposits observed in several sites over the Precambrian bedrock (Fournier, 1998) give the evidence that the Sainte-Anne du Nord Valley became partly deglaciated while ice remained in the axis of the St. Lawrence Valley and middle Estuary. The age of the delta is unknown. In a similar case, lacustrine surfaces and erosional channels observed in central Charlevoix (Govare, 1995), between the Rochette Moraine and the estuary, suggest that local deglaciation preceded the disappearance of the middle estuary ice lobe.

Northward and westward retreating ice front in Charlevoix

In southern Charlevoix, according to Fournier (1998) and recent field work, the ice front was retreating northward and westward. A discontinuous series of moraines, the Rivière Brûlée ice front position, indicates a significant halt and slow retreat of the ice front. In central Charlevoix, the ice front retreated with the same pattern, after the deposition of the Rochette Moraine. Ice lobes in the Gouffre and Malbaie valleys were probably still active. In northern Charlevoix, the deglaciation features are not completely studied. From the outline of the later St. Narcisse Moraine, the same pattern of northward and westward retreat can be inferred. Local ice lobes probably converged toward the estuary.

The Rivière Brûlée ice front features and Rochette Moraine are the evidence of a significant slow down of the ice front retreat, without topographic and apparent ice dynamics forcing. These major ice front features are tentatively correlated to the Dryas II cooling phase, between the Bölling and Alleröd warm phases, circa 11,800. The Rivière du Loup readvance could be a concomitant ice surge of the estuary lobe toward the east-northeast.

Deglaciation between the Rivière Brûlée-Rochette Moraine deposition and the St. Narcisse Moraine episode seems to have been rapid and did not left prominent ice front features. Some lobes features are described by Govare (1995). Some glacial cirques may have been reactivated (Rondot, 1989; Govare, 1995).

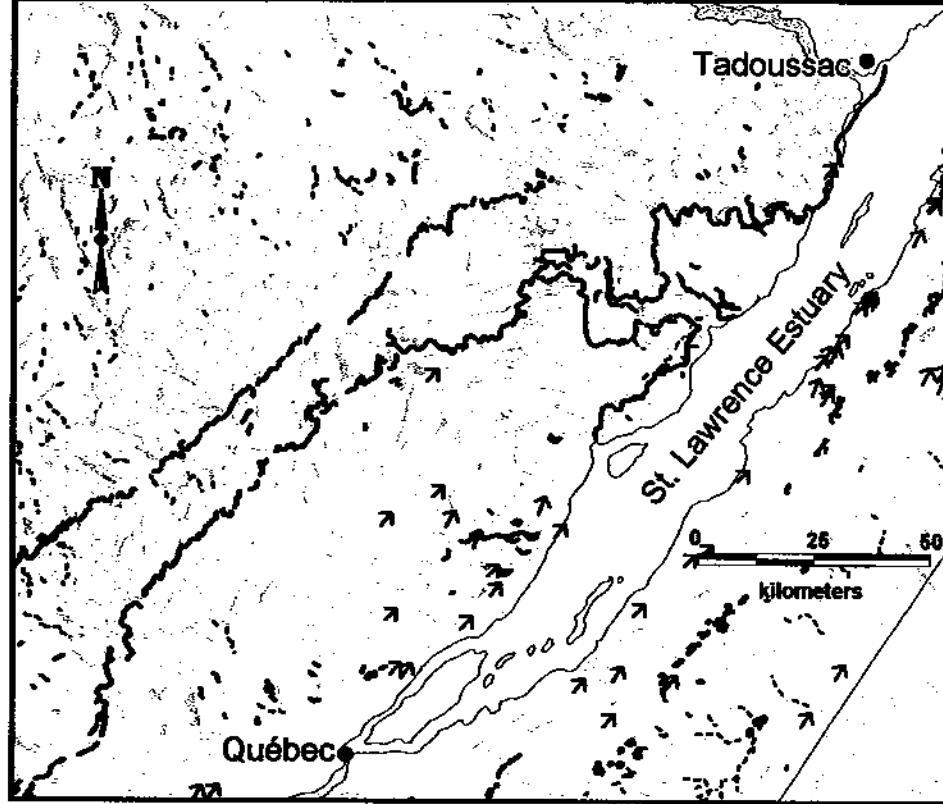


Figure 1.7: NE group of striations (phase E in Charlevoix).

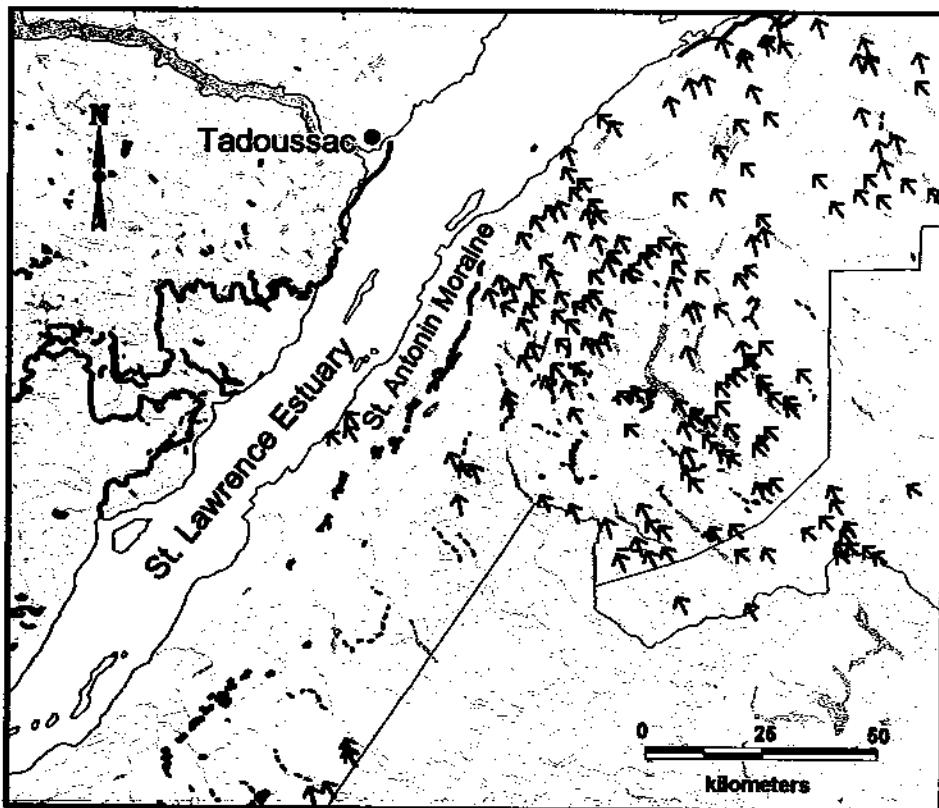


Figure 1.8: NW group of striations (late ice flows in the Appalachians), from Lowell, 1985, and Rappol, 1993.

The St. Narcisse morainic complex

The St. Narcisse morainic complex in Charlevoix comprises a main morainic ridge in the highlands of southern and central Charlevoix, a major lobe represented by a series of 28 concentric morainic ridges at the north of central Charlevoix, very arcuate ridges in northern Charlevoix, and discontinuous features in the Saguenay area (Fig. 1.9; Govare, 1995).

The ridge in the highlands indicates a stable ice front or a minor readvance. North of the Astrobleme, the ice front readvanced for several km (between 17 to 35 km) to the south and formed a lobe, as indicated by the outline of the external morainic ridge over an area of eastward ice flow indicators and perpendicular to the Rochette Moraine. The morainic complex is composed of a major external ridge, and locally up to 27 other concentric ridges (Govare, 1995). An intermediate major ridge was assigned to be the St. Narcisse Moraine by LaSalle (1977). In northern Charlevoix, the morainic ridges form local lobes which indicate a minor readvance of about 2.5 km (Hardy, 1972; Govare, 1995). In the Saguenay area, the ice front is documented by discontinuous ridges (Miller, 1973), an ice marginal kame in the estuary (Dionne, 1996a), a diamicton interstratified in marine clays and the Tadoussac complex (Dionne and Occhietti, 1996).

Extension of the St. Narcisse Moraine to the Ottawa Valley

The outer limit of the St. Narcisse Moraine in the central Charlevoix lobe is related to the early phase of glaciomarine deposition observed in the Trois Rivières area and dated later than 11.3-11.1 ka B.P. The intermediate major ridge is probably the equivalent of most of the lateral main ridge followed from the Saguenay River to the Ottawa Valley. The St. Narcisse Moraine event is related to the early cold phases of Dryas III, between about 11 to 10.6 ka BP. Recent work with F. Robert (current MSc research) shows that the St. Narcisse Moraine extends towards the west, from the previously known western limit (Lake Echo) to the arcuate ridges across the Ottawa Valley described by Barnett (1988)(Fig. 1.10). Further west, the outline of the moraine can be followed until the ice front features mapped in the Algonkin Highlands by Chapman and Putnam (1984)(Fig. 1.11). The total outline can be followed along a linear distance of 850 km. The new extension to the west discard previous correlation of the St. Narcisse Moraine with the Cartier morainic belt (Fig. 1.11). Above all, the transversal morainic ridges in the Ottawa Valley precludes any drainage of meltwater through the Ottawa Valley before the Younger Dryas. As a consequence, the hypothesis of a Younger Dryas cold episode initiated by the routing of meltwater from lake Agassiz to North Atlantic through the Ottawa-St. Lawrence valleys (Broecker et al., 1989) is inappropriate.

The Mars-Batiscan Moraine

In Charlevoix, the St. Narcisse phase is followed by a slow ice front retreat until the Mars-Batiscan Moraine episode (Fig. 1.12). This moraine has been identified in Charlevoix (Govare, 1995), in the Parc des Laurentides Highlands (Bolduc, 1995) and mapped to the west beyond the Saint-Maurice River (Robert, current MSc research) for a total length of 170 km. The distance between the main ridge of the St. Narcisse Moraine and the Mars-Batiscan Moraine is 17 km in Charlevoix and 70 km in the Saint-Maurice area. The slow ice front retreat in Charlevoix, in comparison with the fast retreat observed prior to the St. Narcisse episode, is due to the region's proximity to the ice center of New Québec. In the Saguenay area, the deglaciation pattern reflects the predominantly southeastward flow of the Saguenay Lobe.

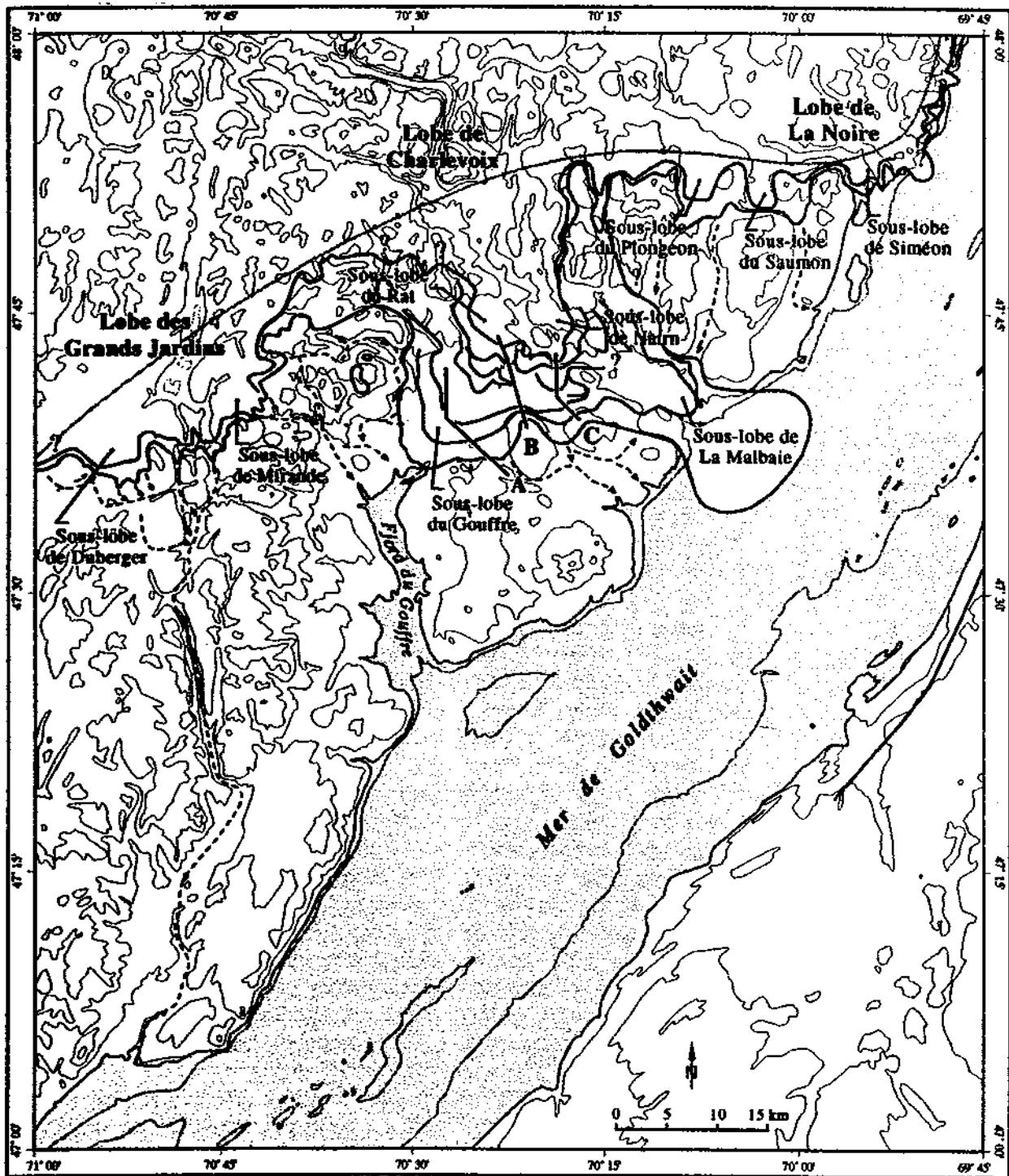


Figure 1.9: St. Narcisse morainic complex mapped by Govare (1995).

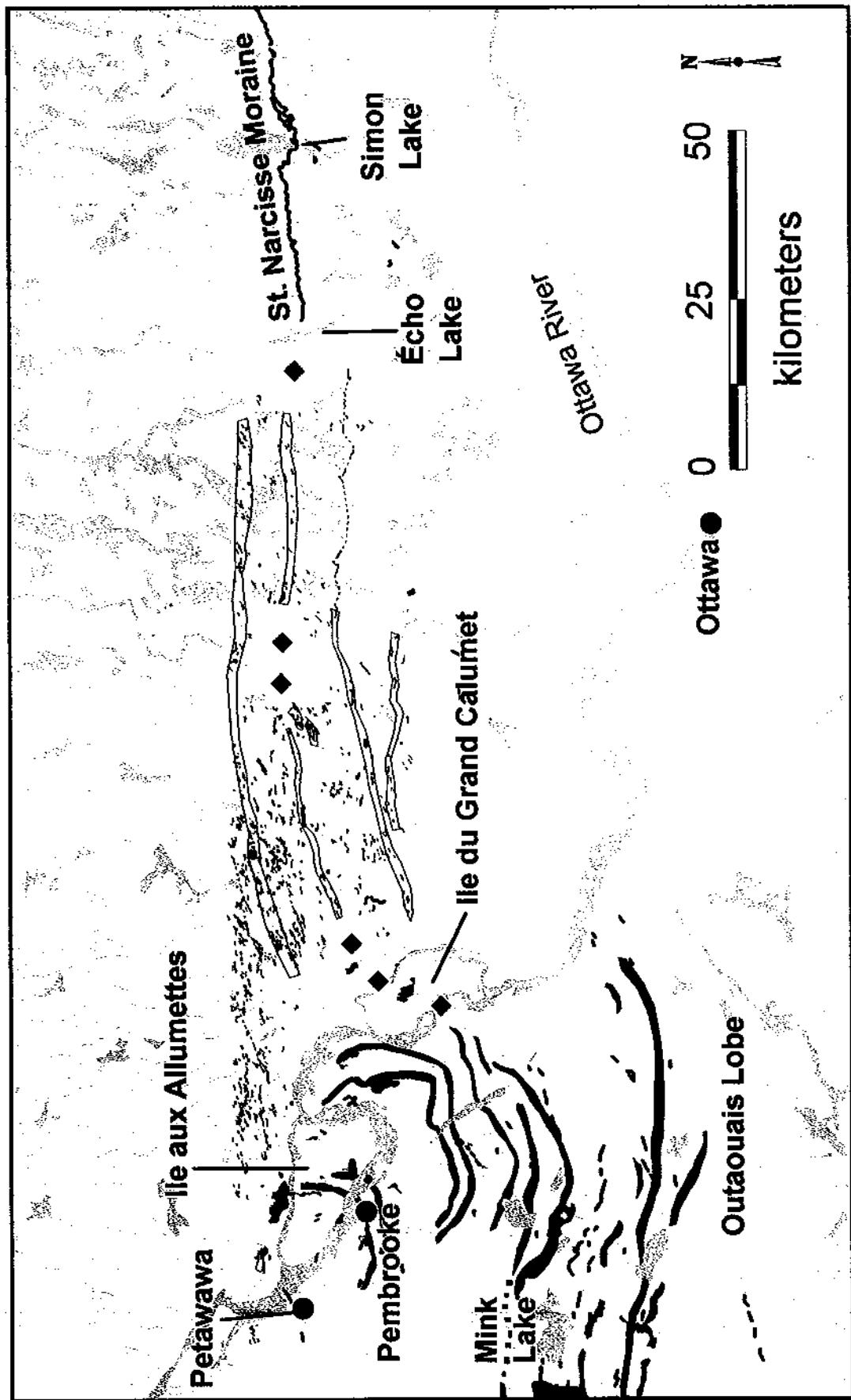


Figure 1.10: Extension of the St. Narcisse Moraine to the arcuate morainic ridges described by Barnett (1988) in the Ottawa Valley.

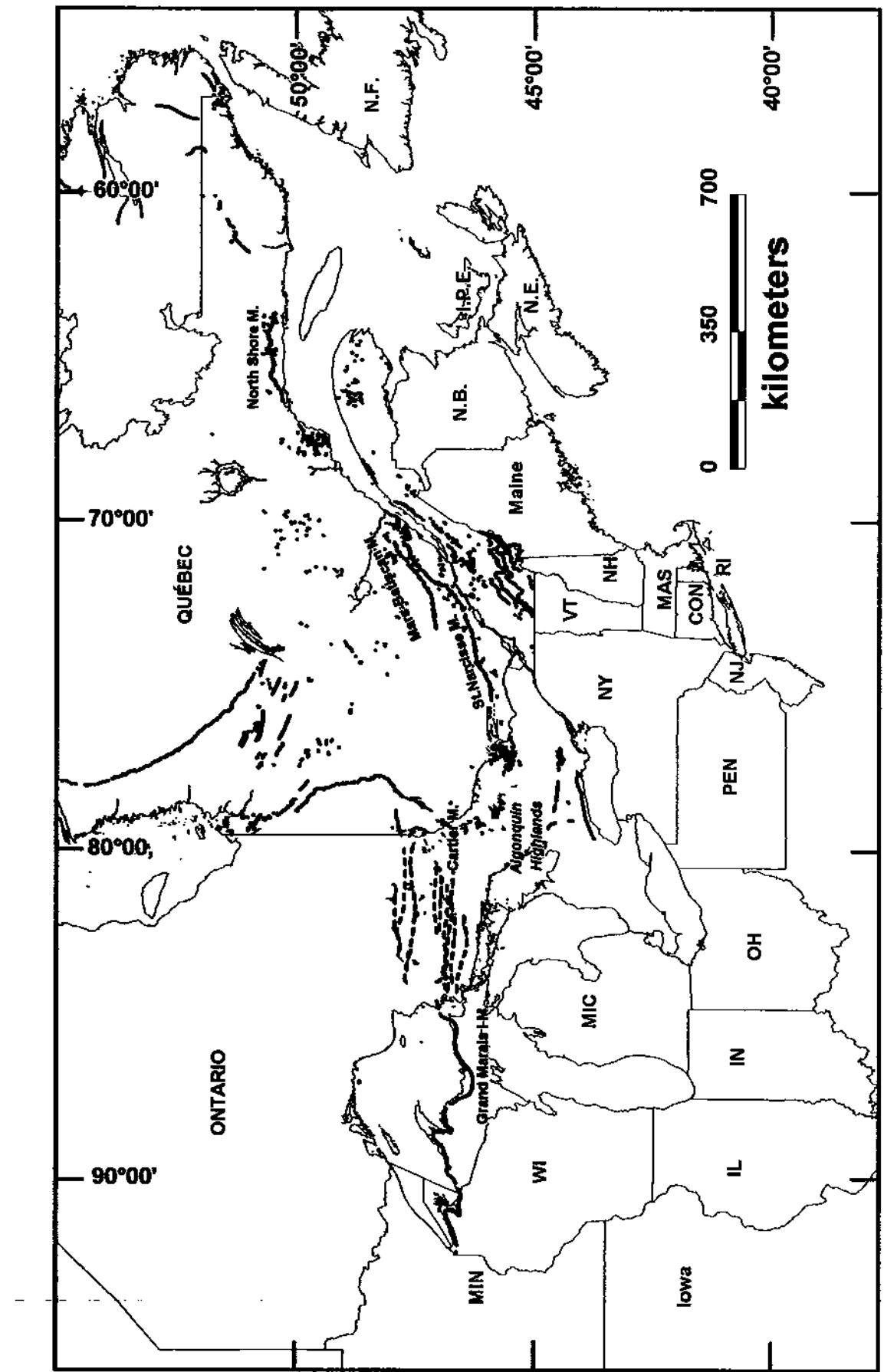


Figure 1.11: Younger Dryas moraines. The St. Narcisse Moraine is related to early phases of Younger Dryas. The Mars-Batiscan, Cartier and Grand Marais I Moraines are related to late Younger Dryas. The North Shore Moraine could be related to Younger Dryas.

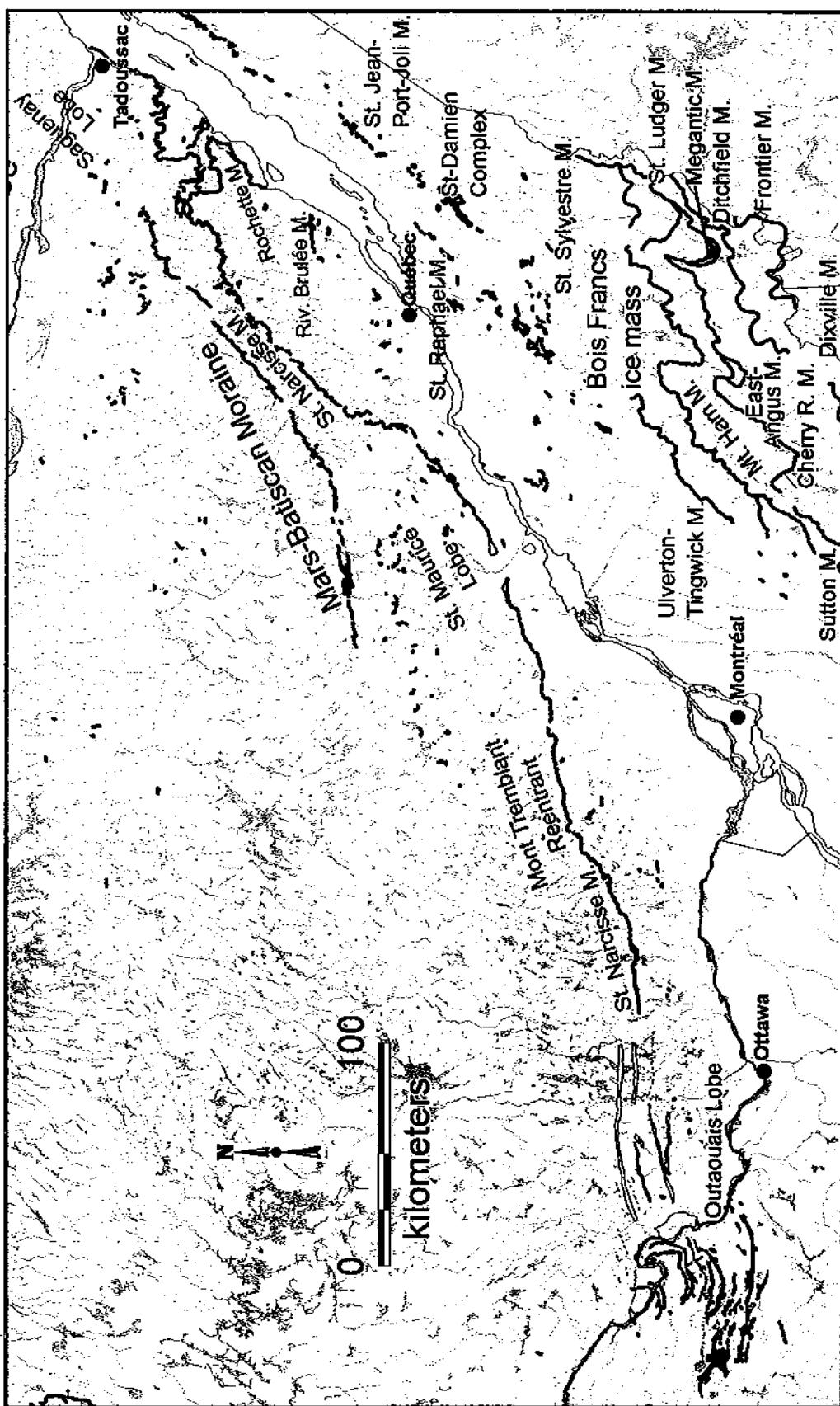


Figure 1.12: Position of the Mars-Batiscan Moraine, north of the St. Narcisse Moraine.

Chronology of the deglaciation in Charlevoix

In Charlevoix, the only datable materials are marine shells and some bottom lake sediments. The latter gave too young ages regarding the other chronological regional evidence. The limits of ^{14}C ages from marine have been thoroughly debated, and recent ^{14}C ages obtained in Charlevoix and at the Saint-Nicolas site confirm these limits (Table 1.1). Within the limits of the available ^{14}C ages, a tentative chronology of deglaciation of the Charlevoix can be proposed (Table 1.2) taking into account some assumptions. Among the assumptions, the ^{14}C ages from marine shells calculated with $\delta^{13}\text{C} = 0 \text{ ‰}$ are closer to the ages from continental materials than the conventional ages calculated with $\delta^{13}\text{C} = -25 \text{ ‰}$. From recent crossdating of samples of marine shells and wood from the Saint-Nicolas site (Occhietti et al., in press), the marine shell ages ($\delta^{13}\text{C} = 0 \text{ ‰}$) may be up to about 350 years older than the ages from wood. This discrepancy is indicative of the range of Champlain and Goldthwait Seas reservoir effect on ages from marine shells. Ages from marine shells sampled in carbonated sediments are highly suspect. This case applies to the Charlesbourg age of 12,400 y. BP.

Conclusion

The late glacial-deglaciation pattern of Charlevoix both reinforces previous hypothesis and brings new insight to the general deglaciation history of the southeastern margin of the LIS. Based on the synthesis of data presented in this paper, the following conclusions can be made:

- 1) Ice flow over the Charlevoix during the LGM was towards the S/SSE.
- 2) The post-LGM related ice flow was progressively deflected towards the SE and east.
- 3) The rapid deglaciation of Charlevoix is directly linked to the St. Lawrence Ice Stream which accelerated the ice ablation on the eastern side of the Parc des Laurentides Highlands.
- 4) Northward striations in southern Charlevoix are related to the northward ice flow reversal observed on the north flank of the Appalachians. This event is poorly constrained in time.
- 5) The extent of an early calving bay in the middle estuary, upstream the Saguenay mouth, and prior to an ice readvance documented on the side of the St. Antonin Moraine, is unknown. The questionable age of the Charlesbourg overridden marine clay is presently the only weak evidence of such an extensive early ice retreat.
- 6) The St. Antonin Moraine, probably an interlobate feature, marks the beginning of recorded deglaciation in the middle estuary.
- 7) In Charlevoix, the first deglaciated areas are "button holes" located on southern uplands and along the eastern margin of the Astrobleme. An ice lobe in the middle estuary was still present, which dammed glacial lakes in the St. Tite basin and in central Charlevoix. The transversal calving bay model of deglaciation does not apply to the middle estuary.
- 8) Two local ice front features, the Rivière Brûlée complex in the south and the Rochette Moraine in central Charlevoix indicate a significant slow down of the retreating ice front. These features are tentatively ascribed to the Dryas II cooling (between the Bölling and Alleröd warm phases).
- 9) A northward and westward retreat of the ice front follows, until the St. Narcisse episode. Few glacial landforms were deposited during this phase ascribed to the Alleröd.
- 10) The St. Narcisse morainic complex in Charlevoix comprises a main morainic ridge in the highlands of southern and central Charlevoix, a series of 28 lobate and concentric ridges in central-north Charlevoix, very arcuate ridges in north Charlevoix, and discontinuous features in the Saguenay area. In central Charlevoix, a large lobe indicates a readvance of the ice front for 25 km, at the beginning of the St. Narcisse episode. The St. Narcisse morainic system is believed to be related to the early cold phases of Younger Dryas.
- 11) The Mars-Batiscan Moraine, which is located 17 km north of the St. Narcisse main ridge, is related to the last cold phase of Younger Dryas.

Table 1.1 : 14C ages referred to in the text.

Lab No	Published or calculated ages (y. BP) ($\delta^{13}\text{C} = 0\text{\textperthousand}$)	Conventional ages (y. BP) ($\delta^{13}\text{C} = -25\text{\textperthousand}$)	Species or material	Elevation (m)	Site	Reference
Continental sites						
QU-55		11,050 \pm 460	gyttja	423 m	Lac Mimi	Richard & Poulin, 1978
Goldthwait Sea						
Beta-143295	11,910 \pm 100		shell fragments	140 m	Les Éboulements	unpublished
UL-2174	12,170 \pm 110		<i>Hiatella arctica</i>	140 m	Les Éboulements	unpublished
UL-535	11,100 \pm 80		shells	149 m	Bale St-Paul	Bonenfant, 1993
UL-1029	11,740 \pm 80		<i>Macoma balthica</i>		Tadoussac	Dionne & Occhietti, 1998
TO-2890	11,130 \pm 80		<i>Macoma balthica</i>		Tadoussac	Dionne & Occhietti, 1998
TO-2889	11,040 \pm 80		<i>Macoma calcarea</i>		Tadoussac	Dionne & Occhietti, 1998
Beta-79125	11,120 \pm 60		<i>Macoma balthica</i>		Tadoussac	Dionne & Occhietti, 1998
Champlain Sea						
Beta-143294	11,200 \pm 40		shell fragments		St-Henry	Occhietti et al., in press
	Previous age of 12,200 should be discarded					
Beta-143297		9470 \pm 40	wood	60 m	St-Nicolas	Occhietti et al., in press
Beta-143298	9810 \pm 70		<i>Hiatella arctica</i>	60 m	St-Nicolas	Occhietti et al., in press
Pre-Late Wisconsinian units						
Beta-54140	29,280 \pm 680		shell fragments		Bale Ste. Catherine	Dionne & Occhietti, 1996
TO-3990	34,510 \pm 380		shell fragments			Dionne & Occhietti, 1996
Beta-143296		49,880 \pm 2170	wood fragments		Les Éboulements	unpublished

Table 1.2: Tentative correlation of events in the area of the St. Lawrence middle Estuary

Estimated age (^{14}C ka BP)	Charlevoix	Lower Saguenay and middle estuary	Québec City - Chaudière River area	Climatic phases
10 - 9.65		Laflamme Sea invasion	Stable relative marine level (St. Nicolas): eustatic rise	Early Holocene
10.1 - 9.9	Mars - Batiscan Moraine <i>slow ice front retreat</i>	Saguenay Lobe		
10.6	late phase			
10.7	St Narcisse main episode	Tadoussac proglacial delta		
10.8	Moraine	ice readvance		Younger Dryas
10.9	early phase	submarine fan	St. Nicolas surge or readvance	
11.7	<i>northward and westward retreat</i>	western arm of Goldthwait Sea	Champlain Sea Invasion western arm of Goldthwait Sea	Alleröd
11.8	Rochette Moraine, Brûlée River ice front	post-St. Antonin Moraine surge or readvance and middle estuary lobe	(Beauce Event: ice readvance in the Chaudière/Etchemin area?)	Dryas II
12	early incomplete deglaciation? Les Eboulements (north shore)	early deglaciation: Rivière du Loup area (south shore)		Bölling
12.2				

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CHAPTER 2

QUATERNARY OF THE ST. LAWRENCE BASIN (VALLEY, ESTUARY AND GULF)

by Occhietti Serge (revised from a text in press, Encyclopedia of Quaternary Science)

The St. Lawrence basin is a structural depression located between the Laurentide Highlands to the north and the Appalachian Uplands to the south. This large intracontinental sedimentary basin (*sensu lato*) includes the St. Lawrence Gulf and Estuary with their adjacent lowlands, the St. Lawrence Valley with the tributary lowlands of the Ottawa River and Lake Champlain, and the Lake Ontario basin. Repeatedly throughout the Quaternary period, allochthonous ice masses invaded and isostatically depressed the basin. The mid-latitudinal location of the central part of the basin (the central St. Lawrence Valley and middle Estuary) and its placement between former New Quebec Ice Domes and Appalachian Ice masses have allowed glacial fluctuations of intermediate amplitude to be recorded in the Quaternary sediment cover. As a consequence, the sedimentary units reflect a unique example of middle and upper Pleistocene epicontinental-continental discontinuous sedimentation in the northwest continental façade of the Atlantic Ocean.

TECTONICS

There is no evidence of major neotectonic movement in the basin during Middle and Late Pleistocene. Minor neotectonics in the Great Lakes area have not altered the regional drainage pattern. Based on the orientation of buried valleys on the south shore of the St. Lawrence River in the central valley, a previous system which drained southward towards Hudson River has been proposed. However, this hypothesis is equivocal due to lack of Early Pleistocene units in the basin.

GLACIAL HISTORY

The St. Lawrence basin was repeatedly invaded by allochthonous ice originating from the New Quebec-Labrador ice dome. Following inception of each major ice advance, the Laurentide Ice Sheet (LIS) required several thousand years of spreading from its New Quebec-Labrador centers before it flowed south into the basin. Once ice reached the basin, channelization of ice occurred in the lowlands due to the subdued topography. Channelization was also typical during deglaciations and ice retreats. During these

channelization events, ice converged towards a fast-moving ice current in the St. Lawrence Estuary, which terminated in a calving bay in the Gulf area. As ice advance proceeded into the basin, ice lobes to the south (Hudson Valley-Lake Champlain lobe) and the southwest (upper St. Lawrence Valley toward Lake Ontario) were fed by the LIS. Coeval ice masses, independent of the LIS, accumulated over the Appalachian uplands. These Appalachian ice masses were typically overridden and incorporated into Laurentide ice as it flowed south, and became separated from the LIS during deglaciations and ice retreats. Each major ice advance eroded much of underlying unconsolidated material, reshaped the bedrock and deposited a discontinuous sheet of glacial drift.

The glacial history in areas surrounding the Gulf of St. Lawrence is more complex. Regional satellite ice caps developed transitionally during early glacial stades, and separated from the main ice sheets during phases of glacial retreat. These ice caps covered the Nova Scotia mainland, Cape Breton Island, the New Brunswick plateau, the Gaspé Peninsula, Newfoundland, the continental shelf in the Gulf (Prince Edward and Magdalen Islands) and offshore Nova Scotia. The glacial record in the Gulf of St. Lawrence area reflects competition between these autochthonous Appalachian ice caps and allochthonous ice flowing from the LIS center in New Quebec-Labrador (Grant and King, 1984; Grant, 1989; Stea, 1994).

Major problems in the establishment of a reliable larger-scale Quaternary stratigraphy of the St. Lawrence basin are caused by the highly discontinuous nature of the glacial and non glacial cover, a general lack of ^{14}C datable material, and the absence of reliable dating methods for older sediments (outside the ^{14}C dating envelope). It is understood, therefore, that the succession of events described below may be drastically revised as methods of dating older sediments are improved, as more subsurface core and seismic data in the St. Lawrence Estuary and Gulf is collected, and as systematic studies of tills in poorly studied regions are carried out.

GLACIOISOSTASY, GLACIAL LAKES AND MARINE INVASIONS

Because of ice-loading, the basin has been depressed by glacioisostasy during glaciations, and subsequently raised by isostatic rebound during and following deglaciations. Isostatic depression and tilting , and ice damming transverse to the St. Lawrence corridor have created glacial lakes in the upper part of the middle estuary, in the central valley and in the Ontario basin at various times during ice advances and retreats.

During deglaciations, marine waters from the Atlantic Ocean have invaded the depressed lowlands. These inland seas extended as far as 500 km inland from the present limit of estuarine brackish water close to Quebec City, and up to 250 m a.s.l. as observed north of

Montreal. Raised shorelines record progressive regression of the inland sea during glacioisostatic rebound. During interglacials and major interstadials, fluvial drainage networks similar to the present day St. Lawrence river system were established (Table 2.1).

SEDIMENTARY SEQUENCES WITH CLIMATIC CONTROL

The stratigraphic framework of the Quaternary units of the basin is a consequence of the interplay of these ice advance/retreat, isostatic depression/rebound and fluvial processes. Thus, in the valley and middle estuary, each main climatic cycle is characterized by an idealized sedimentary sequence (fluvial erosional disconformity or condensed estuarine deposits/overlying fluvial sediments/varves and proglacial turbidites/proglacial sediments/subglacial till/ice-retreat drift/glaciolacustrine varves/marine sediments/lacustrine and deltaic sediments) representative of the sequence of events (fluvial/englaciation/full glaciation/deglaciation/marine transgression and regression)(Occhietti, 1990; Occhietti and Clet, 1989). Each new sedimentary sequence is inset into previous sequences. The observed sedimentary successions usually do not contain all of the units of the idealized sequence, due to local differences in depositional response to paleogeographic change and to small-scale climatic fluctuations.

OFFSHORE EVIDENCE OF EARLY GLACIATIONS

Because of a strong erosional episode during the Illinoian Glaciation, pre-Illinoian continental and epicontinental units in the St. Lawrence basin are either scarce or concealed. Evidence of glacial and interglacial events older than the last Sangamonian Interglacial (isotopic stage 5) occurs offshore in the continental shelf margin and slope. Studies of deep-sea cores from the Fogo Seamounts (Alam and Piper, 1977) and the J-Anomaly Ridge (Piper et al., 1994) concluded that a major erosional episode in the Cretaceous-Tertiary strata occurred on the continental shelf during isotopic stage 14, and a deepening of the Laurentian Channel in the Gulf of St. Lawrence occurred during stage 12. Seismic reflection profiles record corresponding changes in the Laurentian Fan (Piper and Normark, 1982). Although older glacial units are not present offshore, the ash-layer dated continental record in the USA (Boellstorff, 1978) gives reasonable evidence that the St. Lawrence basin was repeatedly glaciated since early Quaternary time.

PRE-ILLINOIAN AND ILLINOIAN RECORD

The continental and epicontinental succession of lower and middle Pleistocene events is poorly understood in the St. Lawrence basin, and the Illinoian chronostratigraphic range is commonly applied to any pre-Sangamonian Interglacial beds. Offshore, pre-Sangamonian quiet water muds and foram-nanno oozes from the Pogo seamount record a mid-Illinoian glacial event, a cooler-than-today interglacial event at isotopic stage 7, a late Illinoian glaciation and an erosive event at the end of it. According to the chronological scale of Boellstorff (1978), the units referred to as Illinoian in North America extend to isotopic stage 14. The equivalence of the three glaciations of the Saalian in Western Europe with this extended Illinoian is therefore fortuitous. Upper Illinoian will be used in this paper as the last glacial stage of the middle Pleistocene, correlative with isotopic stage 6 (Table 2.1).

In the Toronto area, stratified units and a diamicton unit underlying upper Illinoian till have been observed in cores and subway excavations (Karrow, 1989). Stratified silt is exposed below the Becancour Till near Pierreville in the St. Lawrence Valley. In the southern Appalachians of Quebec, pre-Johnville rhythmites and stratified sand are exposed at the lower part of several section (McDonald and Shilts, 1971; Shilts, 1981), and some gold-bearing colluvium was reached by drilling below these units (Shilts and Smith, 1986). Cores and seismic lines from the middle estuary show that the Baie-Saint-Paul Glacial Complex drapes several older deposits. These deposits infill several major incised paleochannels (100s m deep) (Fig. 2.1) and a >150 m deep tunnel-valley (Fig. 2.2)(Occhietti and Long, unpublished). The head of the Laurentian Channel shows a pile of glacial, prodelta, glaciomarine and marine estuarine units (Fig. 2.3; Long and Occhietti, unpublished; M. Massé, submitted MSc thesis). In Nova Scotia, only one unit, a diamicton containing *Mercenaria* shells, is believed to be related to an interglacial older than the upper Illinoian (Wehmiller et al., 1988).

The upper Illinoian Glacial episode eroded almost all of the previous Quaternary deposits and left a very discontinuous till cover which directly overlies bedrock, except in the pre-Illinoian sites described above. Most of the present bedrock morphology was reshaped as a consequence of this episode. The glacial deposits and tills related to the upper Illinoian Glaciation lie directly below organic bearing sediments of the Sangamonian Interglacial climatic optimum (Eemian, isotopic substages 5e). These include the York Till in the Lake Ontario region (Karrow, 1989), the Rigaud Till in the Ottawa Valley (Anderson et al., 1990), the Baie-Saint-Paul Glacial Complex in the middle estuary (Occhietti et al., 1995), the Johnville Till in the southern Appalachians of Quebec (McDonald and Shilts, 1971) and the Miller Creek Till in Nova Scotia (Grant and King, 1984; Stea et al., 1992)(Table 2.2). In the

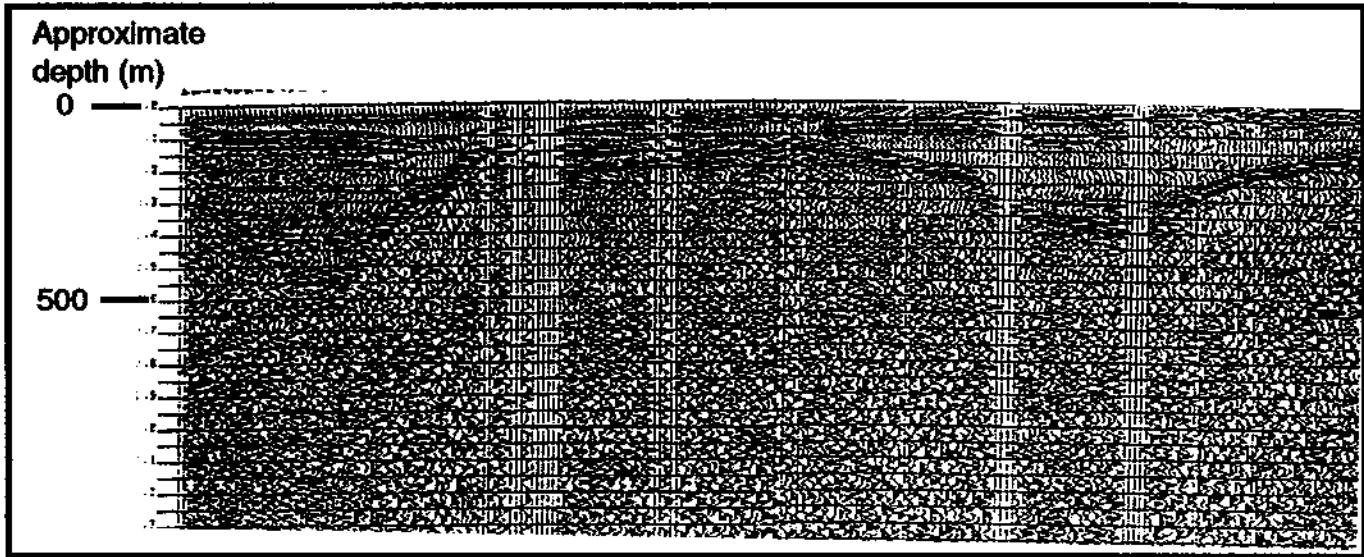


Figure 2.1: Seismic profile across the St. Lawrence middle Estuary.
 (Source 360 cubic inches air gun for SOQUIP, 1971, from Lamontagne et al., unpublished.)

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

Table 2.1: Quaternary main stades, interstades, lacustrine and marine events in the St. Lawrence basin.

St. Lawrence Valley, several lower tills with distinct lithologies (Becancour Till and its correlatives, Gadd, 1971; Lamothe, 1989; Portneuf Till, Bernier and Occhietti, 1991) are likely correlative. Thin inter-till deposits exposed at several places (near Pierreville, Gadd, 1971; Donnacona, Clet et al., 1991) indicate that strata assigned to the upper Illinoian may actually represent one or two distinct glacial phases.

THE ILLINOIAN-SANGAMONIAN (6/5) TRANSITION AND THE GUETTARD SEA EPISODE

On a global scale, the Illinoian-Sangamonian transition is only documented in the Kattegatt Sea (Seidenkrantz and Knudsen, 1994) and in cores from the St. Lawrence middle estuary (Occhietti et al., 1995). Here, overlying the Baie-Saint-Paul Glacial Complex is the Ile aux Coudres Formation - a stratified sequence from 125 to 2m below present sea level (Table 2.3). The sequence records the invasion of Atlantic marine waters (Guettard Sea) into the isostatically depressed basin. The Ile aux Coudres Formation is composed of four sedimentary facies, which are from the base (1) a lower compact marine clay, (2) marine rhythmites, (3) prodeltaic silts and deltaic sandy silts, and (4) sand with brackish water benthic foraminifera. The spore and pollen content indicates that an initial shrub tundra was followed by an afforestation sequence which grades from a boreal to a fir (*Abies*) forest and to an interglacial mixed forest with *Juglans*, *Carpinus*, *Ostrya* and *Carya*.

Following the rapid marine invasion of Guettard Sea waters into the estuary, was a period (approximately 3500 years) of progressive regression where depositional environment changed from deep marine (+/- 300m) to shallow fluvial. In the St. Lawrence Valley and its tributaries, some unnamed rhythmites (Lamothe, 1989; Besré, 1990), the lower clay bed at Pointe-Fortune, and the Pierreville Varves (Gadd, 1971) have the same stratigraphic position as the Ile aux Coudres Formation, and may be representative of the same widespread marine and/or glaciolacustrine phase during late Illinoian/early Sangamonian time.

RECORD OF THE CLIMATIC OPTIMUM OF THE SANGAMONIAN INTERGLACIAL (EEMIAN, ISOTOPIC SUBSTAGE 5e)

The climatic optimum of the last Sangamonian Interglacial is evidenced by warmer-than-today floral and faunal remains collected from organic beds at various locations throughout the basin (Fig. 2.4). Depositional environments related to the interglacial vary significantly from inland regions to the shores of the Gulf. Sedimentary facies of the Don Formation in the Lake Ontario area (Coleman, 1933; Karrow, 1990) are interpreted as lacustrine lower shoreface sediments (Eyles and Clark, 1988) deposited in a lake referred to as Lake Coleman. The Quercus member of the Pointe-Fortune Formation in the lower Ottawa River

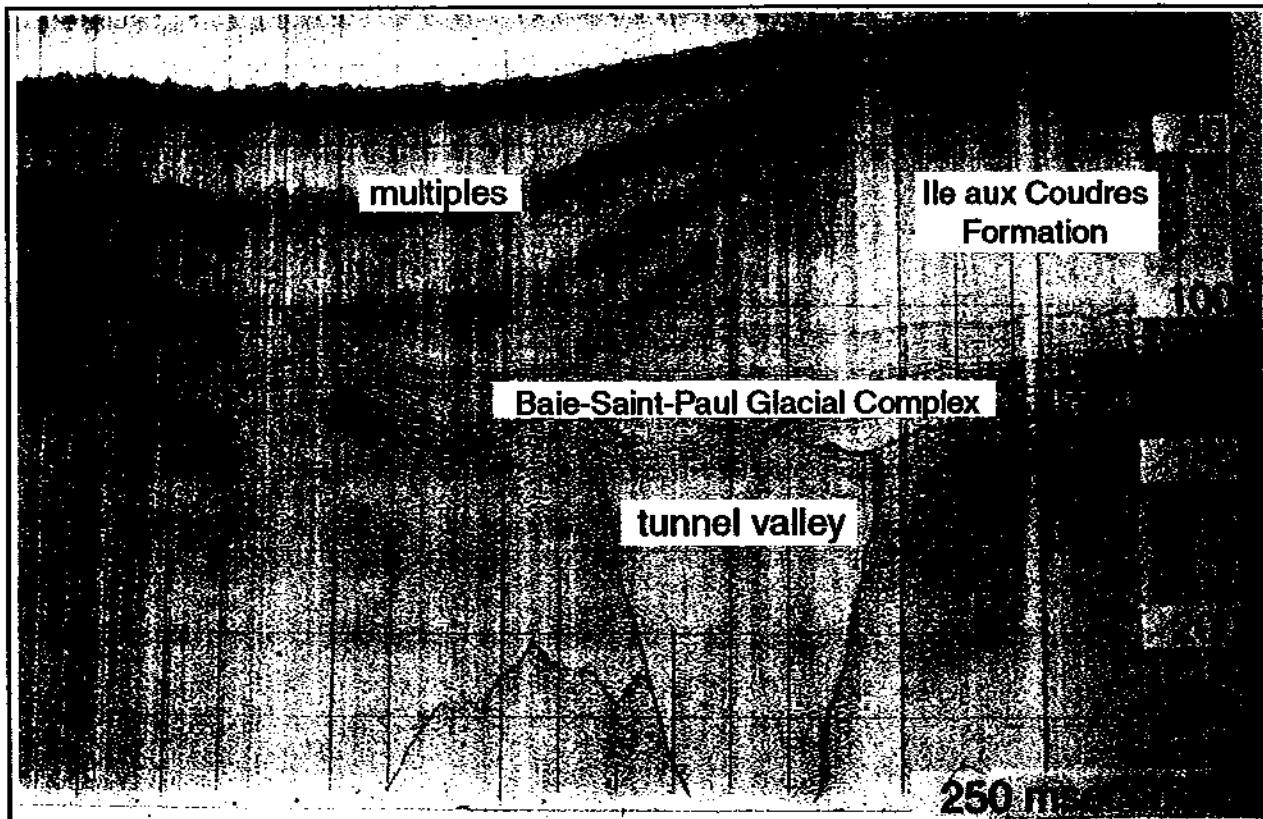


Figure 2.2: Pre-Illinoian tunnel valley incised into two older units.
(Sparker 400 j., Occhietti and Long, unpublished)

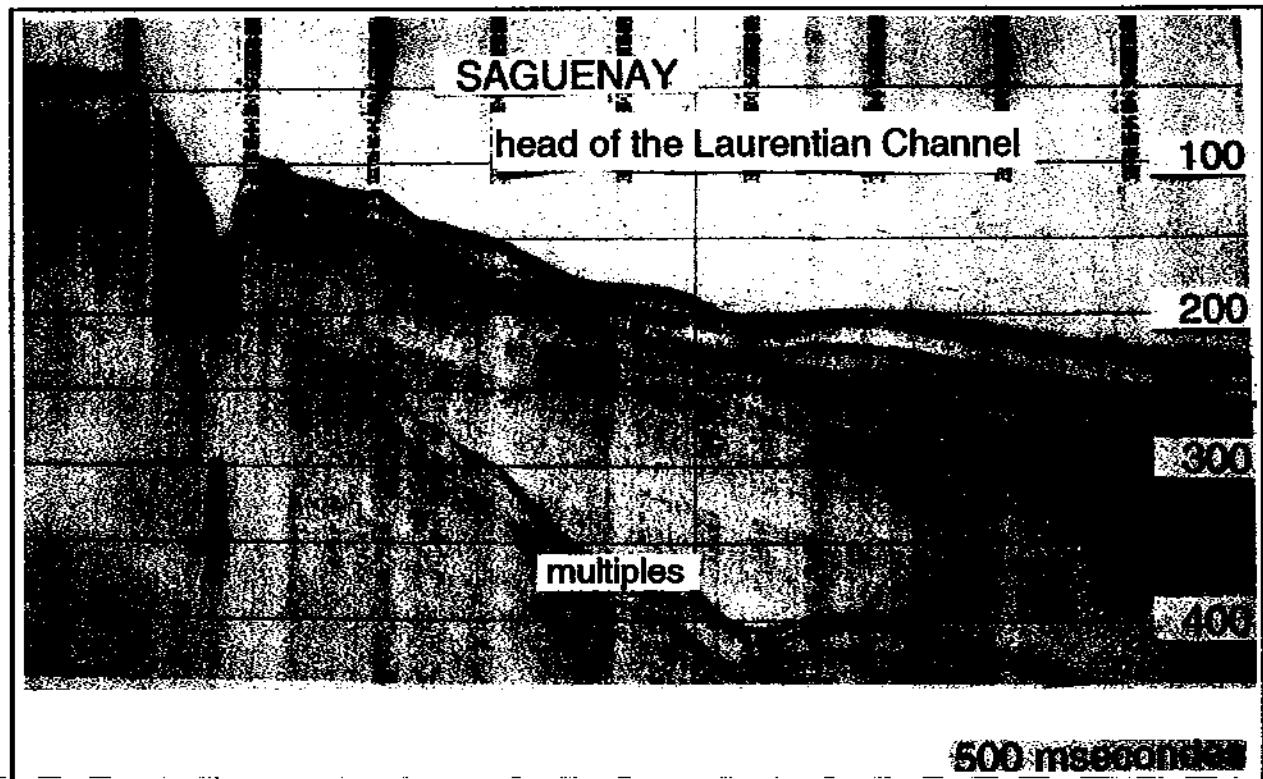


Figure 2.3: Piled Pleistocene and Holocene sediments at the head of the Laurentian Channel.
(Sparker 800 j., Long and Occhietti, unpublished)

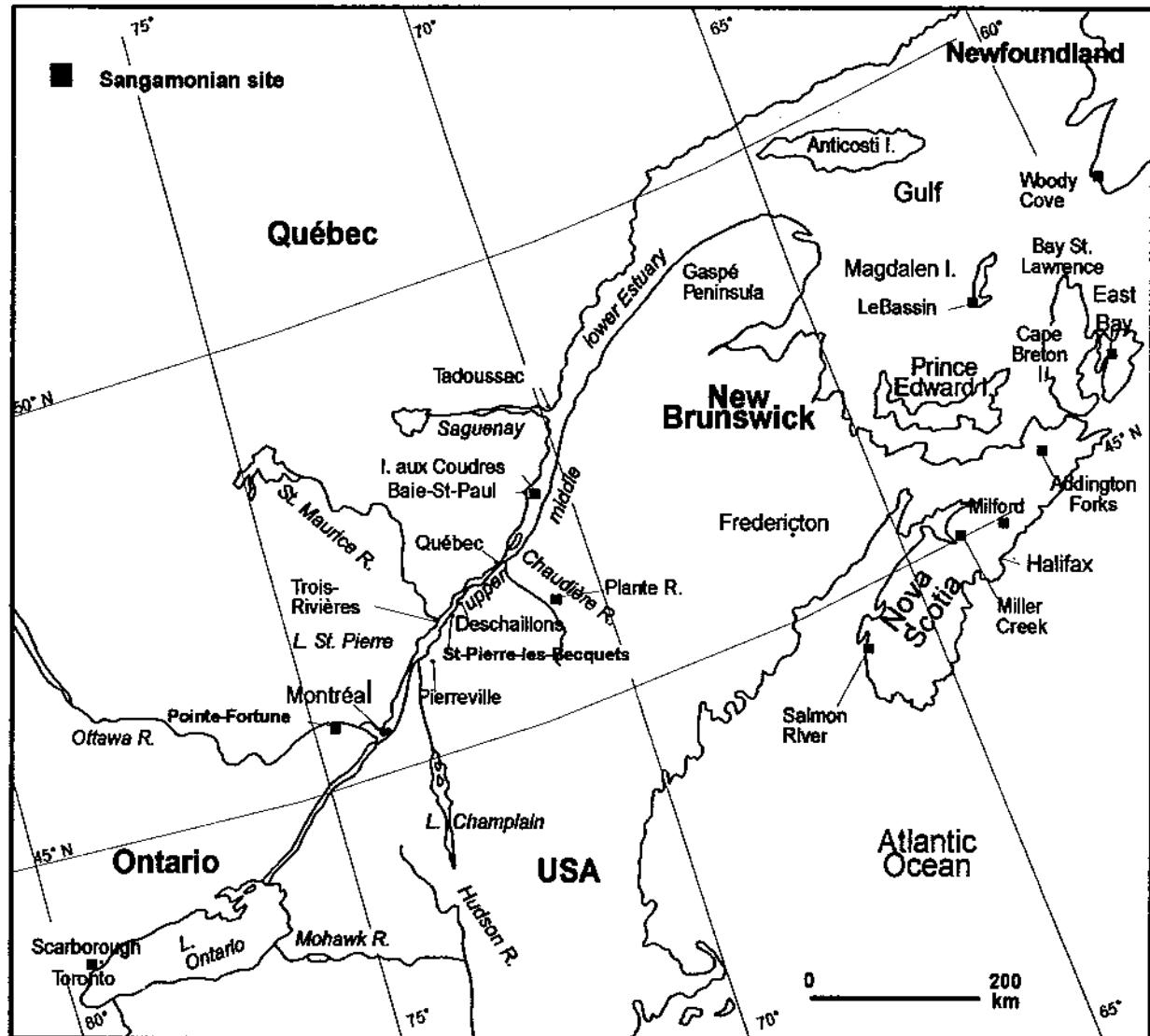


Figure 2.4: Main Sangamonian sites in the St. Lawrence Valley, Estuary and Gulf.

Time scale stages	lacustrine Lake Ontario	St. Lawrence Valley	Middle estuary of St. Lawrence	Quebec southern Appalachians	Nova Scotia mainland	Cape Breton Island	Canada	Europe
ka								
10-1	Holocene deposits	Holocene	Lenticular and fluvial	Holocene deposits	Goldthwait Sea deposits	local ice-flow reversal	Younger Chignecto phase Scotian phase	HOLOCENE
2	Halton Till Sand and Gravel (Wentworth Till)	Champain Sea deposits	St. Narcisse Moraine	Sandy bed	Leamington Till	Lamonttonen Till or Sauvileville Till	Eicomimac Phase till: local stratified sediments	HOLOCENE
30	Upper Thorncastle Formation:		Gentry Till (with 2 unnamed beds)	shelly sand	Grayhurst Formation	McClarnon Brook Till or East Milford Till or Herten Till	Caldeonia Phase till: local stratified sediments	WISCONSINAN
3	Middle Meadowcliffe Till			sandy bed			Richmond Till	WEICHSELIAN
60	lower Sunnybrook Drift	Sunnybrook Till		stratified silt	Chaudiere Till			
75	Pottery-Road Formation:			proglacial sand	Massawippi Formation e. s.	organic beds	organic beds	
a	Glaciaturrial bed fluvial bed	Ville-Étangue Sands St-Pierre Sand & St. Maurice Rhyth.	I.e. Paradise Clay	-carbonated till -rhizolithes				
b	Scarborough Formation		Levendar Till	Unit II			local till?	
5	c	Deshellions Varnes	Deshellions Sand	Unit II				SANGAMONIAN
d		Lobiniere Sand		Unit II				
		Pointe-Fortune F.:upper beds						
125	e Don Formation	Pointe-Fortune F.:lower beds	Ile aux Coudres F.:sand beds	local interglacial beds	Salmon River Sand (raised platform)	East Bay peat (raised platform)	climatic optimum	EEMIAN
6 to 5		Pierreville Varnes ? unnamed stratified clay	Ile aux Coudres F.:clay beds					
130	f York Till						Little Brook Till ? tills below 5e organic beds	ILLINOIAN 5. I.
(and older?)								SAALIAN 5. I.
older than 6	g scarce stratified sediments						old shells in till Bridgewater conglomerate	
							tunnel-valley sediments encased into older sediments	Mabou conglomerate

Table 2.2: Quaternary lithostratigraphic units of the St. Lawrence basin. (The framework of Quaternary for Canada is from Fulton, 1989).

is a fluvial terrace deposit, and the upper sand of the Ile aux Coudres Formation in the middle estuary is interpreted as deltaic. In the gulf area, the interglacial is represented by continental peat bogs (Addington Forks and East Milford, Nova Scotia), peat bogs close to the ocean (Le Bassin, Magdalen Islands, and East Bay, Cape Breton) and coastal deposits (Portage du Cap, Magdalen Islands; Mabou, Cape Breton Island; Woody Cove, Newfoundland). Pollen analysis of these units shows they represent either: (1) a deglacial to warmer-than-today transition, (2) the climatic optimum (warmer than today only), or (3) a warmer-than-today to subarctic transition (Mott, 1990). The complete climatic cycle is recorded at the Ile aux Coudres (Clet and Occhietti, 1995; Occhietti et al., 1995) and Woody Cove (Brooks et al., 1982) sites.

With onset of the climatic warming, forests with abundant thermophile hardwoods (*Quercus*, *Carya*, *Tilia*) established themselves between Lake Ontario and the Gulf. A boreal forest of spruce and *Abies balsamea* populated Newfoundland (Mott, 1990). *Liquidambar*, a taxon which is presently found only south of the Ontario basin, is reported in interglacial pollen diagrams from the Don Formation, and represents 1% of the taxa in the Pointe-Fortune flora. In the gulf area, white pine (*Pinus strobus*) reached the Magdalen Islands.

A laterally continuous raised shoreline which is locally covered with beach sands and cobbles exists in Nova Scotia (Grant and King, 1984). The elevation of this shoreline (+2 to +6 m) accords with the average elevation of the 5e isotopic substage eustatic base level shorelines observed around the world.

THE INTERGLACIAL-GLACIAL TRANSITION

A cooling trend following the 5e substage optimum is inferred by the pollen assemblages characteristic of the upper part of the organic interglacial beds. This pollen indicates a transition from warmer-than-today forests to: (1) mixed forest to boreal forest in the upper meter of Don Formation (Terasmae, 1960), (2) deciduous, fir (*Abies*) and *Picea/Pinus* boreal forests at Pointe-Fortune (Anderson et al., 1990), (3) *Abies* followed by *Picea/Pinus* boreal forests in the basal beds (Unit II) exposed at Ile aux Coudres (Clet and Occhietti, 1995) and in the upper part of interglacial units in Nova Scotia (Addington Forks, East Milford, and East bay)(Mott, 1990), and (4) *Pinus/Picea* boreal forest in Newfoundland (Woody Cove)(Brooks et al., 1982).

Sedimentary facies related to this climatic transition indicate significant changes in depositional processes, such as: (1) regression associated with a drop of base-level below the present-day level in Lake Ontario basin, (2) fluvial and bog deposition in the alluvial plain of the Ottawa valley, (3) condensed sedimentation in the middle estuary, and (4) deposition

¹⁸ O	Age and events	Lake Ontario	Saint-Lawrence central Valley	Saint-Lawrence middle Estuary	Appalachians of southern Québec	Sedimentary sequences
1	Floocene				Goldthwait Sea	Postglacial sediments
2/1	Champlain Sea					
2						
3	Trois-Rivières Stage	Thorncliffe Formation	Gentilly Till	Upper Till	Lennoxville Till	upper
4	La Vérendrye Lake	hiatus	Vieilles-Forges Sands			
	La Vérendrye Lake		Saint-Maurice Rhythmites			
5a	Les Bécquets Event	Pottery Road Formation erosional surface	S. Pierre Sediments (D1-6) erosional surface	IAC - IV (sands and peat) erosional surface	Gayhurst Formation	
5a/5b	Cartier Sea			La Pérade Clay	hiatus	
5b	Nicolet Stage	Scarborough Formation	Lévrard Till	IAC - III (varves)	Chaudière Till	middle (cap Lévrard)
	Deschaillons Lake		Deschaillons Varves			
5c	Grondines Event	hiatus	Lotbinière Sand erosional surface	IAC - II (sand) erosional surface	Massawippi Formation <i>sensu stricto</i>	
5d			Leclercville Rhythmites			
			Rivière aux Vaches silts	IAC - II a (silt)	hiatus	
5e	climatic optimum	Don Formation		IAC - I IAC - 5	Rivière Plante beds erosional surface	climatic optimum
6/5	Guétard Sea		Pierreville lower Varves	île aux Coudres Formation IAC - 2-4	hiatus	
6	Illinoian Stage	York Till	Bécancour, Portneuf and Odanak Tills	Baie-Saint-Paul Glacial Complex	Johnville Till	Illinoian
7/6?	lake event marine event		Pre-Odanak Rivière-aux-Vaches silt	Petite-Rivière clay and silt	Pre-Johnville sediments	
?				Petite-Rivière lower Till		

Table 2.3: Correlation of events in southern Québec.

of sediments with higher clastic:organic grain ratio with respect to underlying interglacial beds in Nova Scotia.

The age of this transition is still debated. Incorporation of recent infra-red stimulated luminescence (IRSL) and amino acids dates obtained on a younger unit (see La Pérade Clay) into the global framework suggests this cooling event should be correlated with the 5e/5d transition in the isotopic record.

EARLY GLACIAL EPISODE IN THE INTRACONTINENTAL BASIN AND PERIGLACIAL AND/OR LOCAL GLACIAL PHASE IN THE GULF AREA

The post-interglacial cooling trend continued until cold or full-glacial conditions returned to the basin. During the early-glacial in the Toronto area, a 50 m thick accumulation of prodeltaic and deltaic silts and sands (the Scarborough Fm.) was deposited at the mouth of a bedrock valley (the Laurentian Valley) in larger-than-today paleo-Lake Ontario (Lake Scarborough)(Karrow, 1984,1989; Kelly and Martini, 1986). Pollen (Terasmae, 1960; Richard et al., 1999) and caddisflies (Williams and Eyles, 1995) collected from the Scarbourough Formation indicate that this event occurred in a subarctic forest tundra or tundra environment, with mean temperature about 10° C below the present. Concurrently, cold lacustrine environment is indicated by the ostracodes (Poplawski and Karrow, 1981). The raised elevation of the lake necessitates a coeval ice-sheet dam downstream in the St. Lawrence Valley. Correspondingly, in the central St. Lawrence Valley, outliers of a sequence of fluvial sands (Lotbiniere Sand), varves (Deschaillons Varves), subglacial till (Levrard Till)(Lamothe, 1989) and marine clay (La Pérade Clay)(Ferland and Occhietti, 1990) suggest an erosional and depositional fluvial phase and an early-glacial episode associated with a stadial period referred to as the Nicolet Stade (Lamothe, 1989). Pollen from the Lotbiniere Sand and Deschaillons Varves indicates a transition from boreal forest to tundra environment (Clet and Occhietti, 1994). The post-glacial La Pérade Clay corresponds to a short glacioisostatic marine invasion (Cartier Sea, Occhietti et al., 1996), and a return from tundra to an interstadial boreal forest. In the middle estuary area, the early glacial episode is recorded either by varves which are truncated by a fluvial erosional contact (Ile aux Coudres Unit III) or by a carbonated till overlying local rhythmites (Fournier, 1998). It is probable that the ice sheet did not extend to the gulf area (Grant, 1989; Stea et al., 1998). In Nova Scotia, some local tills might be related to advances of Appalachian ice caps. In southern Quebec, the first upper Pleistocene till, referred to as Chaudiere Till (MacDonald and Shilts, 1971), indicates the presence of a regional ice cap over most of the Appalachian mountains in New England and Québec. However, the precise chronology of this event is still debated (Lamothe et al., 1992).

The sequence of the Nicolet Stade is the earliest upper-Pleistocene evidence of a continental ice sheet which extended to middle latitude in NE of North America. From the IRSL and amino acids age of the post-glacial marine La Pérade Clay, this glacial event occurred as early as about 100 ka (Occhietti et al., 1996). From the accepted 5a age of the following Les Becquets Interstade (75 ka), the Nicolet Stade would be correlated to substage 5b. This age would mean that cold substages 5d is recorded, in the St. Lawrence basin, by an erosional unconformity at the top of Don Formation in Ontario and at the base of Lotbiniere Sand in the valley. The fluvial Lotbiniere Sand, related to the Grondines Interstade (Lamothe, 1989), would correspond to the end of cool substages 5c.

LES BECQUETS INTERSTADE (OR ST. PIERRE EVENT): A BOREAL FOREST EPISODE

In the St. Lawrence central Valley, a ≤30 km wide and 400 km long fluvial/acustrine interstadial (Les Becquets Interstade) sedimentary system incised into the La Pérade marine Clay and older units, at about + 8 m to + 20 m above present sea level. The associated basal unconformity is overlain by the fluvial sand, silt and peat beds of St. Pierre Sediments. The fining upward nature of these sediments reflects a progressive lowering of base level in the valley until a low energy fluvial system was established in a poorly drained valley covered by a *Pinus/Picea* boreal forest (Clet and Occhietti, 1996). After a short high-energy fluvial phase, the St. Maurice Rhythmites and the lower zone of the Vieilles-Forges Sands were deposited for about 1000 y. in La Verendrye Lake. Pollen content of the rhythmites and upper sands shows that the boreal forest in the valley lowlands was progressively flooded and was then replaced by tundra over the exondated areas (Clet-Pellerin and Occhietti, 2000).

In the Toronto area, several channels are incised into the Scarborough Formation and filled in by the Pottery Road Formation (Karrow, 1989). They indicate a rapid drop of Lake Ontario level (~50 m) which is associated with deglaciation of the St. Lawrence Valley. The lower fluvial member of Pottery Road Formation contains animal remains, mollusks and vertebrates including bear, bison and an extinct deer (*Cervalces borealis*).

In the gulf area, interstadial organic beds underlie the Wisconsinan till sequence. Outcrops of these beds are numerous on Cape Breton Island, where they occur frequently over colluvium (Grant and King, 1984) of periglacial origin.

The minimum age of the interstade is $74,700^{+2700/-2000}$ y. BP from a ^{14}C age on wood (Stuiver et al., 1978). Based on this date and the pollen evidence of a climate cooler by only a few degrees C than today, Les Becquets Interstade is related to substages 5a. The relative level of drainage at + 8 to + 20 m, during this interstadial eustatic low stand at about -13 m, indicates a glacioisostatic depression of the St. Lawrence Valley of the order of 20 to 30 m.

The St. Pierre fluvial event occurred when continental ice masses were still sufficient to depress the valley.

EARLY WISCONSINAN STAGE

During the early Wisconsinan, a major ice sheet readvanced and completely covered the St. Lawrence intracontinental basin. In the Toronto area, the Sunnybrook Drift, an extensive sheet of clay-silt diamictite, was deposited at the base of ice and/or under floating ice (Karrow, 1984; Eyles and Eyles, 1983; Sharpe and Barnett, 1985; Hicock and Dreimanis, 1989) and is related to Guildwood Stade. In the St. Lawrence Valley and middle Estuary, the lower lithozone of Gentilly Till and other equivalent glacial units is related to the same major glacial episode. In the gulf area, an early eastward ice flow (Caledonia phase 1a) in New Brunswick (Rampton et al., 1984) was followed by a general southeastward flow over most of New Brunswick and Nova Scotia (Caledonia phase 1b). Southeastward fabrics and northerly derived clasts in massive red brown till (Red Head Till, Richmond Till and East Milford Till), indicate a massive ice movement over submerged red Carboniferous rocks and over highlands of southern New Brunswick and Cape Breton Island (Rampton et al., 1984; Grant, 1989; Stea et al., 1998).

Despite some contradictory U/Th ages obtained from wood (de Vernal et al., 1986) and luminescence ages from sediments which show a strong fading, this major glacial episode is generally related to isotopic stage 4. This correlation is in agreement with North Atlantic red sediments which record a significant glacial activity during stage 4 and 3.

EARLY MID-WISCONSINAN INTERSTADE

In the Toronto area, a stratified fluvial and lacustrine unit (lower member of Thorncliffe Formation), older than 50 ka, is related to Port Talbot Interstade. During this episode, which is considered as the warmest mid-Wisconsinan interstade in the region, most of the Lake Ontario basin was deglaciated. The presence of ice in the St. Lawrence Valley is inferred from the high level of Lake Ontario and from the lack of interstadial beds in the valley and in the southern Appalachians of Quebec. Ice retreat in the gulf area is apparently limited to some coastal areas of Nova Scotia (Grant, 1989). Nevertheless, Anticosti Island was free of ice (Gratton et al., 1984), which suggests that the gulf was not invaded by the LIS. The Port Talbot Interstade is related to cool conditions that prevailed during the early part of isotopic stage 3.

MID-WISCONSINAN GLACIAL EPISODE

In the Toronto area, Seminary and Meadowcliff tills are separated by the middle member of Thorncliffe Formation. They record advances of the Ontario lobe of LIS or of floating ice. The extensive Meadowcliff Till is composed of reworked lacustrine clay. The age of the related Cherry Tree Stade is bracketed between > 50 ka and about 30 ka. The other parts of the St. Lawrence basin were ice covered during this episode. The source of the southeastward ice flow over New Brunswick and Nova Scotia, during the continuing Caledonia phase 1b, is not certain. Gneissic clasts found in the tills related to this phase suggest that ice either flowed from the LIS (Rampton et al., 1984), or from the Appalachian Gaspereau Center (Lamothe, 1992). A glacial readvance over the western part of Anticosti Island, between circa 36 and 28 ka (^{14}C years of marine shells) (Gratton et al., 1984), could be related to the Cherry Tree Stade.

THE LIMITED UPPER MID-WISCONSINAN INTERSTADE

In the Toronto area, stratified clays, silts and sands of the upper member of Thorncliffe Formation contain plant debris dated between 32 ka and 28 ka. They are related to the Plum Point Interstade, equivalent to the Farmdalian Substage of Illinois (Frye and Willman, 1960). Ice retreat in Ontario seems to have been less extensive than during the Port Talbot Interstade. On the contrary, in the central and eastern areas of the St. Lawrence basin, interstadial upper mid-Wisconsinan beds are more frequently observed than early mid-Wisconsinan beds which are very scarce. This indicates a more extended deglaciation than during the previous interstade. Interstratified sand beds in the Gentilly Till could be related to this event (or to the previous one). According to Lamothe et al. (1992), the glaciolacustrine rhythmites of Gayhurst Formation record the deglaciation of the Appalachians in southern Quebec, which necessitates the presence of ice in the valley. At the mouth of the Saguenay River, close to Tadoussac, a fluvioglacial unit contains reworked marine shells fragments circa 35 ka in ^{14}C age. This age is in agreement with the epimerisation ratio of the amino acids of the shells (Dionne and Occhietti, 1996). Deglaciation and a limited marine invasion are inferred, at least up to the entrance of the middle estuary. In the gulf area, firm evidence of a deglaciation is limited to restricted peripheral areas of the land. For example on Cape Breton Island, a reworked mastodon femur, a shelly glaciomarine unit, and total carbon in silt gave finite ^{14}C ages of the order of 30 ka (Grant and King, 1984). Some land areas and parts of the Scotian and Magdalen

shelves remained glaciated, and the Saunierville and Laurencetown tills were deposited over Nova Scotia (Grant, 1989; Stea et al., 1998).

LATE WISCONSINAN GLACIAL MAXIMUM

By 20 ka, the LIS reached New York, at the same latitude as Napoli, Italy. This maximum extent during the last glaciation is represented by the lower part of Wentworth Till near Toronto (Nissouri Stade), the upper zone of Gentilly Till and the Lennoxville Till in southern Quebec (upper part of the Trois-Rivières Stade) and by thin, loose and locally derived tills (e. g. Rawdon and Beaver River tills) in the gulf area (Escuminac Phase; Stea et al., 1988).

LATE WISCONSINAN DISMANTLEMENT OF THE SOUTHEASTERN MARGIN OF THE LAURENTIDE ICE SHEET

Deglaciation patterns of the southeastern margin of LIS are related to both climatic and non-climatic factors. Thinning and retreat of the LIS (Dyke and Prest, 1987) are directly linked to Late Wisconsinan global warming (17 ka to 11 ka). Correlations between deglacial events, global climatic oscillations and the oceanic record (bioassemblages, isotopes, oceanic ice-rafting) during this period are yet to be developed or restricted to the gulf area (Stea et al., 1998). Non climatic factors also played a major role in the deglaciation of the region. Below a threshold of the total budget of the LIS, the St. Lawrence topographic corridor channelized a major ice stream (St. Lawrence Ice Stream) which became a major feature of the central part of the St. Lawrence basin. The ice stream caused a flow convergence zone to migrate deeply into the LIS, and thinned the adjacent ice masses north and south of the St. Lawrence Valley and middle Estuary (Parent and Occhietti, 1999). As a consequence of the accelerated ablation, an Appalachian Sector became differentiated from the main ice sheet. Regionally, the terminus of the ice stream was a calving bay that retreated along the Laurentian Channel up to the mouth of the Saguenay fjord (early western arm of Goldthwait Sea). The ice stream and the deglaciated estuary generated an ice flow reversal along much of the northern margin of the Appalachian uplands in southern Quebec (Lamarche, 1971; Lortie and Martineau, 1987; Blais and Shilts, 1989; Rappol, 1993) and northeastern Maine (Lowell and Kite, 1986). During these generalized deglaciation processes, local and regional topographic features influenced the ice dynamics and the final deglaciation patterns. The western Ontario basin became briefly ice free during the regional Mackinaw Interstade. A subsequent rapid readvance of the Ontario ice lobe during the Port Huron Stade is recorded by Halton Till. By about 12 ka, Lake Iroquois inundated the Ontario basin

and overflowed through the Mohawk River to the Hudson River (Karrow, 1989). Later, lake level in this basin fell to a low -water level (Sly and Prior, 1984).

In the western sector of the Appalachians in southern Quebec, five discontinuous recessional morainic belts mark the retreat, at a rate of about 220 m/a (Parent and Occhietti, 1999; Occhietti et al., 2001), of the Laurentide Ice Sheet between about 12,550 and 12,150 y. B.P. (in marine shell ages which probably are 350 y. older than ages from continental material). Proglacial lakes were impounded at the retreating ice-margin. After the retreat of the ice, the western St. Lawrence Valley was inundated by Glacial Lake Candona (Parent and Occhietti, 1988, 1999) or Lake St. Lawrence (Rodrigues, 1992) which formed from the coalescence of Lake Vermont (Lake Champlain basin) and Lake Iroquois. Following the flow of Lake Candona toward the sea, Champlain Sea waters invaded the deglaciated and depressed lowlands circa 12,000 y. B.P. in ¹⁴C ages of marine shells (Parent and Occhietti, 1988), probably circa 11,700 y. B.P. or younger in ages from terrestrial material (Rodrigues, 1992; Ridge, 1998). By 9,500 B.P., after a rapid isostatic rebound, Lake Lampsilis (Elson, 1969) preceded the St. Lawrence River drainage system. In the gulf area, the Escuminac ice center disintegrated as rapid calving was initiated by sea-level rise. The resulting Scotian Phase (18-15 ka) is characterized by ice divides over Nova Scotia and New Brunswick, centrifugal ice flows from these centers, and by an ice mass over the Magdalen shelf. After a rapid ice retreat, between 13-12.5 ka (Chignecto Phase), ice was dispersed from local upland centers and the Magdalen ice mass (Stea et al., 1998).

YOUNGER DRYAS GLACIAL READVANCE AND HOLOCENE

The Saint-Narcisse Moraine records a significant ice readvance (Rondot, 1974) and/or stabilisation (LaSalle and Elson, 1975), north of the St. Lawrence Valley, at about 10,800-10,600 y. B.P. (from marine shells). This laterally continuous ice margin feature can be traced over 850 km, from the Algonkin Highlands in Ontario to the Saguenay mouth (Dionne and Occhietti, 1996; Occhietti, unpublished). Some local moraines in southern Labrador and Quebec North Shore are probably of the same age (Vincent, 1989). The ice front was in contact with Champlain and Goldthwait Seas for 150 km (Occhietti, 1989). A younger morainic belt, 170 km long, was recently discovered about 10 to 20 km north of the Saint-Narcisse Moraine (the Mars-Batiscan moraine, Govare, 1994; Bolduc, unpublished; Robert, current MSc research). These two major features are related to the Younger Dryas cold event and are contemporaneous with a late ice-flow or cold continental phase in the gulf area, recorded by pollen assemblages of lake cores, changes in sedimentation and reactivation of small glaciers (Mott et al., 1986; Stea and Mott, 1998). Post-Younger Dryas local ice masses subsisted over Nova Scotia and the Gaspé Peninsula until 10,000-9,5000

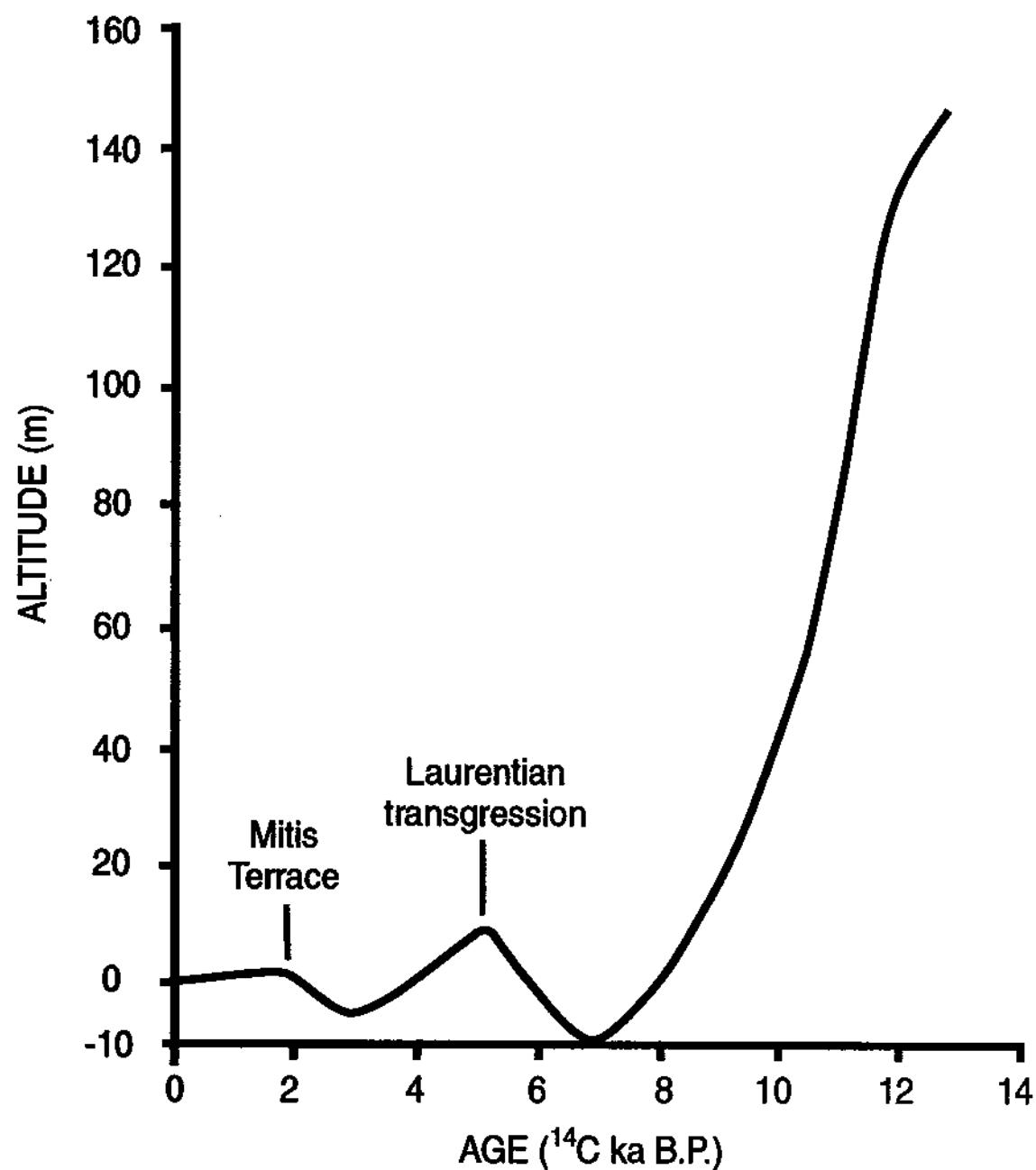
y. B.P. (Richard et al., 1997). North of the gulf and lower estuary, the Quebec North Shore Moraine, more than 800 km long, was built on the Canadian Shield plateau, at about 9.7-9.5 ka (Dubois and Dionne, 1985). The three stages (non-arboreal, afforestation, forest) of post-glacial-Holocene development of vegetation show distinct geographical and chronological distribution in the basin (Anderson, 1985; Richard, 1994; Mott, 1989).

Raised shorelines of the Champlain and Goldthwait Seas record a rapid glacioisostatic recovery during the first three millenia after deglaciation. The relative sea-level stabilized at the beginning of Holocene, as observed at the Saint-Nicolas site located close to Québec-City. Several fluctuations of the relative sea-level are recorded on the southern and northern shores of the St. Lawrence Estuary, including the Laurentian transgression and the Mitis Terrace episodes (Fig. 2.5; Dionne, 2001).

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**Late Upper Pleistocene and Holocene relative sea-level curve
South shore of the St. Lawrence Estuary**



**Figure 2.5: Fluctuation of relative sea-level in the St. Lawrence Estuary.
Data from south shore at Montmagny and Baie-des-Sables, Québec
(Dionne, 2001).**

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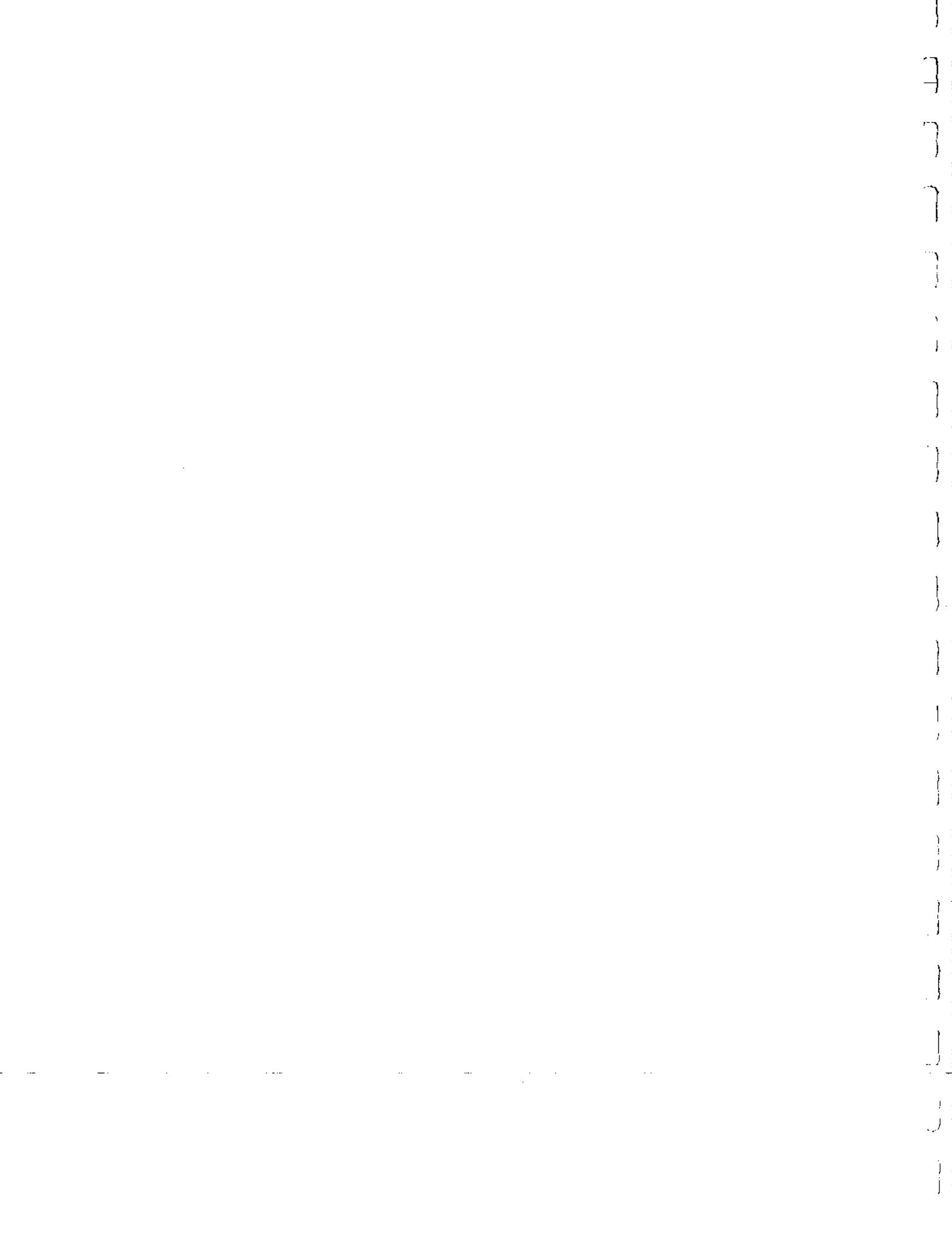
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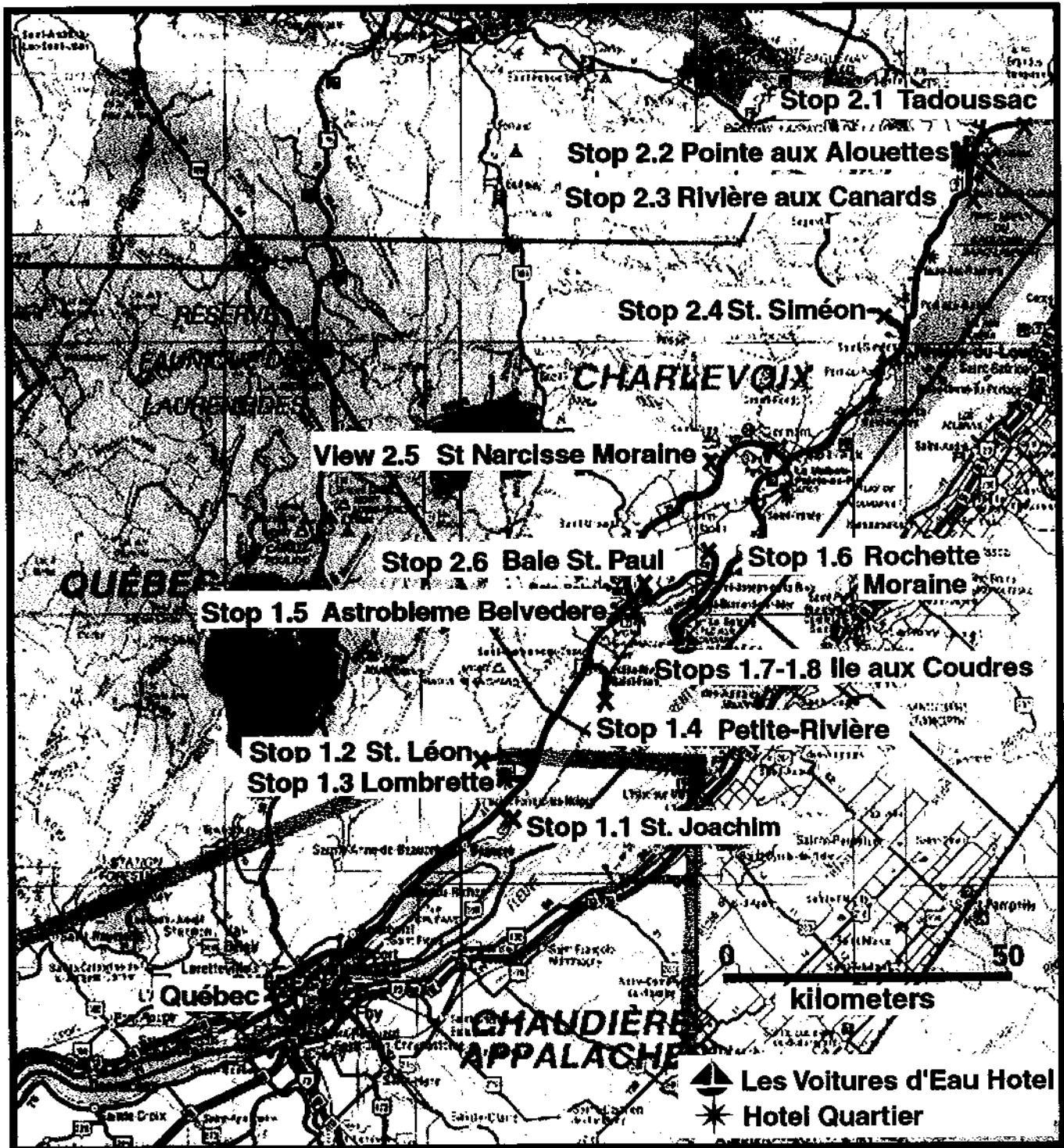
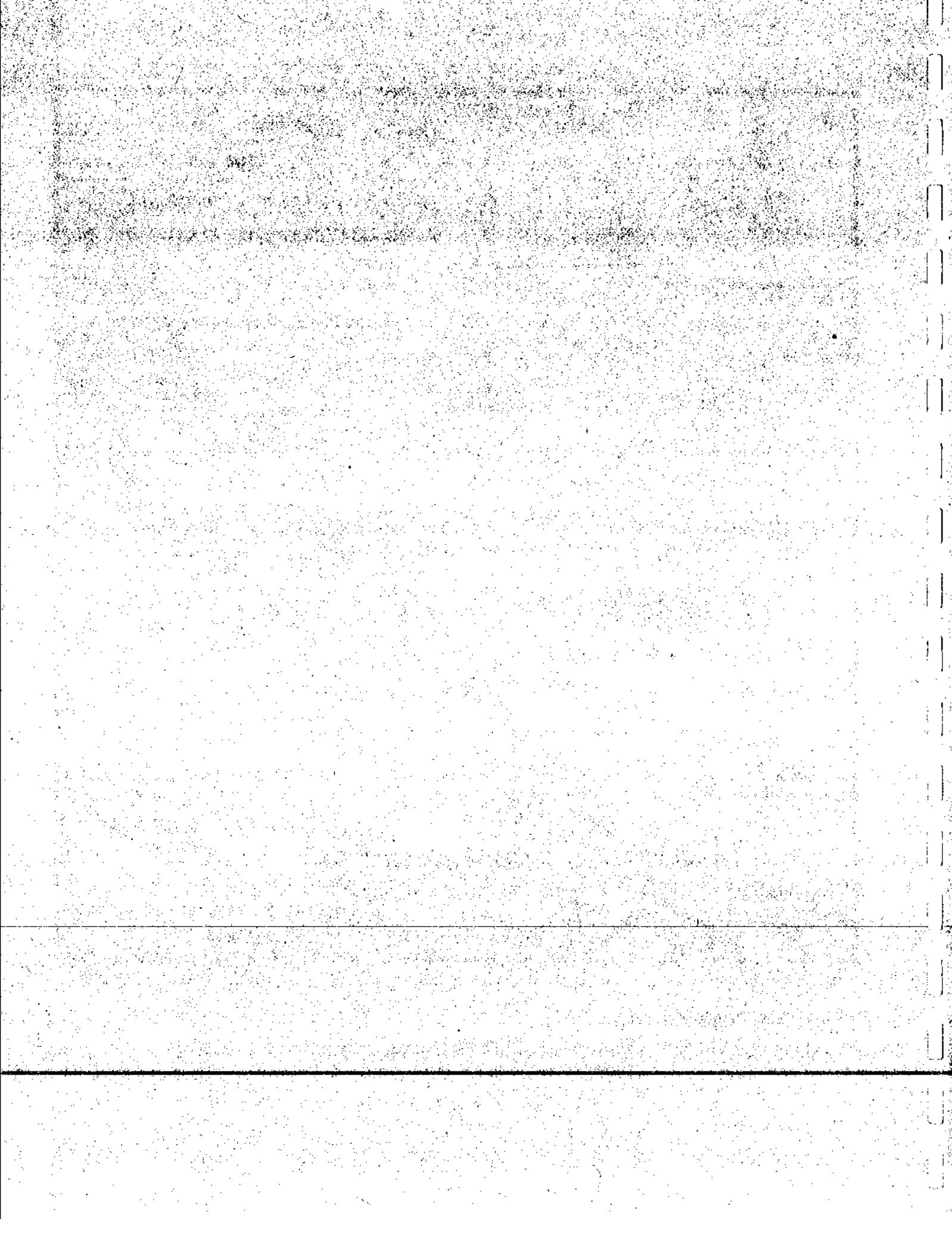


Figure 3.1 Road log map
(from the official Road Map of the Ministère des Transports du Québec)



CHAPTER 3
DESCRIPTION OF FIELD STOPS
Saturday June 2, 2001

8 h 00	Field trip leaves the Hotel Quartier	
8 h 30 - 9 h 15	Stop 1.1	Section at Saint-Joachim
9 h 30 - 9 h 50	Stop 1.2	Delta of Saint-Léon
10 h - 11 h 15	Stop 1.3	Walk to the Lombrette Section Collation
11 h 45 - 13 h	Stop 1.4	Petite-Rivière-Saint-François Section and drilling site Pic-Nic
13 h 15 - 14 h	Stop 1.5	Belvedere at Baie-Saint-Paul Oral presentation by Martin Bouchard, of Randonnée Nature Charlevoix
14 h 30 - 15	Stop 1.6	Rochette Moraine and deglaciation in central Charlevoix
15 h 30 - 16 h		Ferry to Isle aux Coudres - Collation
16 h 15		Stop at Les Voitures d'Eau Hotel
16 h 30 - 17 h 30	Stop 1.7	Isle aux Coudres: Calvette Section and drilling site
17 h 30 - 18 h	Stop 1.8	MicMac Terrace
18 h		Return to Les Voitures d'Eau Hotel

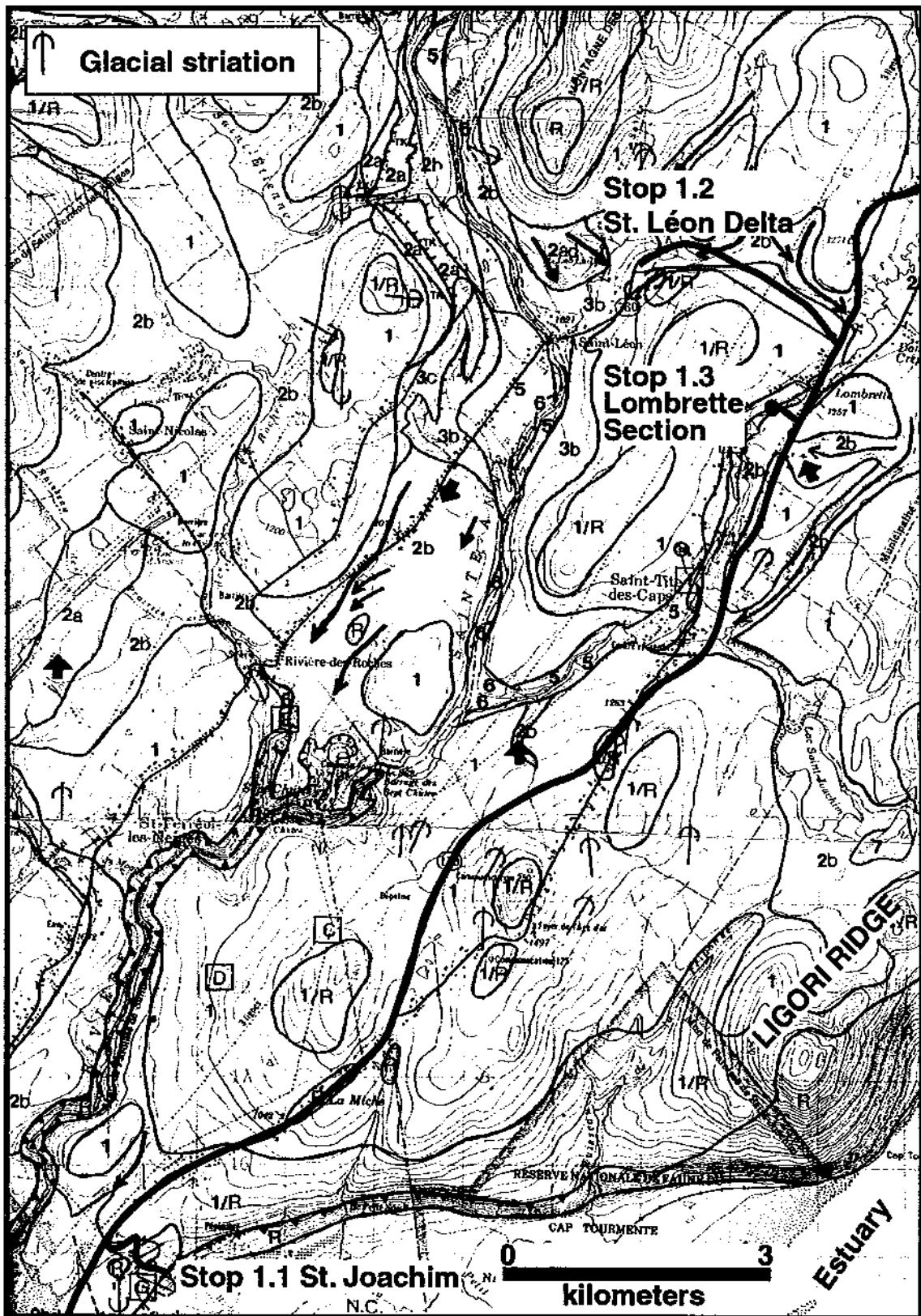


Figure 3.2 : Stops 1.1, 1.2, 1.3. Map from Fournier, 1998. 1: Till
2: Fluvioglacial deposits 3: Glaciolacustrine deposits 4: Marine
deposits 5-6: Fluvial deposits 7: Peat
Arrows: Direction of meltwater flows

STOP 1.1 SAINT-JOACHIM SECTION

From Road 138, turn right to Saint-Joachim-Cap Tourmente. The section is 1 km down from the intersection.

Paleogeography of the Saint-Joachim region, Québec: stratigraphy and sedimentology (Najat Bhiry)

Stratigraphical and sedimentological studies of three sections allow a paleogeographical reconstruction of the Saint-Joachim region, Québec. Five sedimentary units are observed in the study region. The first one (Unit I) is a till overlying striated bedrock (Section 1). The older striations on the bedrock are southward (175° - 177°). A younger set of striations indicates an ice flow toward the ESE (100°) and the last set of striations is NE (50°) (Lanoie, 1995). The second unit (Unit II) is a finely stratified marine silt and clay observed on Section 3, about 60 to 80 m below Sections 1 and 2. This clay is related to deep sedimentation in Goldthwait Sea. The third environment is represented by regressive facies, composed of massive sand that may correspond to a subaqueous marine fan (Unit III). The isostatic uplift, the availability of sediments and a distant glacial readvance may have contributed to the formation of this unit. The fourth sedimentary environment (Unit IV) is represented by marine stratified silt overlain by a littoral facies. The fossiliferous silt suggests a rising of sea level which became stable at about 10,100 y. B.P. before marine regression. The last environment was fluvial and started about 6,000 y. B.P. (Unit V, on Section 3). The FOP field trip will stop at Section 3.

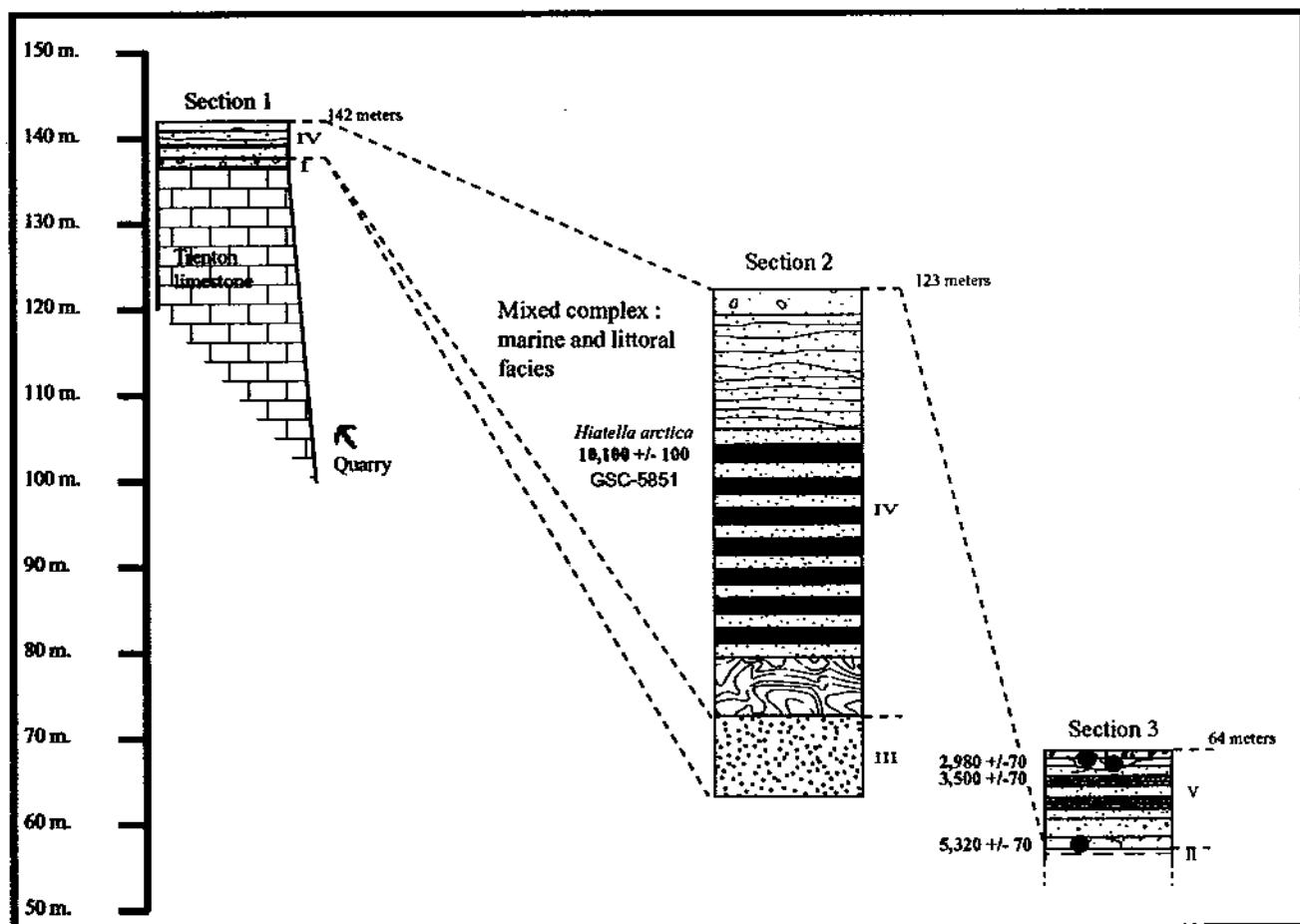


Figure 3.3 : Correlation of the three sections, Saint-Joachim.

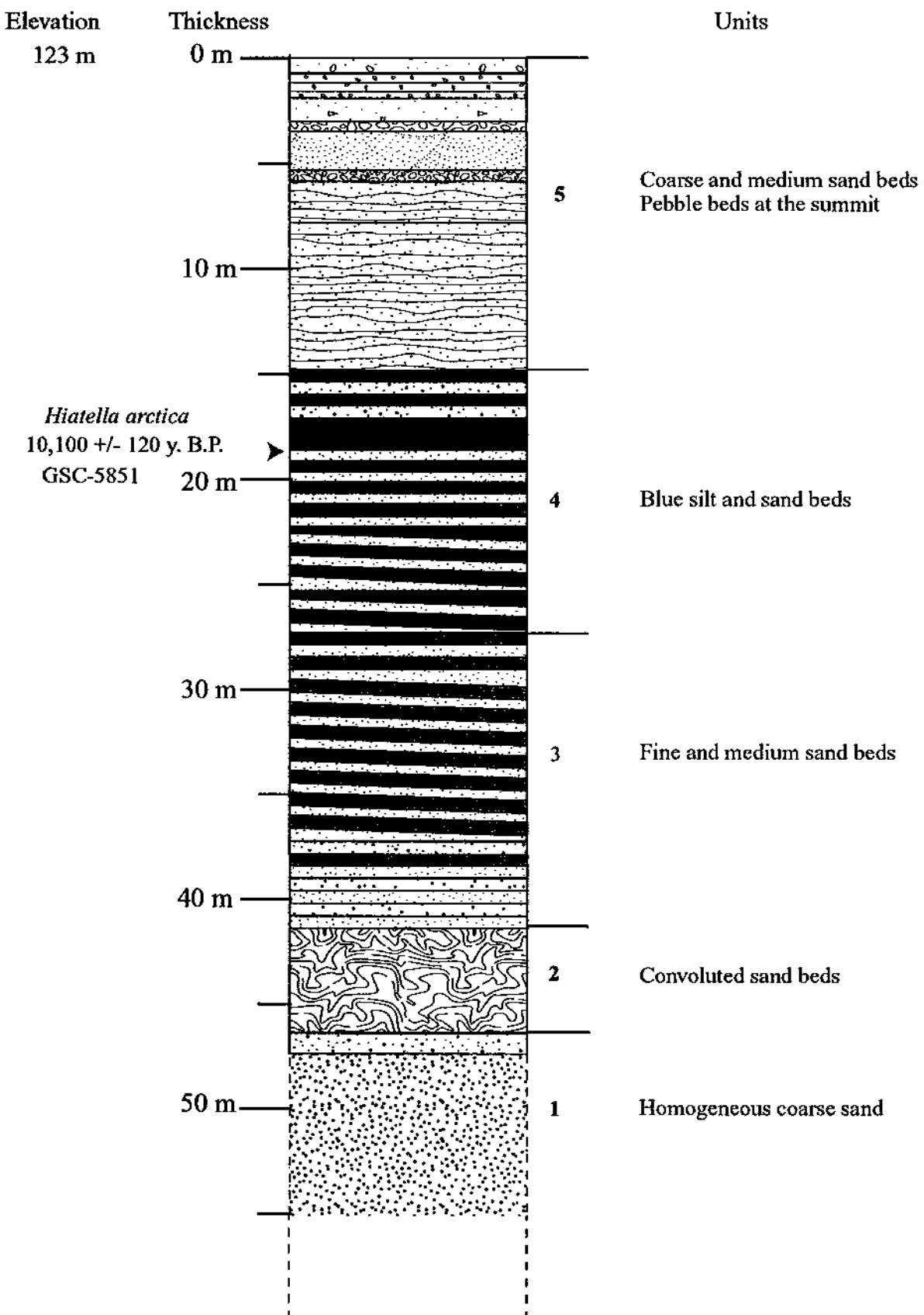


Figure 3.4: Stratigraphy of section 2, Saint-Joachim

STOP 1.2 SAINT-LÉON DELTA

From Road 138, turn left to Road 360 - Saint-Ferréol-des-Neiges, drive for 2.6 km.

(Serge Occhietti, from the MSc Thesis of Fournier, 1998)

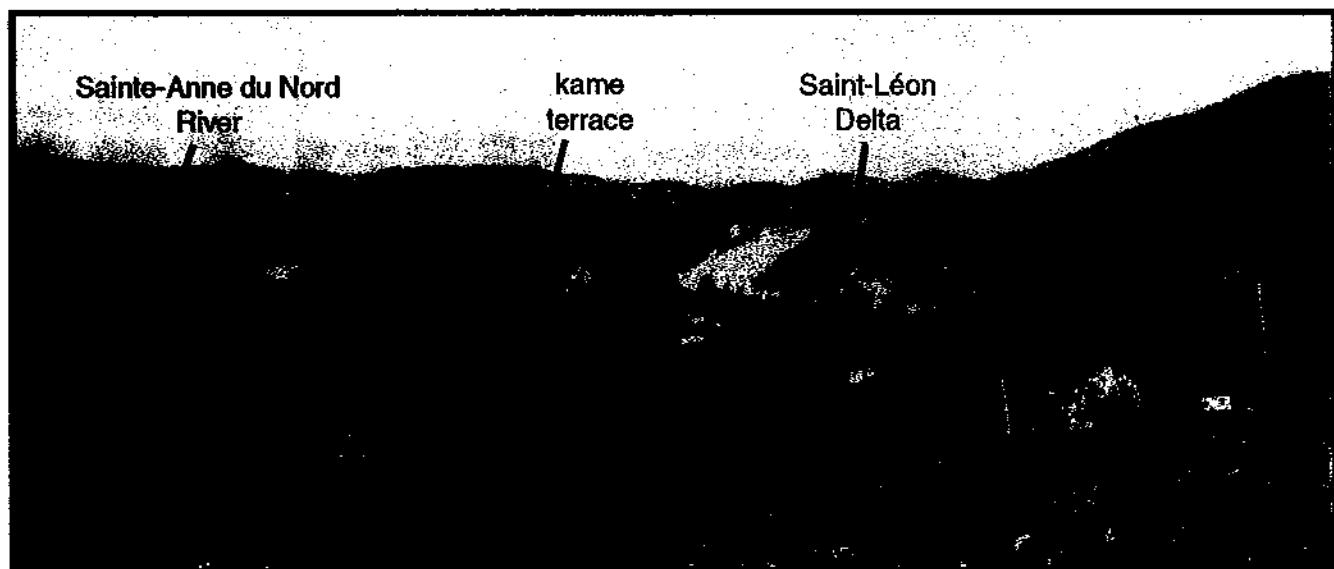


Figure 3.5: Saint-Léon Delta and kame terraces of the Sainte-Anne du Nord Valley.

At Saint-Léon, a delta is built on the left side of the Sainte-Anne River. The top of the delta is at an elevation of 360 m (1180 feet). Sedimentary structures in the sand indicate currents towards the SE (126°). The top sets are built with sub-angular gravel and cobble.

The Saint-Léon Delta is a kame-delta which indicates meltwater flows on the left side of a local ice lobe in the Sainte-Anne Valley. The elevation at the top of the delta, and of lateral kame terraces (between 370 and 390 m) on the right side of the valley, is higher than the Goldthwait Sea local upper limit at about 200 m. Several outwash fans are observed on the sides of the Sainte-Anne Valley. All these features are related to a glacial lake dammed in the lower reaches of the valley. There was still ice in the St. Lawrence Valley and middle Estuary (middle Estuary lobe) when the southern edge of Charlevoix was deglaciated.

Sedimentary clasts in outwash deposits, and outwash fans sedimented toward the Saint-Tite basin from the Ligori Ridge are other evidence of this deglaciation model (see Fig. 1.1).

STOP 1.3 LOMBRETTE SECTION

From Saint-Léon, go back to Road 138. Turn right on Road 138, drive for 300 m. The section is 0.7 km (0.4 mile) down a private road, on the right bank of Rivière Lombrette.

(Serge Occhietti, Martine Clet, and Najat Bhiry).

The Lombrette section was discovered by Fournier (1998). The section is located at the margin of the Saint-Tite topographic basin, at an elevation of between 370 and 350 m (1130-1060 feet), at the same elevation as the Saint-Léon Delta.

The following units are exposed from the bottom to the top (Fig. 3.6) :

1. Lower carbonated varves (1 to 8%), with pollen.
2. Lower carbonated till (4 to 6%), with sedimentary clasts (6%) in the lower part and apparently no sedimentary clast in the upper part. A till fabric (A and C axes) indicates a WNW origin of the ice.
3. Coarse outwash deposits with no sedimentary clasts.
4. Peat bed and wood debris (*Picea*, *Larix*) in stratified silty sand. The pollen content indicates a boreal forest (Fig. 3.7). Macrorests of *Larix laricina*, *Viola* sp., four species of *Carex*, and a few leaves of *Sphagnum* are related to a peat bog (N. Bhiry, unpublished report).
5. The diamicton is mostly matrix supported and weathered. A till fabric in the intermediate zone indicates a north-northwest source of ice.
6. Upper non carbonated rhythmites, 40 to 80 cm thick. The rhythmites are coarser at the base. The pollen content indicates a *Picea* boreal forest. About 160 rhythmites were exposed.
7. Upper non carbonated till. The till, 9.6 m thick, is matrix supported. The matrix is silty in the lower part and sandy in the upper part.

From the Lombrette Section, and others sections of the Saint-Tite area (Fournier, 1998), a distinct stratigraphy can be established. The Saint-Tite basin, which comprises the lower Sainte-Anne River Valley and the Lombrette River Valley, formed a lateral basin to the main St. Lawrence Valley Estuary. This adjacent basin records the transitional phases of glaciation and deglaciation.

During early phases of glaciation, an ice lobe expanding in the St. Lawrence dammed the Saint-Tite basin, which resulted in glaciolacustrine deposition of fine sediments of sedimentary origin.

During deglaciation, the same setting of an ice lobe in the estuary with lateral deglaciated area was repeated at least two times (Fournier, 1998). The formalisation of the units is in process.

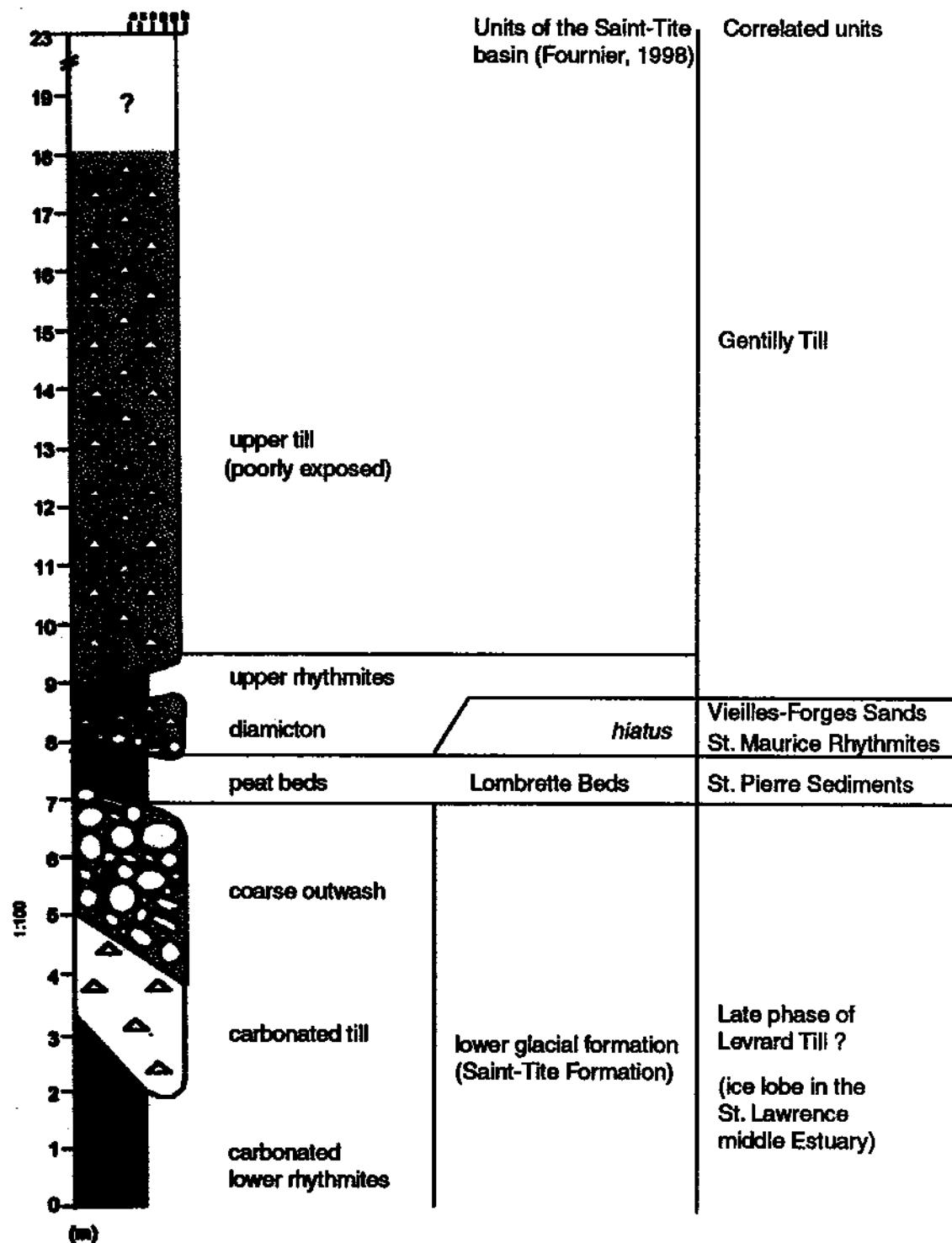


Figure 3.6 : Lombrette section, Saint-Tite-des-Caps (Fournier, 1998).

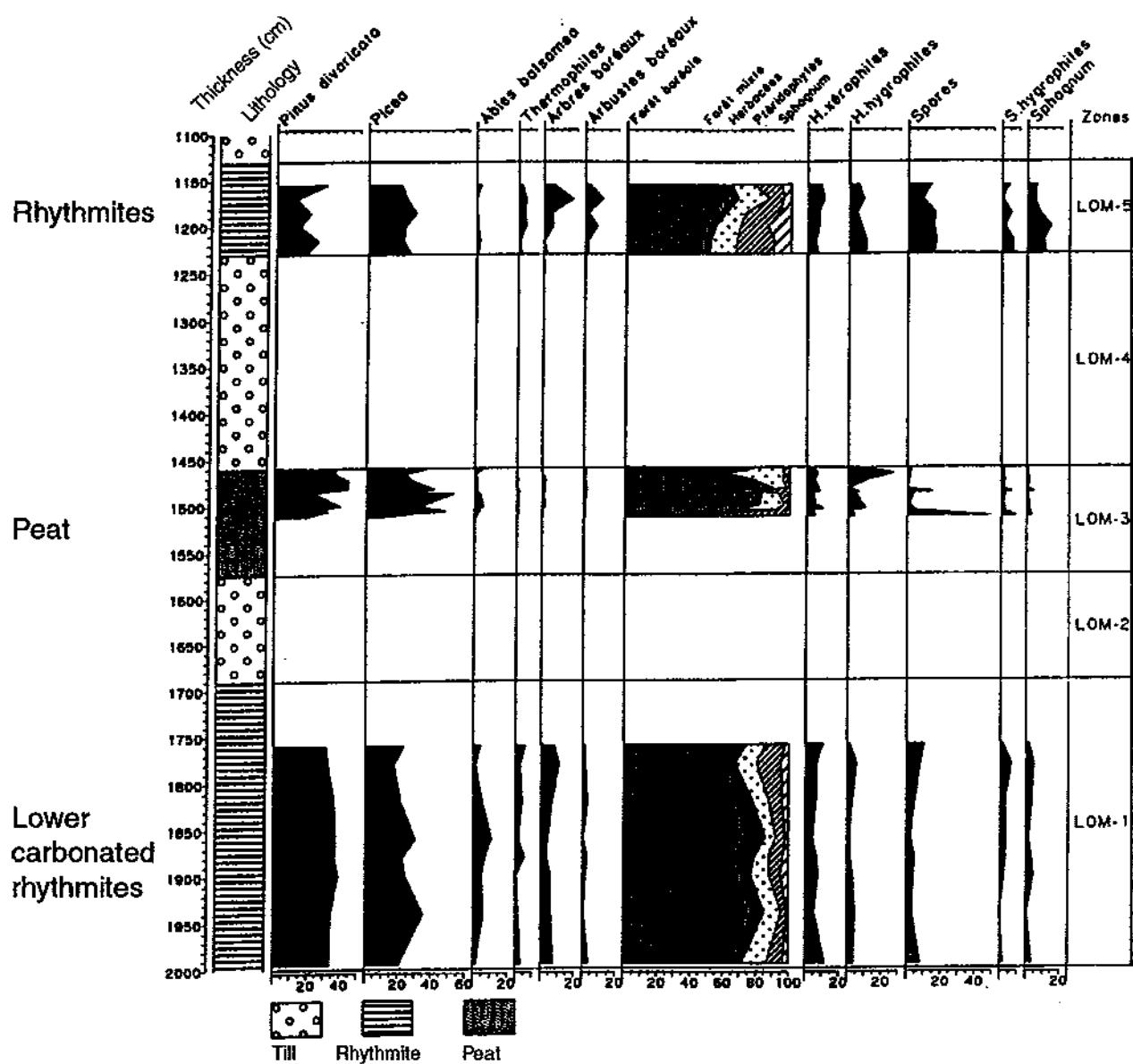


Figure 3.7 : Pollen diagram of the non glacial units of the Lombrette Section (Clet, unpublished ; Fournier, 1998). The peat bed is tentatively related to the St. Pierre Sediments.

STOP 1.4 PETITE-RIVIÈRE

Turn right on Road 138 to Petite-Rivière. Drive for 9.5 km (6 miles) until a garage. The site is located at the end of a private way, after a 200 m walk.
(Serge Occhietti, Jean-Claude Dionne and Martine Clet)

The Petite-Rivière area offers an exceptional series of data on regional and general Pleistocene – Holocene stratigraphy, and on littoral processes.

Original seismic profiles (Occhietti, S. and Long, B., unpublished) are validated by a core drilled in November 1991 (collaboration of Occhietti, S., Long, B., Dionne, J.-C., Hétu, B.).

The drilling project was initiated after a field excursion organized by J.-C., Dionne. Dionne (1996) revealed the existence of Pleistocene units along the cliff of the Mitis Terrace. The large tidal flat is eroded in pre-Late Wisconsinan units (rhythmites, till, deposits with wood fragments).

At Stop 1.4, seismic lines, the PR-91 drilling core (sedimentology and pollen analysis), exposed units along the Mitis Terrace, and origin of the megablocks on the tidal flat will be presented.

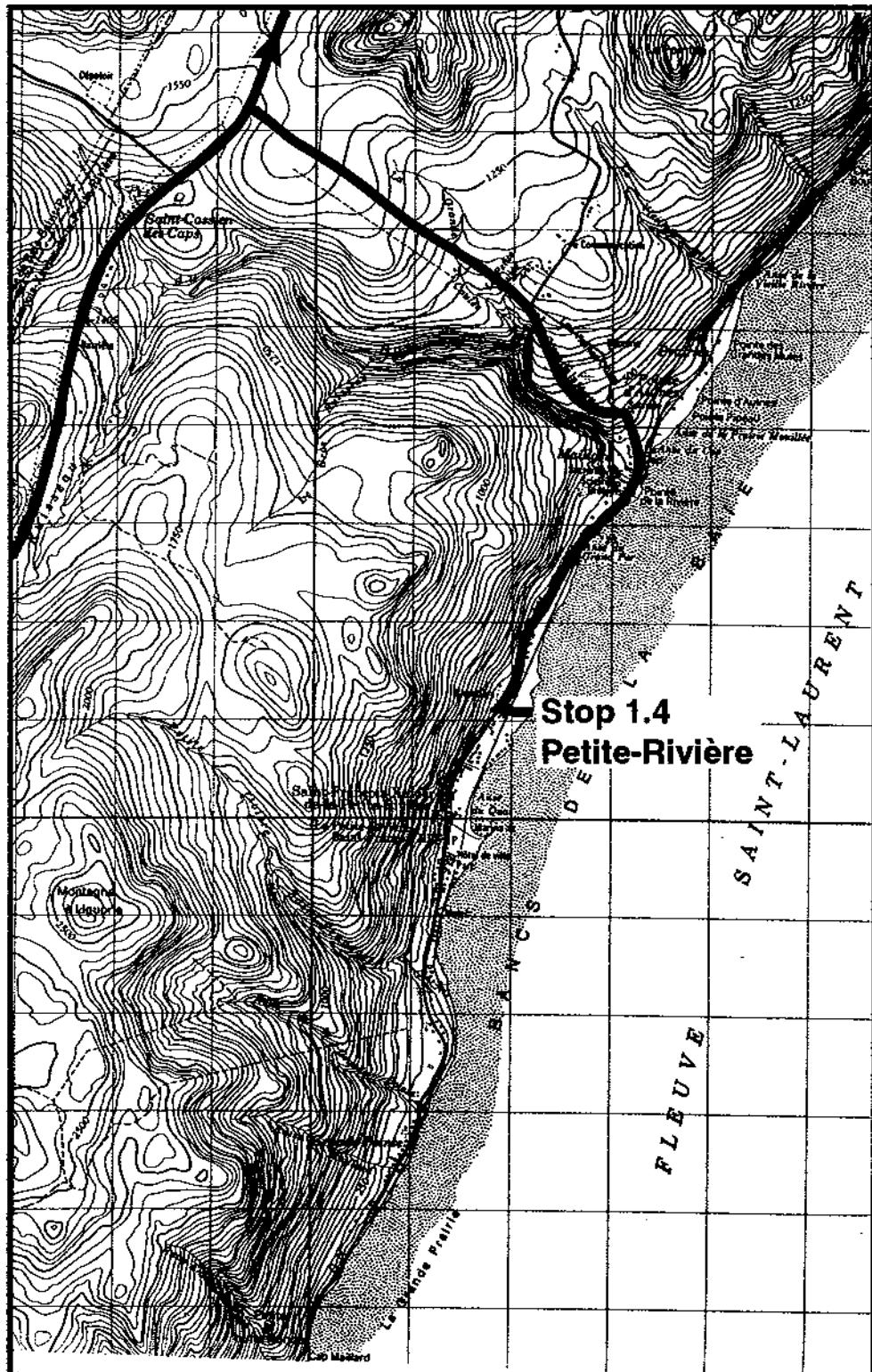


Figure 3.8 : Stop 1.4, Petite-Rivière (1:50 000 topographic map 21M/7)

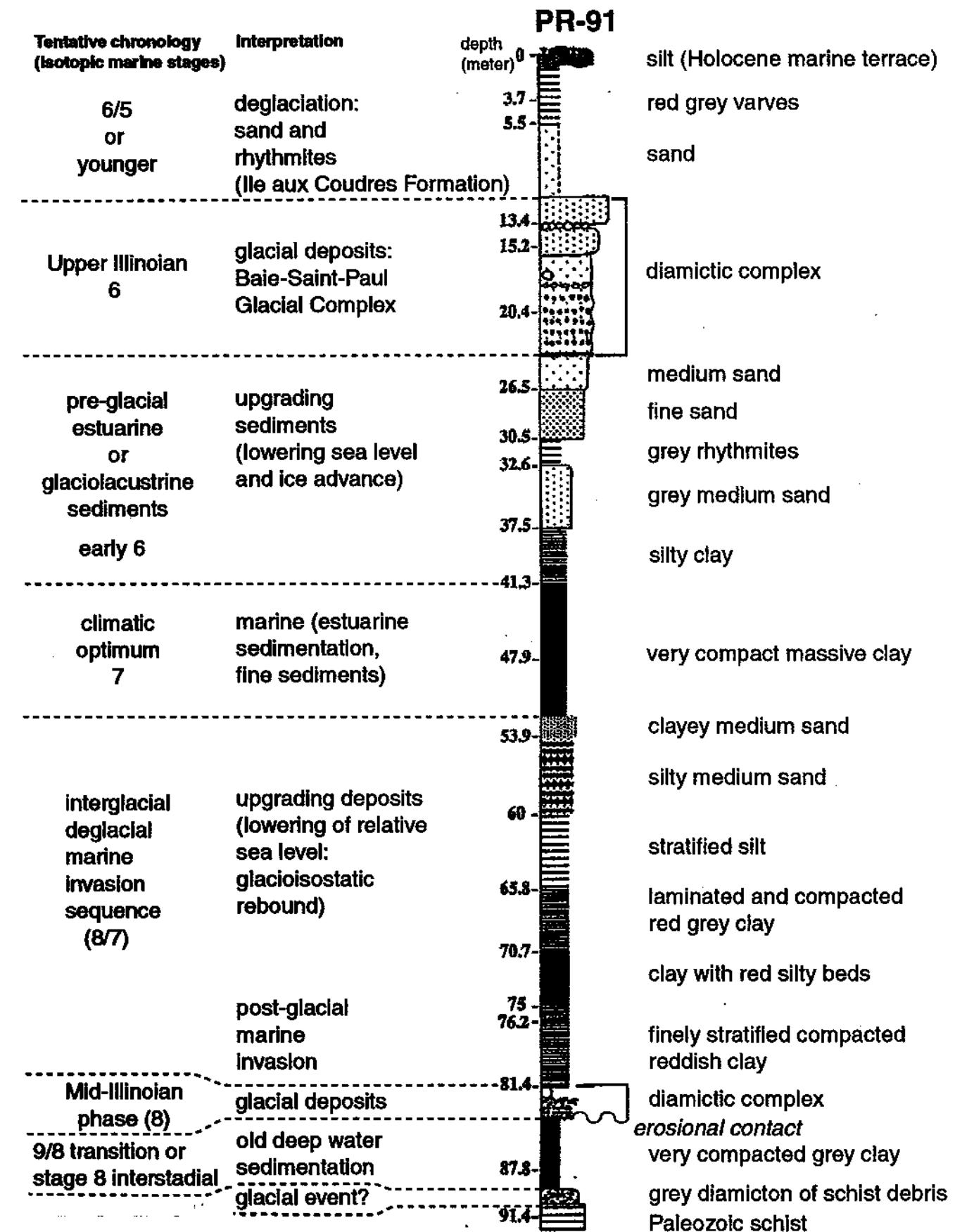


Figure 3.9 : PR-91 drilled units at Petite-Rivière and related sedimentary environments.

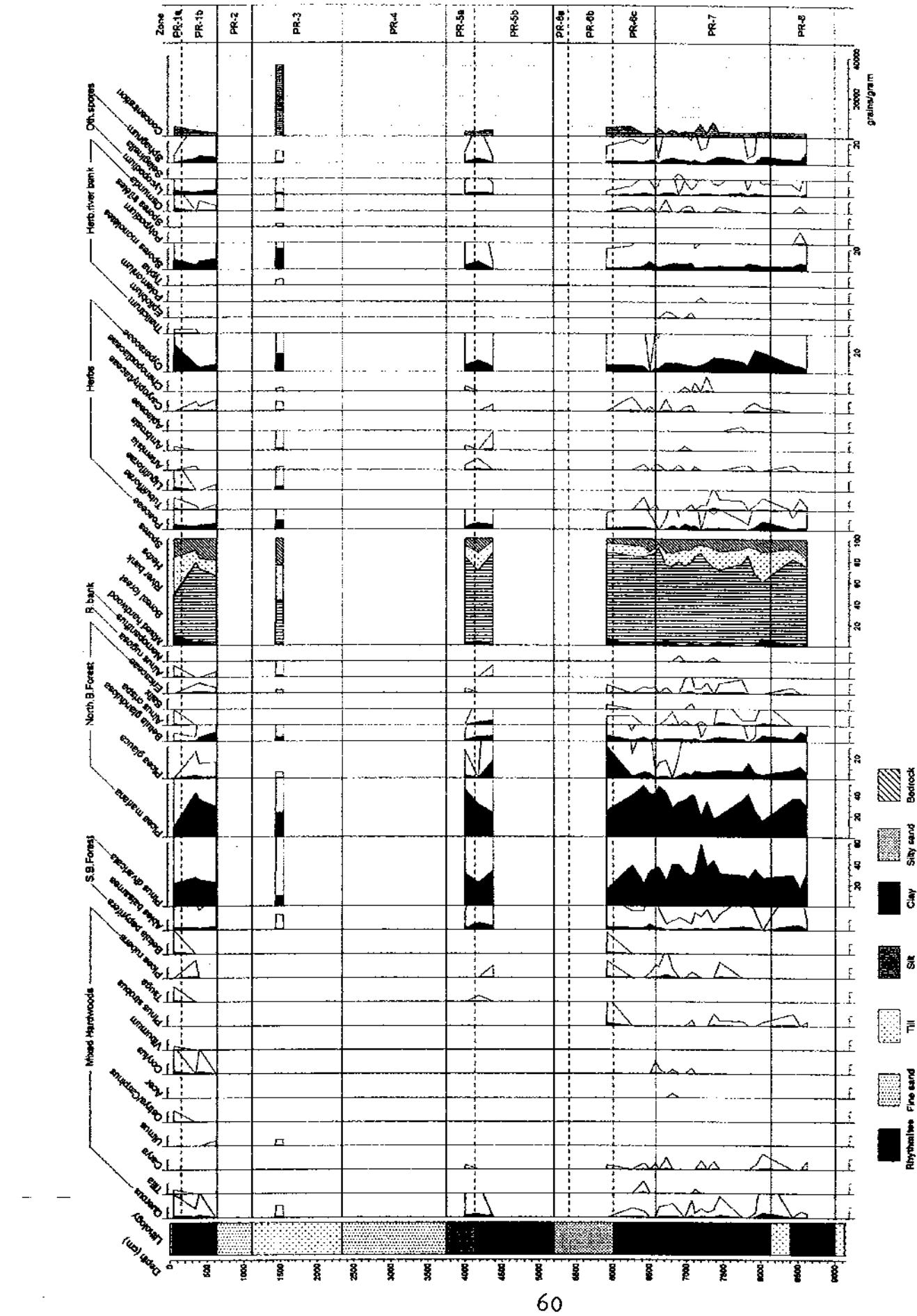


Figure 3.10: Drilled core PR-91 at Petite-Rivière. Pollen content (from Clet-Pellerin and Occhietti, 2000).

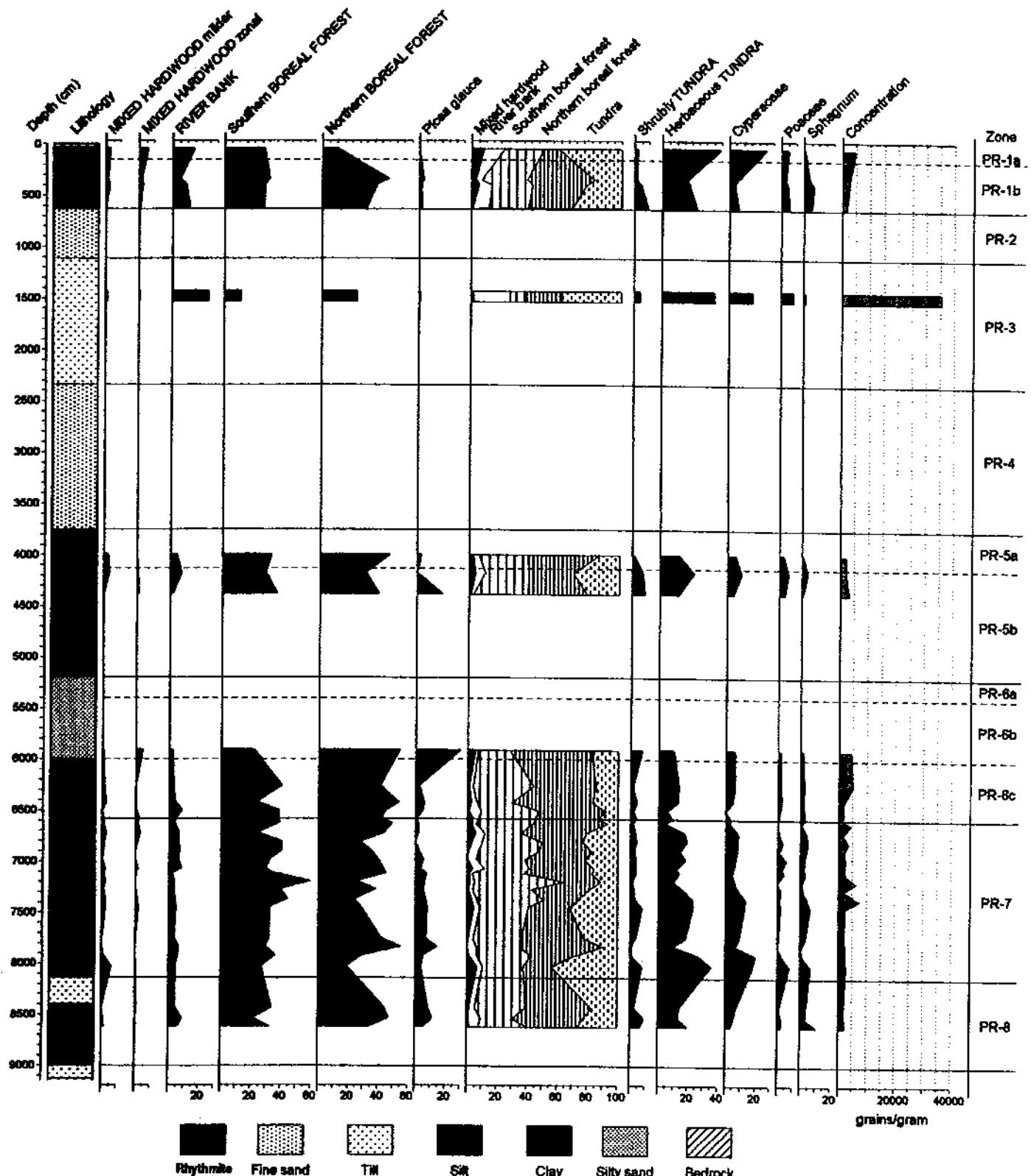
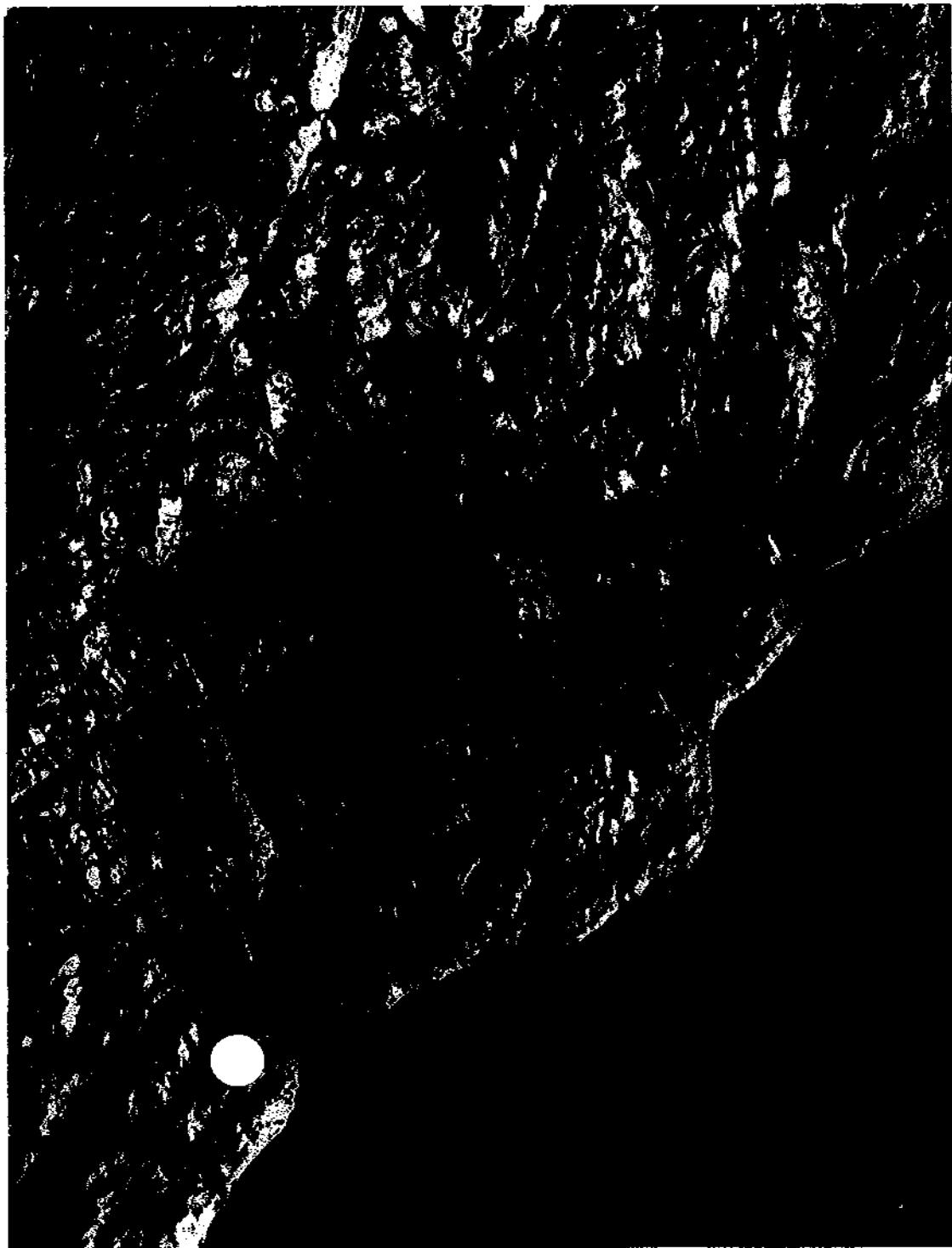


Figure 3.11: Drilled core PR-91 at Petite-Rivière: interpretation of the pollen content (Clet-Pellerin and Occhietti, 2000).

Lithologic units	PR units	Sedimentary environments	Evolution of vegetation	Climatic evolution	Events in the St-Lawrence basin	^{18}O
0 - 10 m	Soil	Holocene terrace			Holocene	1
0 - 10 m	PR-1a PR-1b	Deglaciation in lacustrine or fluvial environment?	SBF, Riv.bank, herbs NBF and SBF3 with herbs	Gradual warming		6/5e
10 - 20 m	Sand PR-2	Ice-retreat drift	NBF with herbaceous tundra	Deglaciation	Guettard Sea	6/5e
20 - 30 m	Till PR-3	Sub-glacial till	Remain of River bank with tundra	Glacial	Baie-Saint-Paul Glacial Complex Upper ILLINOIAN	6
30 - 40 m	Fine sand PR-4	Pre-Glacial estuarine or glaciolacustrine sediments		Proglacial		6
40 - 50 m	Silty clay PR-5a Massive clay PR-5b	Estuarine sedimentation Transgressive phase (rising sea level)	NBF and SBF2 with increase tundra <i>Picea glauca</i> and NBF and SBF (white spruce-fir forest)	End of climatic oscillation? Climatic optimum? Deglaciation	Early 6? Marine event?	7/6
50 - 60 m	PR-6a PR-6b PR-6c	Regressive phase (lowering of relative sea level)	<i>Picea glauca</i> and NBF and SBF (white spruce-fir forest) NBF4, SBF3 and SBF2 (southern boreal forest)	Gradual warming		7
60 - 70 m	Sand and stratified silt PR-6b Clay PR-7	Marine sediments	NBF4, SBF3 with fir NBF4, sedge margin and river bank NBF4, FT5 and sedge margin		Marine event	8/7
70 - 80 m	Clay PR-7	Post-glacial marine invasion	NFB4, sedge and herbaceous tundra			
80 - 90 m	Till Clay PR-8 Till	Glacial deposits Deep water (marine Invasion?)		Glacial Early phase of a postglacial episode	Glaciation hiatus? Interstadial of stage 8?	8
90 - 100 m	Bedrock				Old Glaciation ?	9/8 ?

Figure 3.12 : Biostratigraphy of the PR-91 drilled units at Petite-Rivière (from Clet-Pellerin and Occhietti, 2000).

**Stop 1.5 : Belvedere of Baie-Saint-Paul. General view of the Charlevoix Astrobleme (discovered by Rondot, 1970).
Oral presentation by a guide of Randonnée Nature Charlevoix.**



**Figure 3.13 : Original Radar map by Robert Desjardins,
Département de géographie, UQAM.**

Charlevoix and Sudbury as gravity-readjusted impact structures

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Abstract—On the basis of detailed field investigations and the study of impact breccias at the Charlevoix impact structure (Québec), a structural analysis is given. This analysis shows that the annular arrangement of both topography and lithology can be applied to subdivide the two craters discussed in this review. Successive rings characterize the central uplift and its collapsed ring graben in the Charlevoix structure.

Fault breccias show an annular distribution and indicate diverse directions of movement suggesting progressive readjustment. They formed cohesionless products inside fault planes, named mylonithenite, and are believed to have acted as lubricants during the modification stage of the formation of the structure: listric readjustment by gravity after the formation of the transient crater.

The Sudbury Structure (Ontario) shows fault breccias in a concentric arrangement similar to that of Charlevoix. It may be compared with the Charlevoix structure by applying the same mechanical readjustment model with deep listric faults. The only difference is the amount of the rise structural uplift, that is, the height of central uplift, which is less important in the larger impact structure.

INTRODUCTION

Most well-preserved large planetary impact structures are characterized by a well-defined rim and a depressed, rather flat interior with internal features (central peak, peak ring, etc.). Undulatory or hydrodynamic models are generally used to explain the modification stage of large structures, for instance, by means of acoustic fluidization of the target (Melosh, 1977, 1989). However, it has also been suggested that crater modification occurs by displacement of large crustal masses along deep faults, doubling the diameter of the transient cavity (Rondot, 1970; Spray and Thompson, 1995; Melosh, 1996; Dressler and Sharpton, 1997).

Charlevoix, 360 Ma old and 56 km in diameter, is located on the southeastern edge of the Canadian Shield, 100 km northeast of Québec City, Québec. It has been partly preserved from erosion by a relatively recent isostasy of this part of the shield. Geological mapping of the Charlevoix area and diverse studies related to its origin have taken place since 1964 (Rondot, 1994). The Sudbury Structure, 1850 Ma old and more than 200 km in diameter, is located inside the Canadian Shield, 350 km north of Toronto, Ontario. The impact structure has been deformed by the Penokean Orogeny and heavily eroded. Numerous studies have been done since the first mining discovery of large Ni–Cu ore bodies (e.g., Giblin, 1984; Stöffler *et al.*, 1994). A multiring nature for the Sudbury Structure has been proposed (Deutsch *et al.*, 1995).

A comparison between the Charlevoix structure and other impact structures displaying numerous similarities has shown that two genetic models, one with complete and the other with incomplete crater readjustment, can be applied (Rondot, 1994). A study of fault breccia specific to the impact structure and the geomorphology of the Charlevoix structure yielded details on its geomorphometry believed to be the result of the modification stage of the impact process (Rondot, 1998). The purpose of this paper is to compare the Charlevoix and Sudbury impact structures on the basis of a study of specific faulting before, during, and after the impact event. A simple gravity readjustment model, which implies movement of large rock masses along deep listric faults towards the transient crater center, is applied to both structures.

GEOMORPHOLOGICAL OBSERVATIONS

Charlevoix

The Charlevoix structure straddles the Canadian Shield and the Appalachian Thrust. Between the two, in a narrow and deep corridor, most of the allochthonous breccias have been eroded (Rondot, 1994). The northwestern part of the structure is in the Precambrian shield, whereas the southeastern part is mostly under water in the Saint-Lawrence River. Recent, postglacial isostasy of the whole area is indicated by strong relief, numerous rivers, waterfalls, and rapids. An almost continuous stratigraphic cross-section of the structure is exposed in shoreline outcrops along the Saint-Lawrence River.

Topographically, the northwestern part of the structure shows two major features: a ring graben and a central uplift (Fig. 1). Table 1 lists the terms and their definition used in this paper. The altitude of the Laurentian plateau outside the crater is more than 1000 m above sea level, that is, above the Saint-Lawrence River. The paleosurface, with its cover of 150 m of Ordovician limestone at the time of the impact, is estimated at 1290 m above sea level (Rondot, 1994). The rim of the crater is well outlined by cliffs and defines the apparent diameter of the structure of $D = 56$ km. Hereafter, measurements will be given as decimal fractions of the crater diameter (D) for horizontal as well as vertical measurements. The ring graben is deepest, 17.9 ± 1 km from the crater center, at $0.64 D$, where relics of Ordovician cover of the old Precambrian plateau are exposed. A ring of small hills, ~600 m above sea level, occurs in the outside of the central uplift. Relief of the central uplift is irregular and the central peak reaches 768 m above sea level.

At Charlevoix, the contact between the crater basement and overlying allochthonous fallback breccias and impact melt (crack filling excepted) is the excavated crater floor. Based on empirical relations, the diameter of the transient crater was ~28 km (0.5 D ; Rondot, 1970). The thickness of rocks eroded on the Laurentian Plateau is estimated at 250 m (70 m of breccia cover, 150 m of Ordovician limestone, and 20 to 50 m of Precambrian rocks). It is of the same order inside the crater. The excavated crater floor is seen in two outcrops (in "inner depression" in Fig. 1), where small impact-melt layers are preserved (Rondot, 1971). These remaining

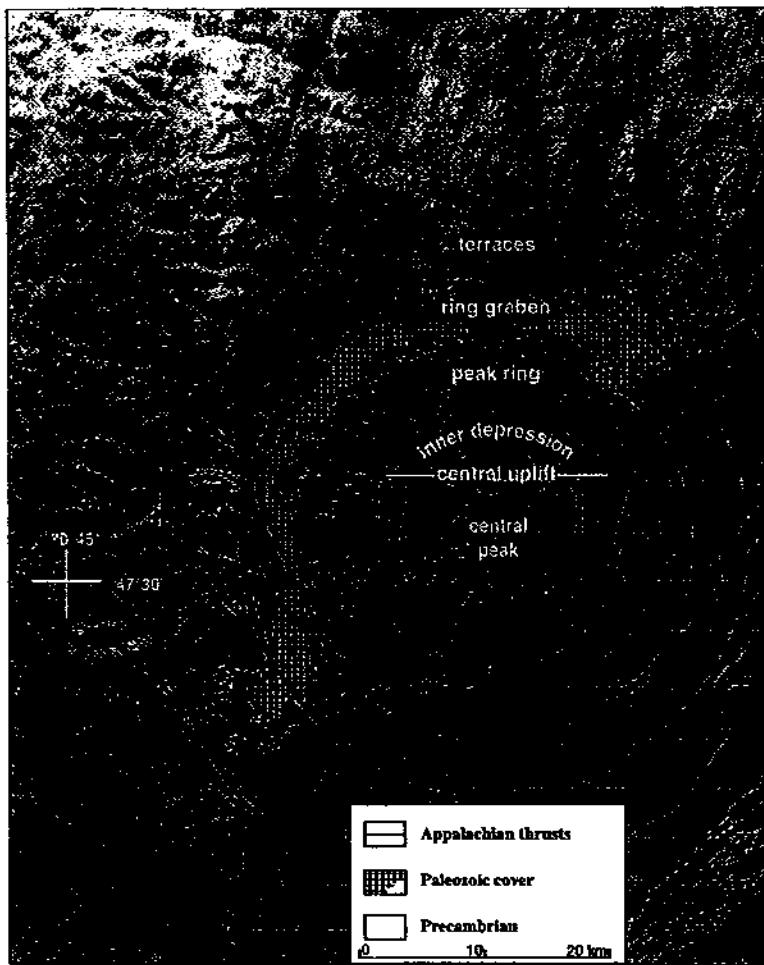


FIG. 1. (left) Relief model of the Charlevoix impact structure illustrating its six morphological annular zones (modified from Rondot, 1994). Abbreviations: SLF = Saint-Laurent normal fault; LL = Logan thrust fault. Black triangles represent impact-melt rock outcrops. See Table 1 for definitions and text for details.

outcrops are located in a topographically depressed region in the border of the central uplift, at 420 and 440 m above sea level, respectively 8 and 10 km from the center of the structure inner ring ($0.32 D$; Fig. 1). This elevation (420 m above sea level) represents the deepest part of the excavated crater floor, however, due to collapse, the ring graben is now at the lowest level. In the center of the structure, the excavated crater floor was uplifted by ~ 5 km (from the estimated bottom of the excavated crater to the present summit of the central peak).

Morphological Elements Description

At Charlevoix, the topography, crater floor, and the Precambrian–Paleozoic contact help to define six zones inside the final crater rim. These zones, from the rim toward the center are as follows (Fig. 2).

The Terraces Ring—Here, large masses of internally undisturbed rocks are downthrown in steps, to reveal a Precambrian–Paleozoic contact with outward facing dips. The first downthrown mass defines the apparent diameter D .

The Ring Graben—Forms an annular depression where the Precambrian–Paleozoic unconformity is at sea level and even below it. The ring graben is outside the transient crater because the thin Paleozoic cover is downthrown but undisturbed. In its deepest parts, rock masses are downfaulted more than 1.3 km ($0.02 D$; Rondot, 1970). Undeformed masses of rocks are of

TABLE 1. Impact features terminology used in the text and their definitions.

Morphology (cf., Fig. 1)	
Rim	Final crater border corresponding to the D value.
Terraces	Step-like collapsed ground along the outer margins of the final structure.
Ring graben	Rocks around the periphery of the transient crater collapse downward and inward along concentric faults, also the same as annular trough.
Peak ring	Ring of hills with a diameter exceeding that of the central uplift.
Inner depression	Small depressed ring inside and in the border of the central uplift.
Central uplift	Deep-seated rocks beneath the center of the transient crater that are uplifted.
Central peak	Topographic high within the central uplift.
Parautochthonous fault breccias	
Pseudotachylite	Network of dark veins, typically <1 cm wide, of rocks and minerals powder in a glassy or aphanitic matrix, often accompanied by high-pressure polymorph such as coesite and stishovite. Small displacement.
Myiolithenite (fault breccia dyke)	Irregular, anastomosing, and dyke-like bodies, abundant and widespread (0.1% of the whole structure), containing numerous large and small angular and rounded inclusions of target rocks and breccia set in a colored matrix of powder of rock and crystals. In the largest impact structures (Sudbury and Vredefort), the matrix is melted and black. (B-type pseudotachylite, Martini, 1991). See text for details.
Allogenic rocks	
Suevite	Melt-fragment breccias composed of discrete fragments of rocks and minerals, together with bodies of melt, in a clastic matrix of similar but finer-grained materials.
Impact melt	Melted rock occurring in stratiform or dyke-like bodies.
Basal breccia	Chaotic mixture of fine and coarse polymictic breccia deposits, usually without fused fragments, outside of the transient crater.

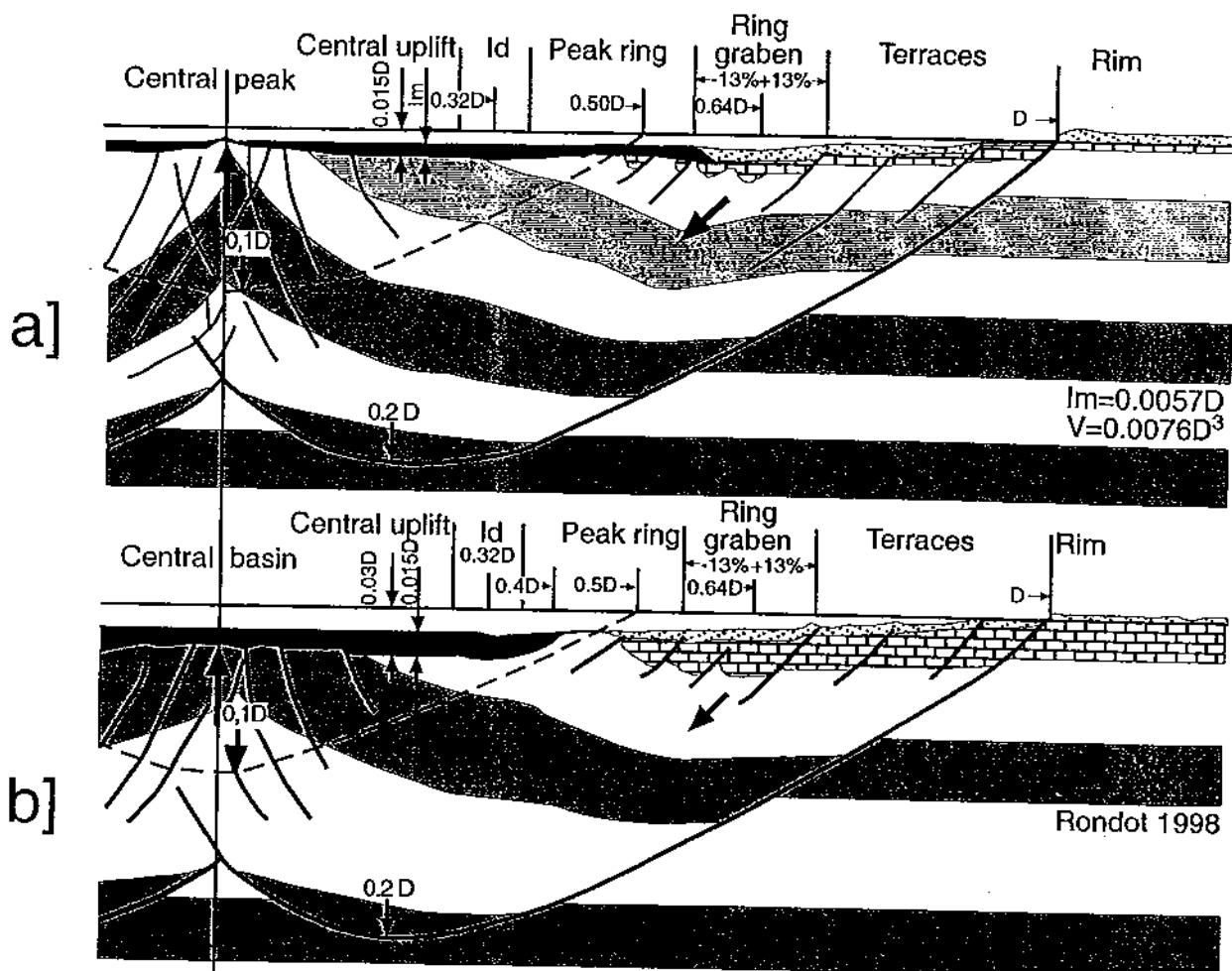


FIG. 2. Schematic cross-sections for readjusted impact structures 20 to 100 km diameter: (a) based on Charlevoix, Manicouagan, Carswell, and Gosses Bluff measurements; (b) based on Ries (after Fig. 40 of Pohl *et al.*, 1977). Abbreviations: D = apparent diameter of the structure which is the basis of all measurements; $0.5 D$ = diameter of the excavated crater (transient crater); Im = impact-melt rocks and breccia in black; V = volume of the excavated crater; dotted = allogenic breccia; bricks = preimpact sedimentary cover; stripes indicate hypothetical horizontal layers in the basement; dashed line represents the level of the excavated crater floor; Id = inner depression.

relatively small size in the ring graben (one square kilometre at the most).

A Ring of Hills or Peak Ring–Rock masses show relatively little vertical displacement. Small hills form a ring at about half the diameter of the structure, between the collapsed ring graben and the central uplift.

The Inner Depression Ring—This unit contains remains of layered impact-melt rocks mentioned above and represents the crater floor currently at the lowest elevation, which is still uplifted. Its diameter is about the diameter of the transient cavity.

The Central Uplift—The central uplift shows blocks of rocks that are shock metamorphosed and uplifted in a series of steps causing stratigraphic repetition.

The Central Peak—A topographic high within the central uplift. Blocks may be hundreds of meters wide.

These six zones outline a succession of rings and, as just described, are expressed by topography and the layout of structural units.

Comparison with Other Astroblemes

Several craters exhibit patterns similar to those of the Charlevoix structure (Fig. 2a; Table 2). The Manicouagan structure

has a thick impact-melt sheet and annular collapsed remnants of the Paleozoic cover (Currie, 1972). An inner depression contains lakes and Memory Bay, and in the ring graben is a spectacular annular lake. The Siljan and Charlevoix structures have about the same size (58 and 56 km; Table 2), but the Paleozoic cover of Siljan is thicker (Rondot, 1975). The Carswell structure (Saskatchewan) has a well-developed ring graben (Carswell Formation), and an uplifted central granitic core, 18 km in diameter. The granitic core at Carswell has the relative diameter of the inner depression of Charlevoix. An ~2 km thick sequence of sandstone, with a steep dip, appears between this core and the annular Carswell Formation (Currie, 1969). The West Clearwater structure (Québec) has no evident central peak but does contain rings similar to Charlevoix. At Gosses Bluff structure in central Australia, the same observations are made. A 900 m thick unit of Hermannsburg Sandstone occurs between the outcrops of the stratigraphically lower Parke Siltstone and of the stratigraphically underlying Brewer Conglomerate (Milton *et al.*, 1978). However, the well-known Ries structure in Germany, with central basin, presents a somewhat different geomorphometry. Its schematic cross-section deduced from geophysical studies (Pohl *et al.*, 1977) shows features similar to Charlevoix: terraces, ring

TABLE 2. Measurements estimated or measured for some impact structures.

	Manicouagan Qc Canada	Siljan Sweden	Charlevoix Qc Canada	Carswell Sk Canada	W-Clearwater Qc Canada	Ries Germany	Gosses Bluff Australia
Age (Ma)	214 ± 1	368 ± 1.1	357 ± 15	115 ± 10	290 ± 20	15 ± 1	142.5 ± 0.5
Apparent diameter (D, km)	88	58	56	52	32	26	23
Erosion minimum from original ground (m)	650	700	190	720	290	weak	315
Target composition	C (S)	C S	C (S)	S C	C (S)	S C	S
Diameter (km) of the lowest part of the ring graben	56.36	35.8	35.8	32.4	20.5	16.6	15

Adapted from Rondot (1994), Table 3. Age from Grieve *et al.* (1995). Apparent diameters are from Rondot (1994); they are based on the estimation of the first collapsed terrace. Grieve *et al.* (1995) give other values, based on the most recent publications. Diameter of the lowest part of the ring graben are measured from the geological maps, except for the West-Clearwater, by the deepest part of the lake, and the Ries as shown in Fig. 40 of Pohl *et al.* (1977). Numbers in bold are observed or measured values; others are estimated values.

Abbreviations: Qc = Québec; Sk = Saskatchewan; C = crystalline; S = sedimentary; (S) = thin Ordovician cover.

graben, peak ring (hills), and a small inner basin filled with suevite (up to 40% of the total diameter, a little thicker near the 0.32 D mark inner depression) and a small central uplift. Whereas at Charlevoix the top of the central peak is at 0.009 D of the old level of the surrounding plain (Fig. 2a), at Ries the central bottom of the crater is at 0.026 D (Fig. 2b). Differences with the Charlevoix cross-section are probably attributable to incomplete readjustment (Rondot, 1994). It may be due to the thick porous sedimentary cover of the Ries. The deficiency of effectiveness in vertical movements may also be due to the obliquity of the meteorite trajectory (Pierazzo and Melosh, 2000).

DISCUSSION

Can this Model be Applied to the Sudbury Structure?

Target rocks of the Sudbury Structure are Archean granitoids, gneisses, and greenstones, unconformably overlain by metavolcanic and metasedimentary rocks of the Proterozoic Huronian Supergroup (Dressler, 1984a). The present distribution of these rock types possibly provides some insight related to the modification stage of the Sudbury impact process. The preimpact Archean-Huronian unconformity deepened to the southeast. An irregular arc of Huronian outliers to the northwest, in an area less disturbed by the postimpact Penokean deformation, helps define a center for the structure (Fig. 3). On the other hand, the presence of Sudbury Breccia ("pseudotachylite") as far as 100 km northeast of that point (Perey and Morrison, 1984; Spray and Thompson, 1995) allows the estimation of a diameter of at least 200 km for the structure (D); 220 km is proposed by Stöffler *et al.* (1994), 200–250 km by Deutsch *et al.* (1995). If we apply the relative measurements of Fig. 2b, we see that the Sudbury Igneous Complex (SIC), considered as impact melt (Deutsch *et al.*, 1995), is almost completely within the limits of the inner depression ring of the Charlevoix model and completely within the 0.4 D diameter of the inside suevite basin part of the Ries model. A thickness of ~3000 m for the SIC has been given by Deutsch *et al.* (1995), including the impact-melt breccias of the Basal Member of the Onaping Formation. This compares well with the estimate for the Ries (up to 400 m thick in the Ries; Engelhardt and Graup, 1984) with a diameter of 26 km or 0.015 D

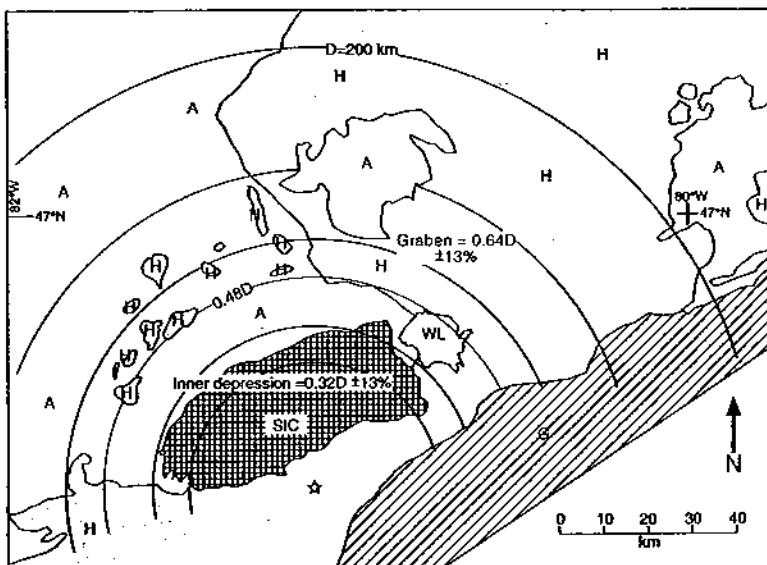


FIG. 3. Simplified geological map of the Sudbury Structure area. The different circles centered in the southwest end of Kelley Lake (star) correspond to the limits of the inner depression ring, the ring graben, and the final diameter of the structure. The 0.4 D circle corresponds to the position of the limit of outliers in other impact structures (e.g., Ordovician in the Siljan structure, Sweden; Rondot, 1975). Abbreviations: A = Archean basement; H = Huronian volcanic and sedimentary cover; SIC = Sudbury Igneous Complex and Basin; G = Grenville province; WL = Wanapitei lake impact structure.

(Fig. 2b). In the Sudbury Basin, the crystalline target rocks were melted to produce the SIC; whereas at the Ries, the porous sedimentary part of the target (carbonates) are believed to have devolatilized at an impact pressure >18 GPa (Vizgirda, 1982). At Sudbury, the northwest ring of Huronian outliers is not in the graben zone but nearer to the estimated center (Fig. 3). The Sudbury-Cobalt map-sheet 2188 of the Ontario Department of Mines shows a large number of faults in the vicinity of the graben ring of Fig. 3, as expected for the graben zone (see also Butler, 1994).

Role of Fault Breccia of the Target in the Modification Stage

At Charlevoix, like in all large impact structures, important structural displacements have occurred: a collapse of Ordovician limestone vertically displaced in the ring graben at about 0.02 D , as

is expressed in Fig. 2a and an uplift at $0.09 D$ in the center (Rondot, 1994). At the Ries, vertical displacements are different, approximately $0.015 D$ in the ring graben and $0.07 D$ for the central uplift (from figures of Pohl *et al.*, 1977; and von Engelhardt and Graup, 1984). At Charlevoix, it seems that movements were focussed only in narrow fault breccia zones (cf., Table 1) commonly using preexisting zones of weakness such as faults or joints, or contacts between different types of rocks. Here, two types of fault breccia are recognized: small veins of pseudotachylite in the center up to the limit of the shatter-cone zone with small displacements, and wide breccia dykes in main fault zones of the whole structure. Such special types of breccia are named "mylolithenite" from *μυλόν* mill, because the rock is finely crushed like flour, and *θαράσσω* to slide, because they are fault breccias and are characterized by the presence of fragments of earlier breccias (breccias in breccia; Rondot, 1989).

Pseudotachylite characterized by a fine network of black glassy, crystalline, or aphanitic matrix are widespread in the vicinity of major deep-seated faults, visible in deeply eroded terranes (Sibson, 1975; Macaudière and Brown, 1982; Killick *et al.*, 1988). Shand (1916) was the first to describe thin veins of pseudotachylite formed *in situ* in the center of the Vredefort structure that he compared to similar rocks found "in the neighbourhood of well-marked fault-planes" of India and Scotland. Martini (1991) distinguishes these thin, dark veins that contain coesite and stishovite (A-type) from the younger great larger breccia (B-type) up to several meters thick, filled with dark aphanitic material.

The term mylolithenite was introduced in 1971 (Rondot, 1989) to designate a special type of fault breccia composed of fragments, angular or rounded, derived from the surrounding rocks in a colored matrix composed of fine powder of the rocks or minerals. There is a progression between fault breccia and breccia dykes, some escaping into fractures in the vicinity of the main fault. A study of the mylolithenite dykes in the Charlevoix structure shows that they contain a highly variable proportion of allochthonous fragments, which on average amount only to 1 vol%. Schwarzman *et al.* (1983) found also various proportions of xenoliths in some breccias of the Vredefort structure. At Charlevoix, these dykes represent about 0.1 to 0.5 vol% of the whole coherent target (Rondot, 1998). Dykes are more abundant in the vicinity of the ring graben and inner depression. The diversity of breccia fragments, their small size, and roundness of the larger fragments imply crushing and abrasion. The presence of various breccia fragments in the vicinity of the breccia dykes and diverse directions of slickensides proves several and successive movements along faults (Fig. 4). A few dykes may be followed for some distances, but generally they are broken and displaced by later dislocations and pinched out to reappear farther. Hydrothermal alteration is observed in the rock in the vicinity of some dykes.

Sudbury Breccia (called "pseudotachylite" by Spray and Thompson, 1995) shows the same distribution as the mylolithenite of Charlevoix. They are abundant near the SIC, which corresponds to the inner depression (Fig. 3), and at some distance from the SIC corresponding to the ring graben (see also Dressler, 1984b).

Model of Modification Stage

Readjustment for Charlevoix is initiated by compression faulting just after the passage of the shock

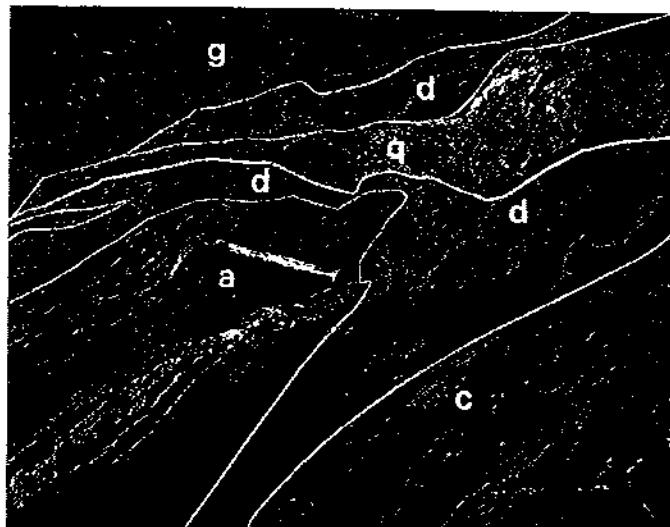


FIG. 4. Example at Charlevoix of successive dislocations in a narrow zone near a fault separating Ordovician limestone and Precambrian gneiss normally separated by at least 100 m of sediments. Mylolithenite dyke (d) (between white lines) separate Precambrian amphibolite (a) and Ordovician limestone (c). Cambrian quartzite (q) and arkosic sandstone (g), both formations located stratigraphically between the amphibolite and limestone, are found overlying the amphibolite. All are separated by the same aphanitic mylolithenite with fragments of earlier breccia (breccia in breccia).

wave (Rondot, 1970). The subsequent movements (modification stage) tend to reduce the relief and level the target rocks along deep listric faults, and the mylolithenites acted as cohesionless material during the readjustment phase. There is thickening of strata by tectonic repetition in the ring graben and in the central part of the structure where the crater floor is uplifted. Figure 5 illustrates the proposed successive effects during an impact event. A modification stage in which breccias were formed by successive gravity-driven ground movements along listric faults better explains the observations made at various impact structures than a gigantic crustal wave of the whole target as proposed in the hydrodynamic model. In the proposed readjustment model, the inner ring of hills (peak ring) between the collapsed and uplifted rocks is not much displaced and represents a zone of few breccia dykes.

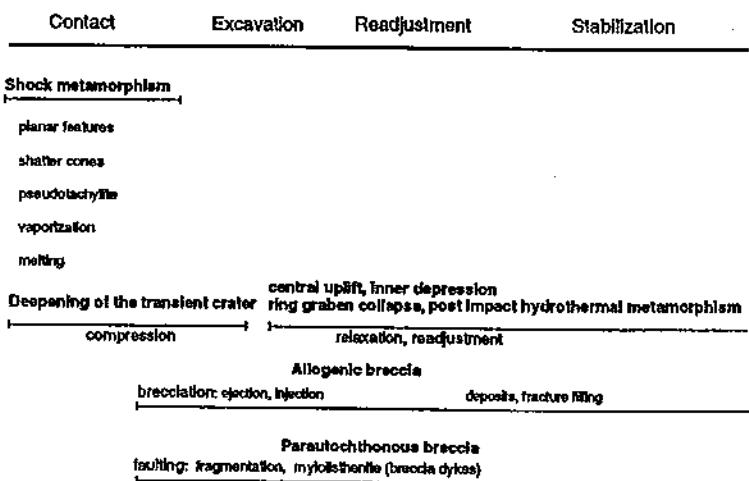


FIG. 5. Schematic distribution with time, from left to right, indicated by the various impact cratering stages, of shock metamorphic, geological, and morphological elements at impact structures.

CONCLUSIONS

A simple model of gravity-driven readjustment along deep listric faults with temporarily cohesionless breccias applies to the Charlevoix and Sudbury impact structures. A zone of little brecciation, ("a zone of silence"; Dressler, 1984b) between the Huronian outliers and the brecciated zone near the SIC (Dressler, 1984a) is at the same relative distance from the center as Charlevoix ring of hills and the Ries crystalline ring. This "zone of silence" may be considered as an ancient peak ring now eroded. The basin occupied by the SIC is proportionally the same as that of Ries.

Acknowledgments-Thanks are due to Danielle and Michel Rondot and Kamal Sharma for their help in the preparation of the manuscript. I express my gratitude to Burkhard Dressler, A. Deutsch, John G. Spray, Alan R. Hildebrand, Hadyn Butler, and an anonymous reviewer for improvements of the text and helpful corrections.

Editorial handling: A. Deutsch

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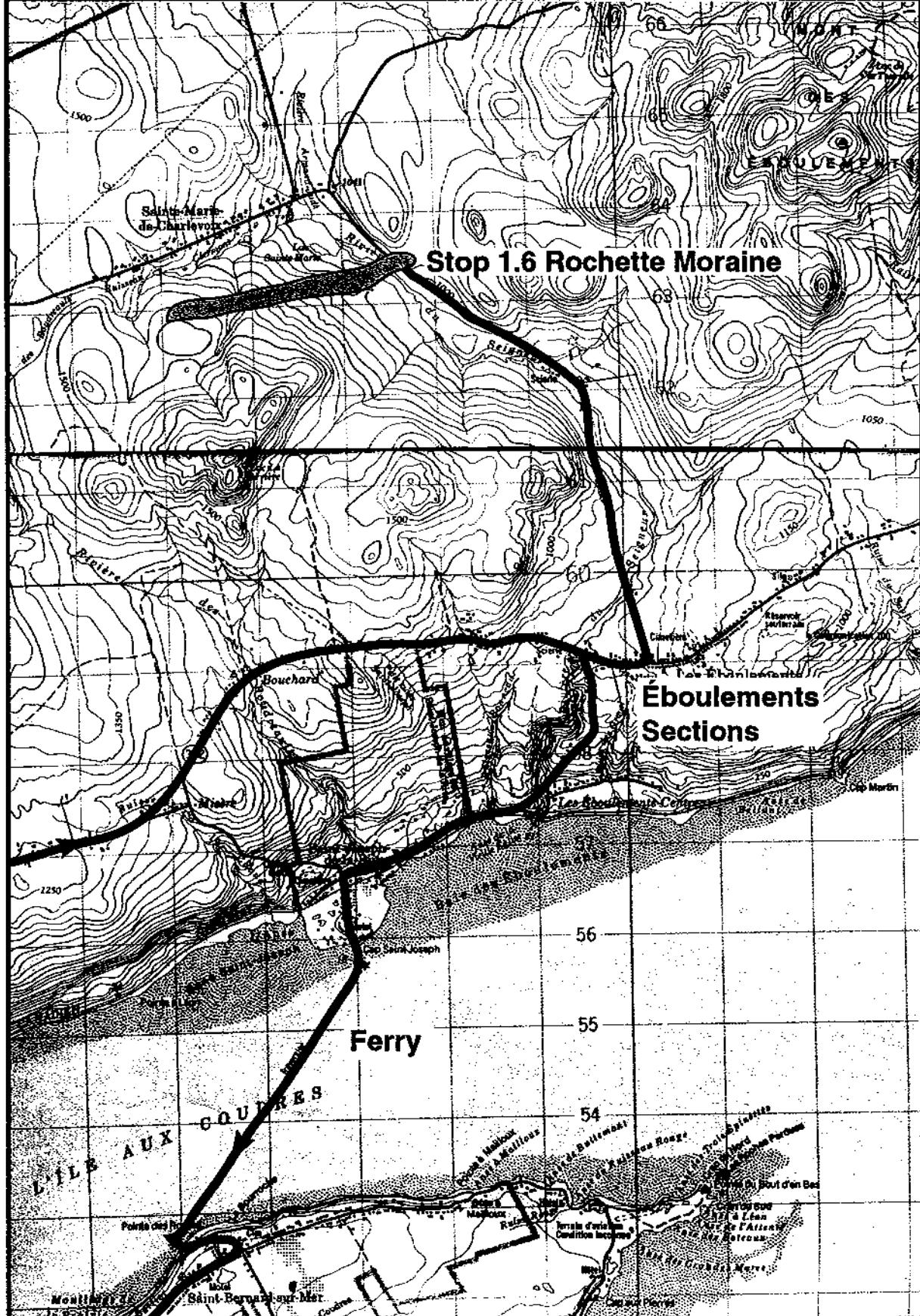


Figure 3.14 : Stop 1.6 Rochette Moraine. Location of the Rochette Moraine ridge from Rondot (1974). (1:50 000 topographic maps 21M/8 and 21M/9).

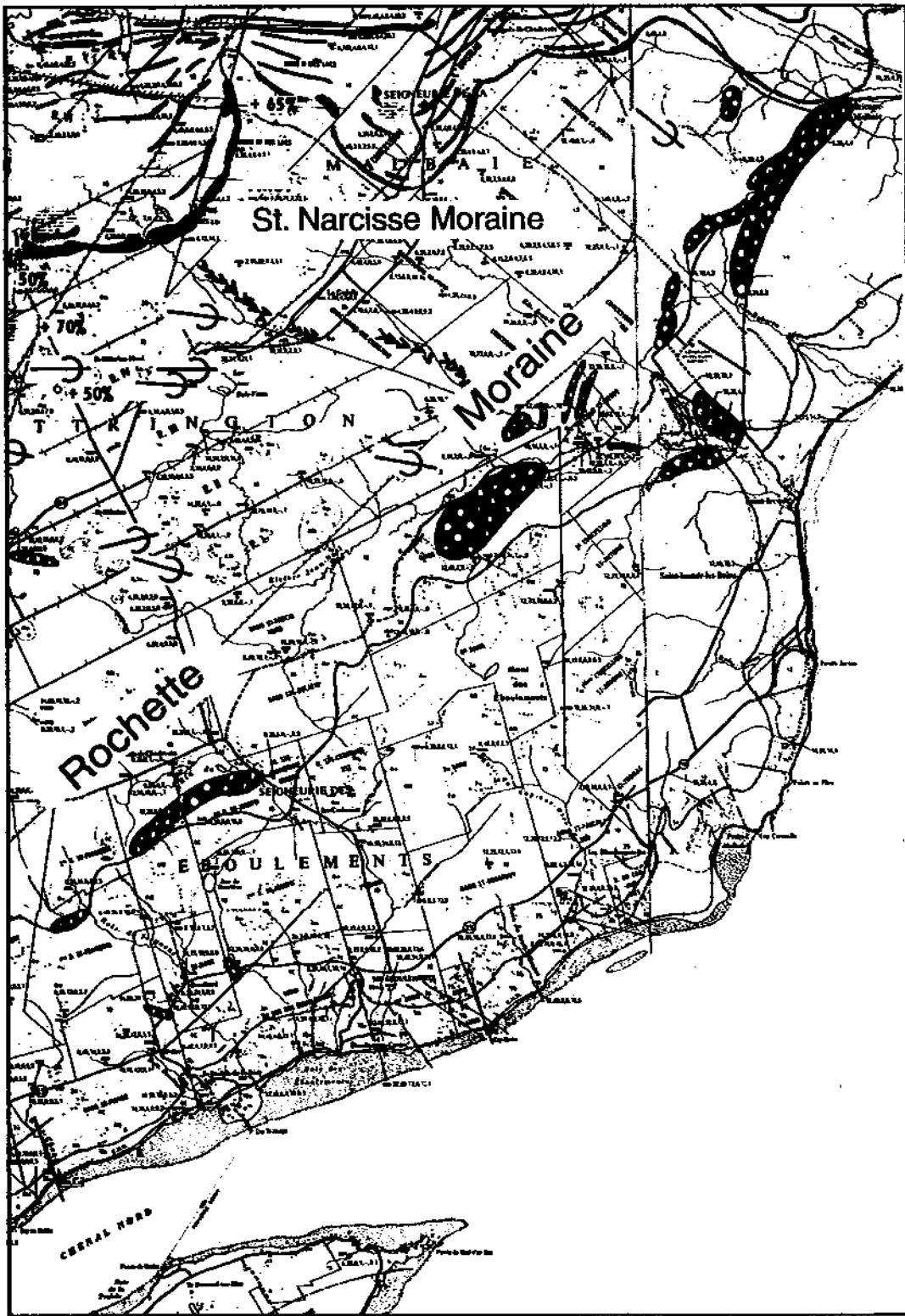


Figure 3.15 : Rochette Moraine mapped by Rondot (1974).

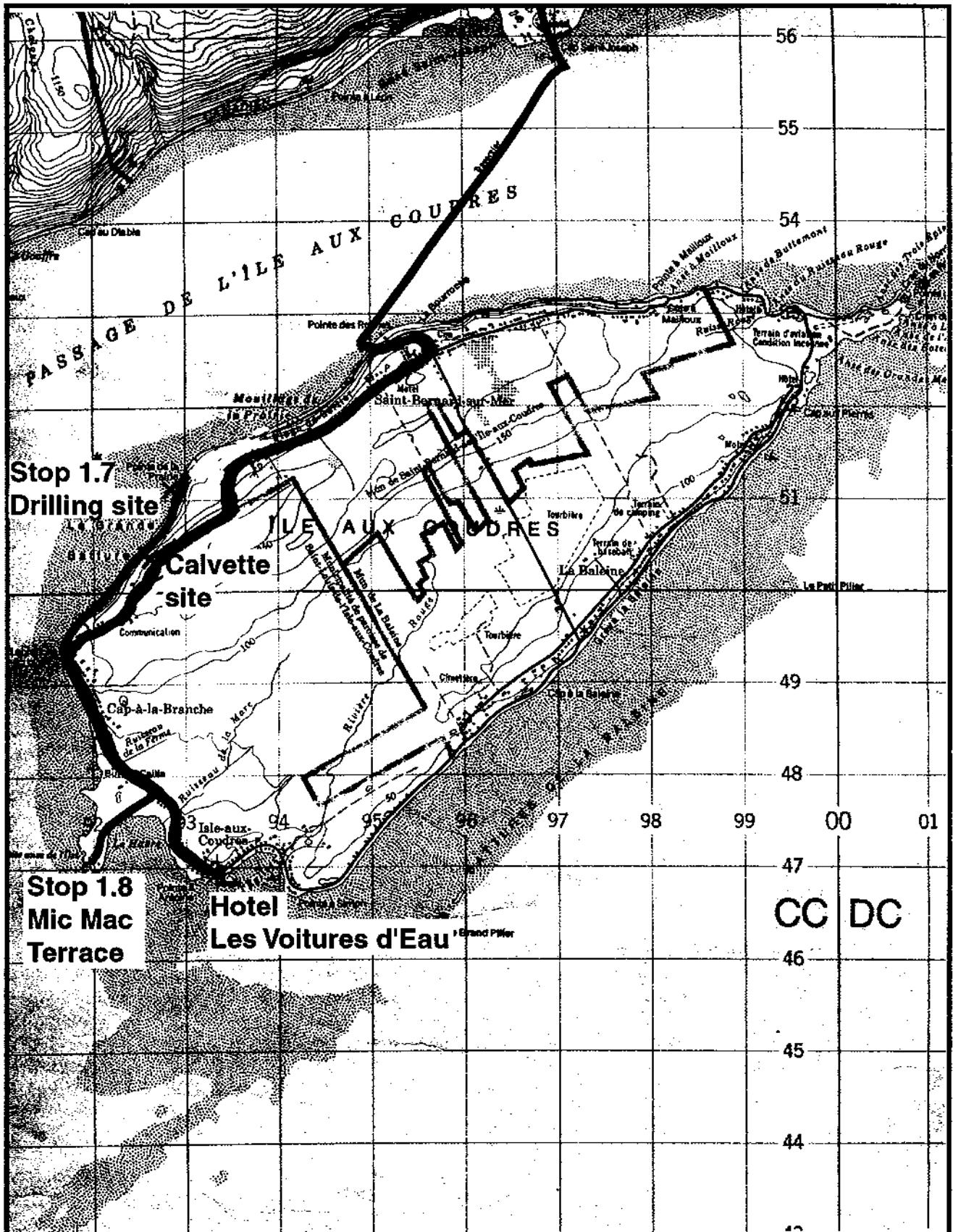


Figure 3.16 : Stops 1.7 and 1.8, Ile aux Coudres (1:50 000 topographic map 21M/8).

STOP 1.7 ILE AUX COUDRES

The Calvette site is located on the NW coast of Ile aux Coudres, beside the Grande Batture gravel road, 1.5 km (1 mile) from the main road.
(Serge Occhietti, Martine Clet and Jean-Claude Dionne).

Brodeur and Allard (1985) published the first and very detailed study on the Pleistocene units exposed on the NW cliffs of Ile aux Coudres.

This discovery initiated preliminary seismic profiles below the tidal flat edge by Jean Vésina and his colleagues from the Department of Transportation of Québec. The seismic profile, limited to a depth of 160 m, did not reach the bedrock.

In june 1990, seismic survey lines were shot by the research group of the Geological Survey of Canada, using high resolution seismic reflection (see the reprint by Todd et al. 1991).

Funding was raised from several sources (UQAM, Université du Québec à Rimouski, Université du Québec Network, individual research grants from the National Sciences Research Council of Canada) to finance a drilling (S. Occhietti, B. Hétu, B. Long, J.-C. Dionne and J.-M. Lancery). J.R. Drilling Ltd, from Hadashville, Manitoba, drilled the units as deep as 155 m, using the rotasonic technique. The drilling team was exceptional and went beyond the usual limits of the rotasonic technique. Unfortunately, below 400 feet, casing of the hole is not possible and the deeper samples could not be recovered.

At stop 1.7, a summary on the exposed and drilled Pleistocene units will be presented.

It must be mentioned that the Ile aux Coudres drilling core is the second example of a detailed sedimentary marine sequence of the transition between glacial stage 6 and the climatic optimum of substage 5e. The other example is located in the Kattegatt Sea, north of Danemark (Seidenkrantz and Knudsen, 1994). The Ile aux Coudres drilling core gave the evidence that most of the tidal flats on the north side of the St. Lawrence middle Estuary are eroded in Sangamonian or interstadial units.

Previous seismo-stratigraphic works of D'Anglejan and Brisebois (1974) and Praeg and Syvitsky (1989) based on the assumption that the tidal flats were eroded in Goldthwait Sea post-glacial clays can now be revised.

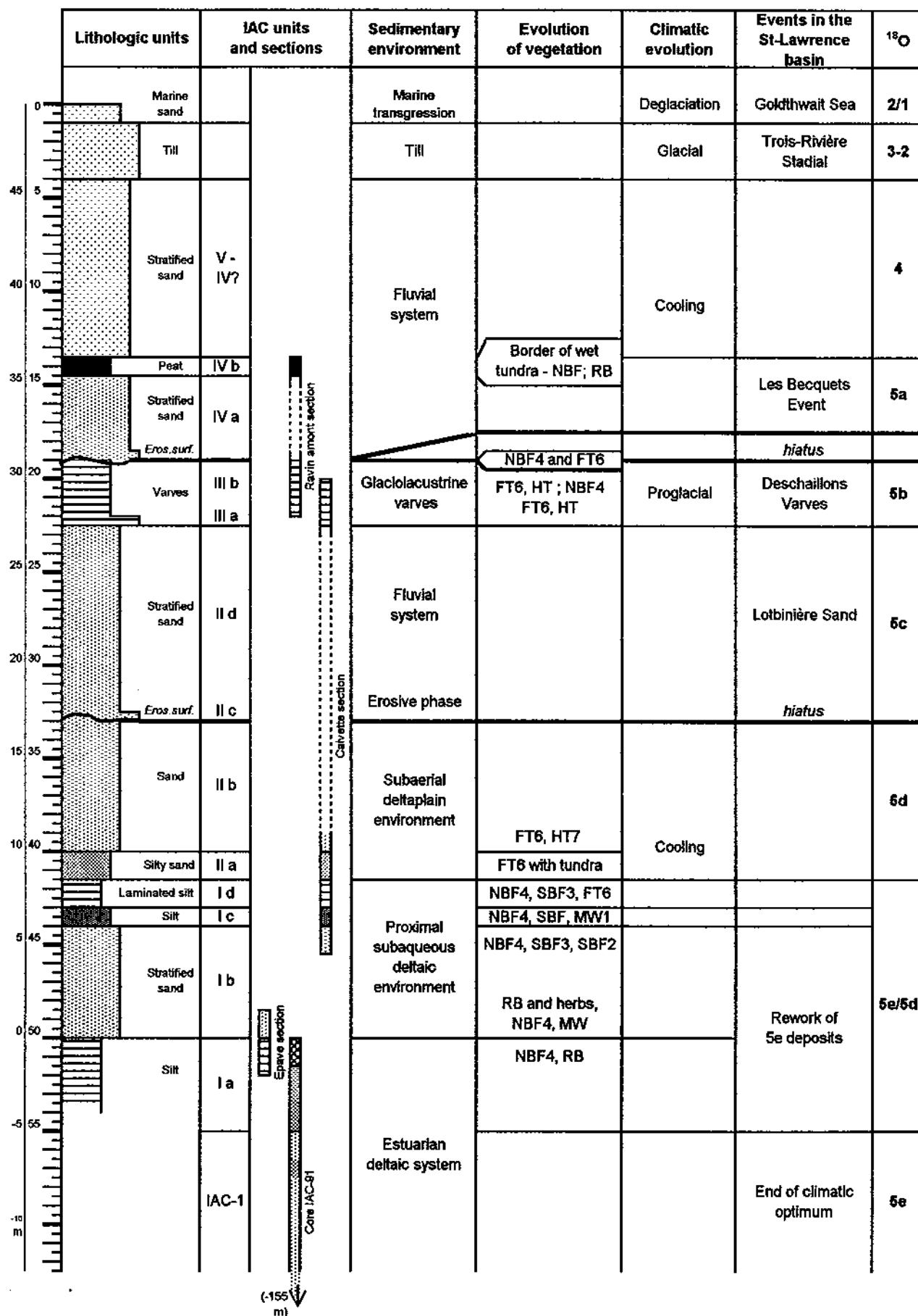


Figure 3.17 : Biostratigraphy of the Ile aux Coudres exposed units (from Clet and Occhietti, 1995)

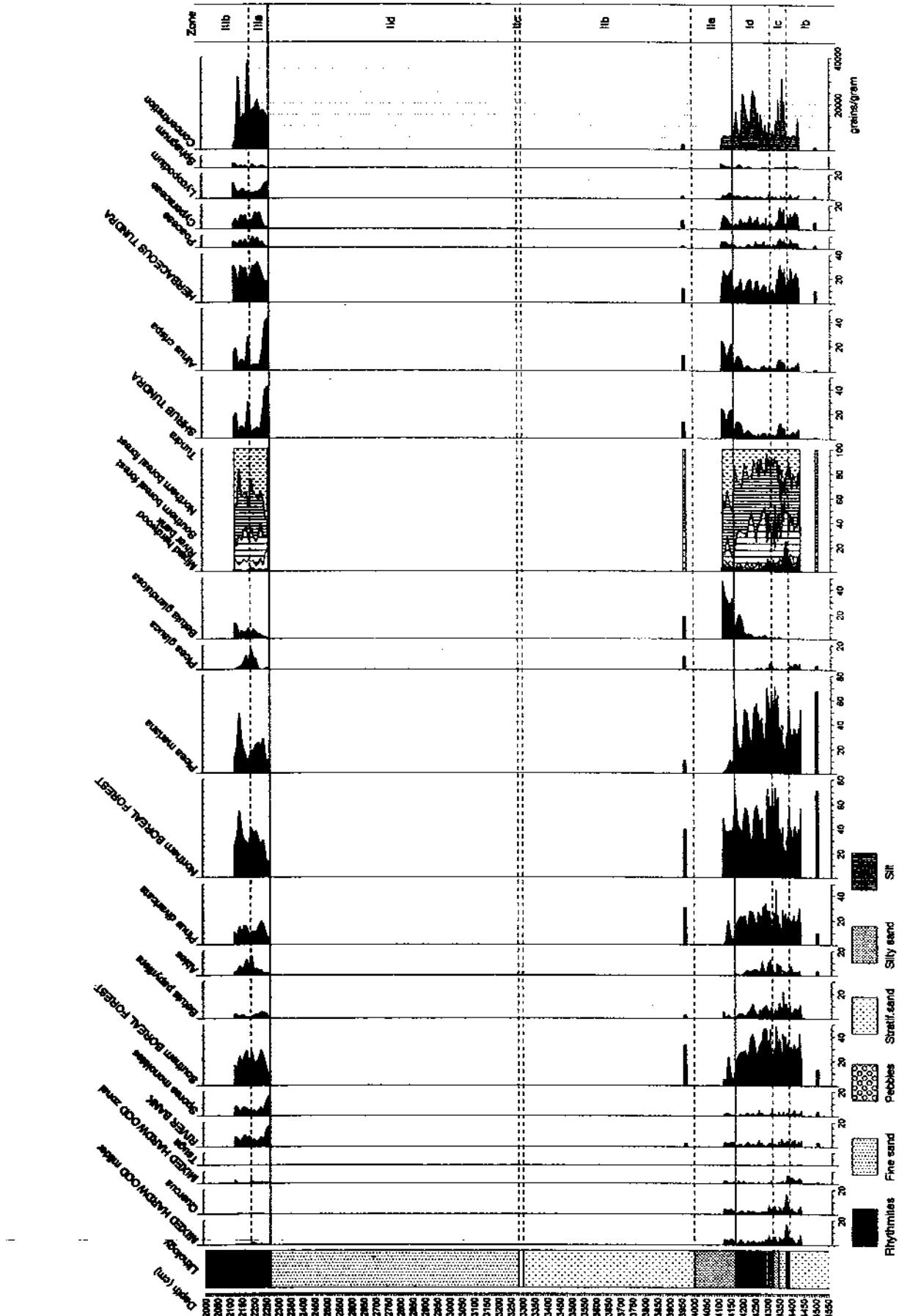


Figure 3.18: Pollen analysis of the fine grained units at the Calvette Section, île aux Coudres (from Clet and Occhietti, 1995).

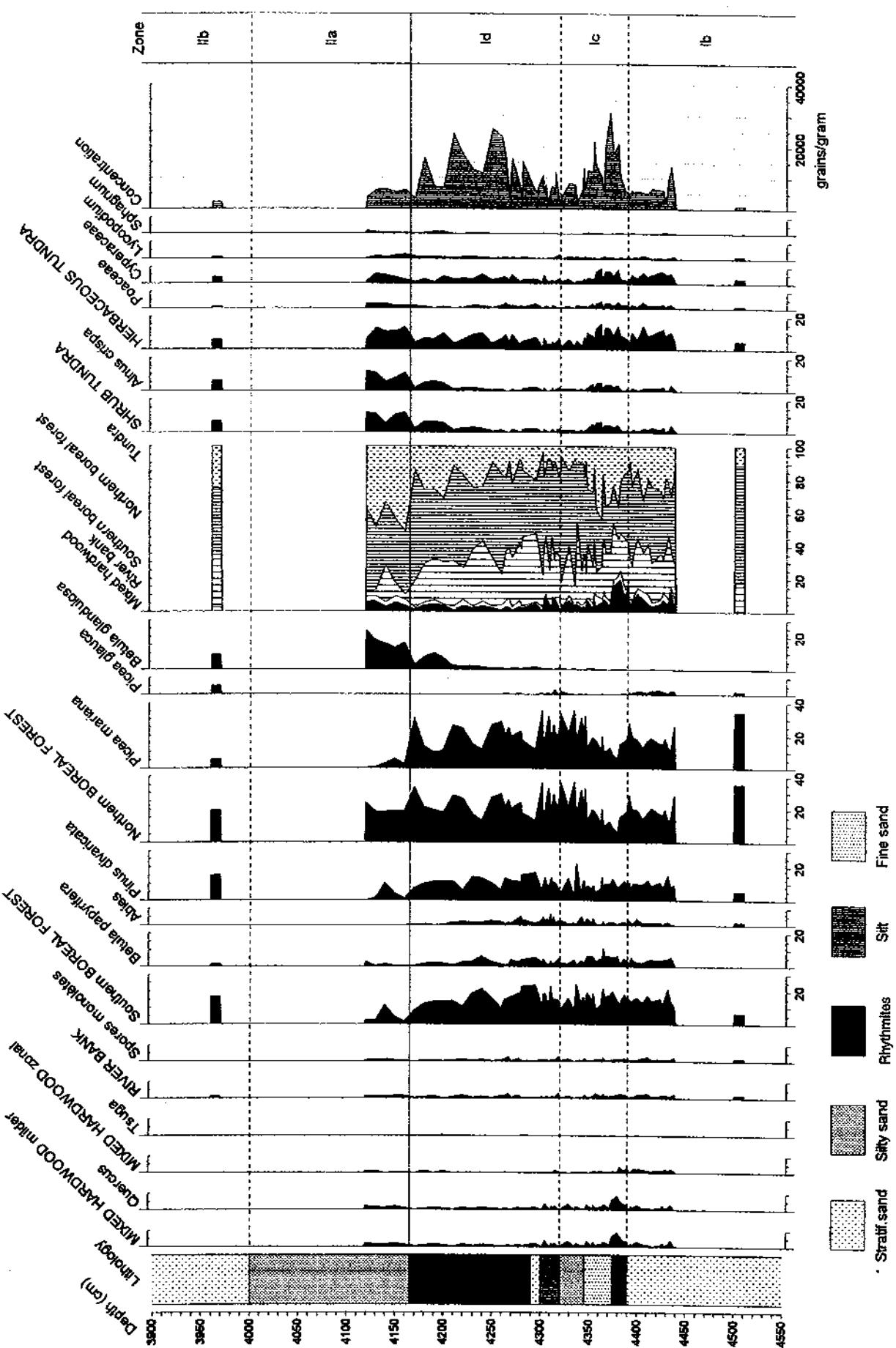


Figure 3.19: Pollen analysis (detail) of the lower units at the Calvette Section, île aux Coudres (from Clet and Occhietti, 1995).

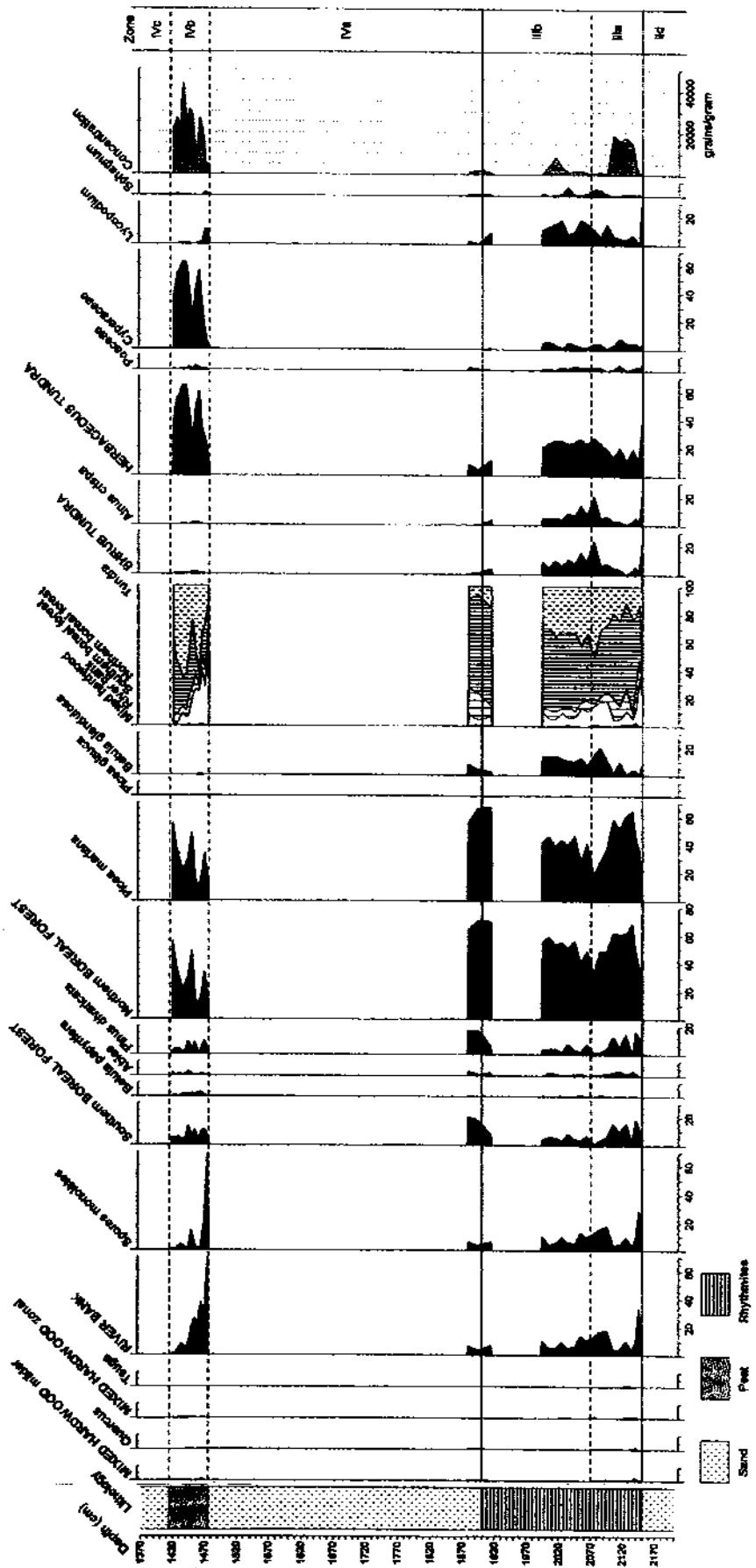


Figure 3.20: Pollen analysis of the fine grained units of the Ravin amont ("upstream gully") Section, Ille aux Coudres (from Clet and Occhietti, 1995).

Seismic reflection mapping of bedrock topography and Quaternary seismo-stratigraphy of the middle St. Lawrence Estuary, Ille aux Coudres, Québec

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Terrain Sciences Division**

Todd, B.J., Occhietti, S., and Burns, R.A., Seismic reflection mapping of bedrock topography and Quaternary seismo-stratigraphy of the middle St. Lawrence Estuary, Ille aux Coudres, Québec; in Current Research, Part D, Geological Survey of Canada, Paper 91-1D, p. 53-59, 1991.

Abstract

Analysis of high resolution seismic reflection data from the north shore of Ille aux Coudres, Québec, shows 160 m of stratified, basin-fill sediment in a broad, U-shaped valley. The sediment is probably glacial marine and would have been deposited during late Illinoian and early Sangamonian time. This seismic reflection work extends previous geological interpretations, based on regional marine seismic surveys, onto land. The results could be used in planning CCDP drillhole locations in the Middle Estuary of the St. Lawrence.

Résumé

L'analyse des données de sismique-réflexion à haute résolution, obtenues sur la côte nord de l'île aux Coudres au Québec, montre la présence de 160 m de sédiments stratifiés de remplissage de bassin dans une large vallée en forme de U. Ces sédiments, probablement d'origine glacio-marine, se sont sans doute accumulés au cours d'une période s'étendant de la fin de l'Illinoien au début et du Sangamonien. Ces travaux de sismique-réflexion étendent aux régions terrestres une interprétation géologique jusque-là faite en fonction de levés de sismique marine régionale. On pourrait utiliser les résultats obtenus pour planifier les emplacements des sondages du PFCC dans l'estuaire moyen du Saint-Laurent.

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INTRODUCTION

A recent Canadian Continental Drilling Program (CCDP) drillhole proposal (Svitiski et al., 1990) has focussed attention, among three projects, on the shore of the Ile aux Coudres Channel in the middle St. Lawrence River estuary (Fig. 1). This site has particular significance in the study of Global Climatic Change because it represents a thick sequence of sediments underlying a well known exposure of material deposited between apparently the end of the climatic optimum of the Sangamonian Interglacial Stage (120-115 ka) and the Holocene Epoch (10 ka) (Brodeur and Allard 1985; Occhietti 1989; Occhietti and Clet, in press). A drillhole at the Ile aux Coudres site would provide detailed information on the Illinoian/Sangamonian transition and the beginning of the Sangamonian (135-115 ka). The continental climatic change during this transitional period is poorly documented. From ocean-bottom drill cores, a decrease in the ^{18}O concentration suggests a rapid decay of the world-continental ice sheets during this time (Svitiski et al., 1990). The Ile aux Coudres site is attractive because approximately 160 m of material was deposited over 20 ka (135-115 ka). This sedimentation rate provides a greater degree of possible stratigraphic resolution than in any oceanic setting, where sedimentation rates are lower.

The application of the seismic reflection technique to Quaternary studies has become well established in the 1980s and the method has been tested in a variety of geological settings both in Canada and worldwide (Hunter et al., 1984; Jongerius and Helbig, 1988). To provide an accurate depth to bedrock and a reconnaissance investigation of the seismo-stratigraphy at the potential drill site, "optimum offset" seismic reflection survey lines were shot in the vicinity of Pointe de la Prairie, northwest Ile aux Coudres, in June 1990 (Fig. 1). Data from this survey are presented in this report, along with a geological interpretation.

METHOD

Under favourable conditions, the "optimum offset" high-resolution seismic reflection profiling technique (Pullan and Hunter, 1990) can provide a detailed picture of the overburden-bedrock contact and of the overburden stratigraphy. The ability of the system to resolve subsurface features depends on the frequency of seismic energy returned from reflectors to the surface. Experience has shown that the best geological conditions for the technique consist of near-surface fine-grained materials that are water saturated. The tidal mudflats on the northwest shore of Ile aux Coudres provide just such an environment.

The "optimum offset" refers to a source-receiver separation that allows reflectors to be recorded without interference from "noise". Each trace on an optimum offset profile represents ground motion recorded by a geophone at a constant distance from a seismic energy source.

Approximately 2 km of optimum offset data were shot at Ile aux Coudres. Line 1 was shot parallel to the shoreline at Pointe de la Prairie (Fig. 1). Line 5, situated in the middle of the mudflats, was shot 348 m WNW of Line 1. Line 2 intersects these two lines and reaches an elevation of approximately 30 m a.s.l. at its southeastern end. Two short lines, 3 and 4, were shot on top of the island at an elevation of about 80 m a.s.l. Lines 1, 2, and 5 are shown in this report. The source-geophone offset in all cases was 18 m and the geophone spacing was 3 m. The data were filtered in the field by high-frequency geophones (50 Hz) and by a pre-A/D 300 Hz high pass filter on the seismograph. A 12-gauge Buffalo gun was used as the seismic energy source (Pullan and MacAulay, 1987). When the gun could not be pushed into the saturated sediment, shot holes were drilled to a depth of 1.5 m.

The data were recorded on a Scintrex S2-Echo engineering seismograph. The record length was 200 ms of 1024 samples for all lines except Line 5, which was recorded to 300 ms. Preliminary processing and plotting were carried out in the field office. Final processing of the data included: 1) shifting traces in time to align first arrivals (refractions from the top of the water table); 2) digital filtering (300-800 Hz bandpass); and 3) the application of an automatic gain control and time-varying gain tapers.

A velocity-depth function was calculated from an analysis of reversed wide-angle spreads shot at the southwest and northeast ends of Line 1. These spreads consisted of 96 channels with a 3 m geophone spacing. Refracted arrivals on the seismic data indicated overburden velocities of 1650-1725 m/s. Depth scales on the seismic sections are given with respect to the ground surface.

SEISMIC RESULTS

Line 1

Figure 2A shows the 972 m-long optimum offset profile along Line 1. Interpretation lines are superimposed on the section in Figure 2B. A prominent reflector (erosional unconformity) at a depth of 120-160 m (U1) is interpreted as the top of bedrock. This reflector forms a broad U-shaped valley. There are no coherent reflectors beneath this surface. The valley is infilled with up to 160 m of highly stratified material. Coherent, conformable reflectors can be traced the length of the section and these reflectors onlap the basement reflector. At the top of the section (<10 m depth), the stratified basin-fill exhibits a low-angle unconformity (U2) with an overlying unit.

Line 5

Line 5 (Fig. 3) shows the bedrock unconformity (U1) farther offshore (Fig. 1). The northerly dipping surface of the bedrock valley extends from 180 to 200 m in depth. Similar to Line 1, the material overlying bedrock exhibits many coherent internal reflectors and is separated from an overlying thin unit by a low-angle unconformity (U2).

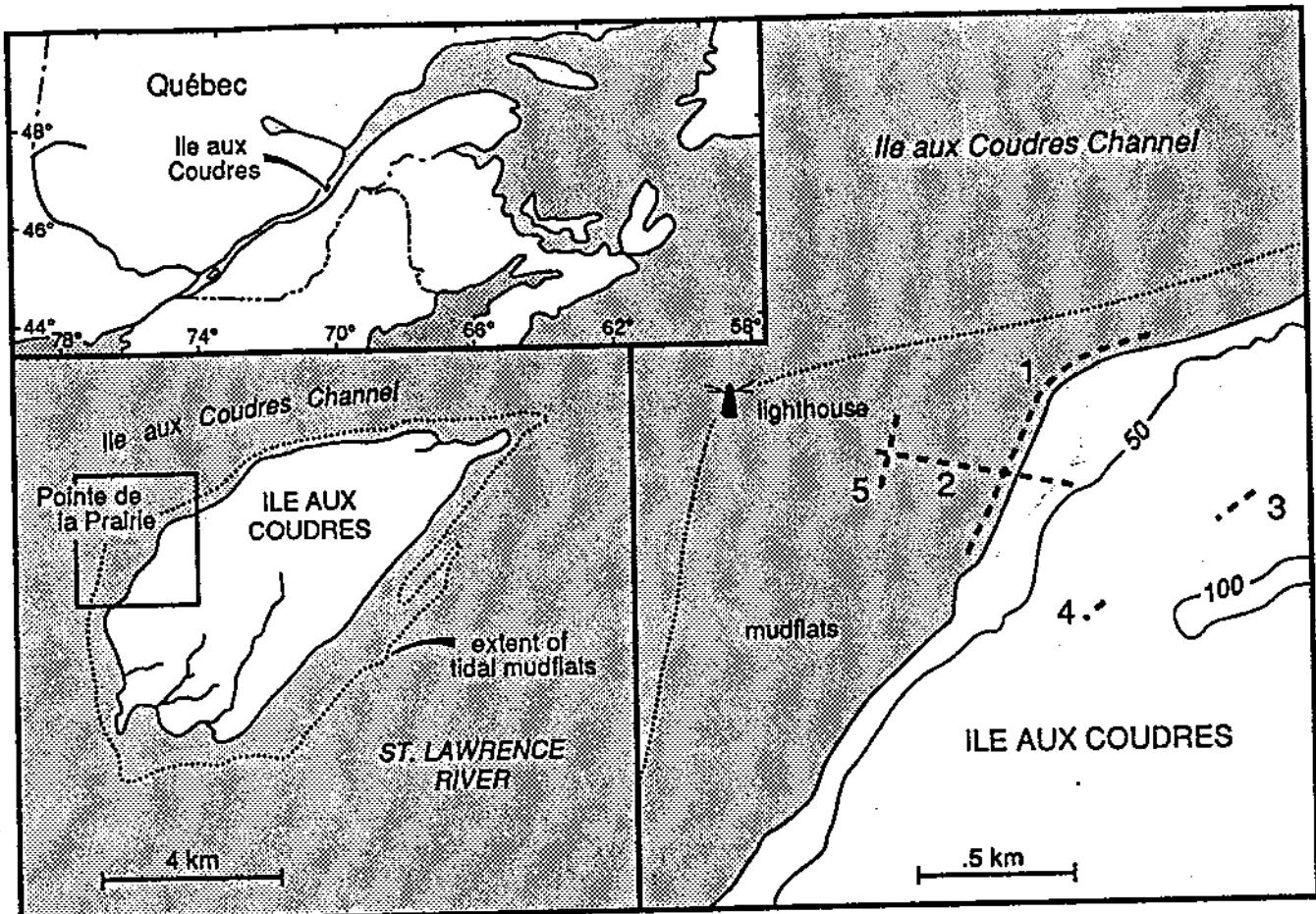


Figure 1. Location map of Ile aux Coudres. Outlined area at Pointe de la Prairie in map at lower left shows extent of detailed map at right where seismic reflection lines 1 to 5 are shown (dashed). The proposed CCPD drillhole site is near the intersection of Lines 1 and 2. Contour interval is 50 m. Modified from Brodeur and Allard (1985).

Line 2

Line 2 (Fig. 4) intersects Lines 1 and 5 (Fig. 1). The apparent dip of the bedrock unconformity (UI) is to the WNW at a depth of about 100 m to >160 m. Reflectors within the valley-fill material can be correlated from Lines 1, 5, and 2.

INTERPRETATION

The pronounced basement reflector on the seismic records suggests a strong velocity/density contrast with the overlying sediments. Refracted sedimentary arrivals show a velocity of 1650-1725 m/s. No refracted basement arrivals were obtained on Lines 1, 2, or 5. However, refracted basement arrivals recorded on Line 3 on top of Ile aux Coudres (Fig. 1) show a velocity of 3.7 km/s. Outcrops of dipping mudstone occur along the northwest shoreline of the island and the velocity of 3.7 km/s may correlate with this material. The basement seen in the seismic profiles could be the eroded surface of this mudstone.

The thick sequence of stratified basin-fill material is interpreted as glacial marine, fine grained, ice-distal sediment. According to the exposed deposits, the sediment would have been deposited during late Illinoian and early Sangamonian. The sediment has similar seismic reflection characteristics as deposits mapped elsewhere in the Middle Estuary using marine seismic methods (Praeg et al., in press), but the latter are correlated to Late Wisconsinan — early Holocene Goldthwait Sea marine clays and silts. These recent deposits are commonly mapped and drilled along the shores of the St. Lawrence Estuary. The Ile aux Coudres U-shaped valley would represent a trap of older sediments.

The thin unit lying unconformably on the thick, stratified valley fill is interpreted as basinal muds and sandy and/or gravelly lags (Praeg et al., in press). This material is evidence of postglacial sedimentation patterns (Svititski and Praeg, 1989).

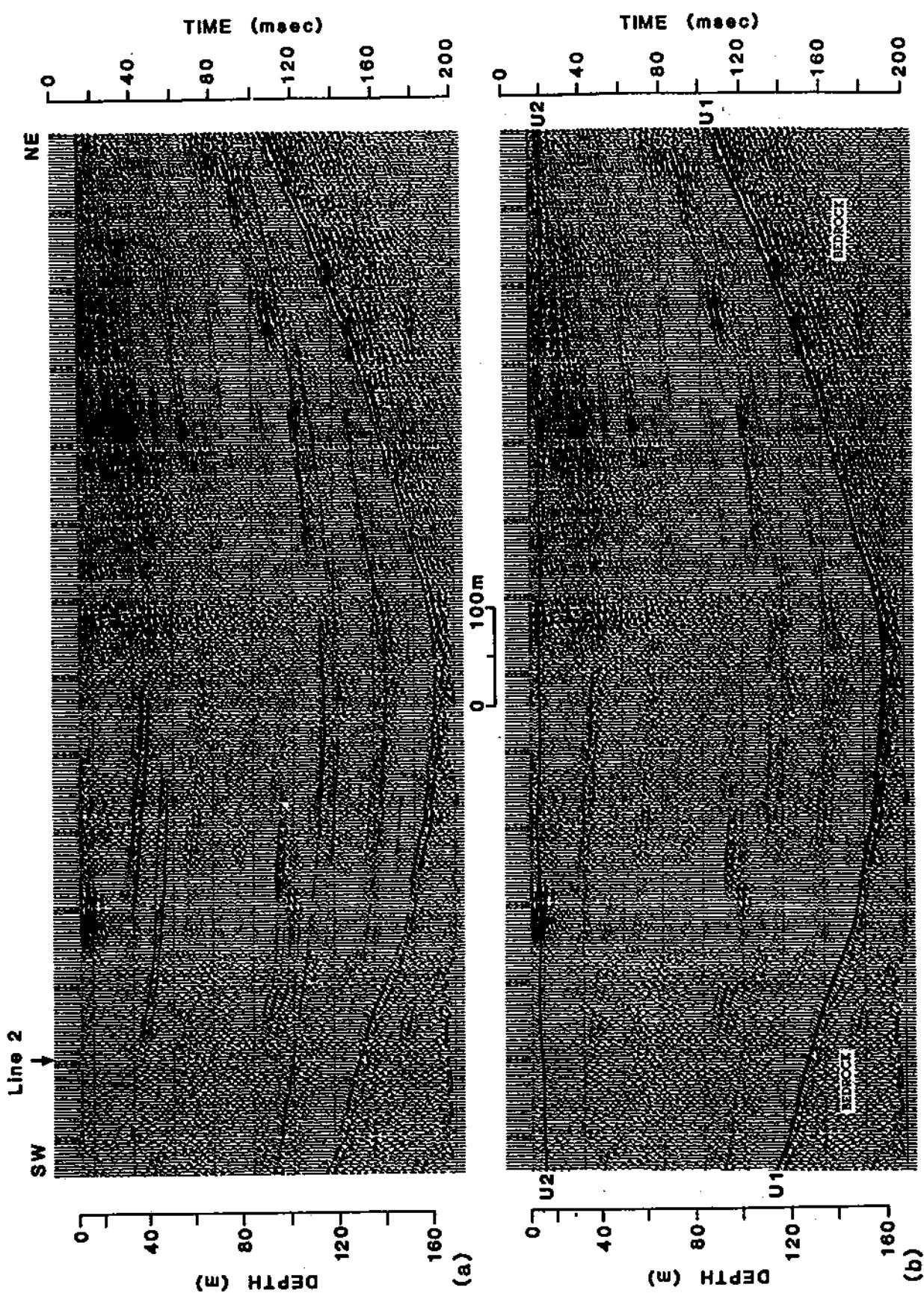


Figure 2. A. Optimum offset seismic reflection profile along Line 1B. Interpretation of A, showing bedrock topography and seismo-stratigraphic units. This section, and subsequent sections, have a vertical exaggeration of approximately 1:1 for a velocity of 3.7 km/s. See text for discussion.

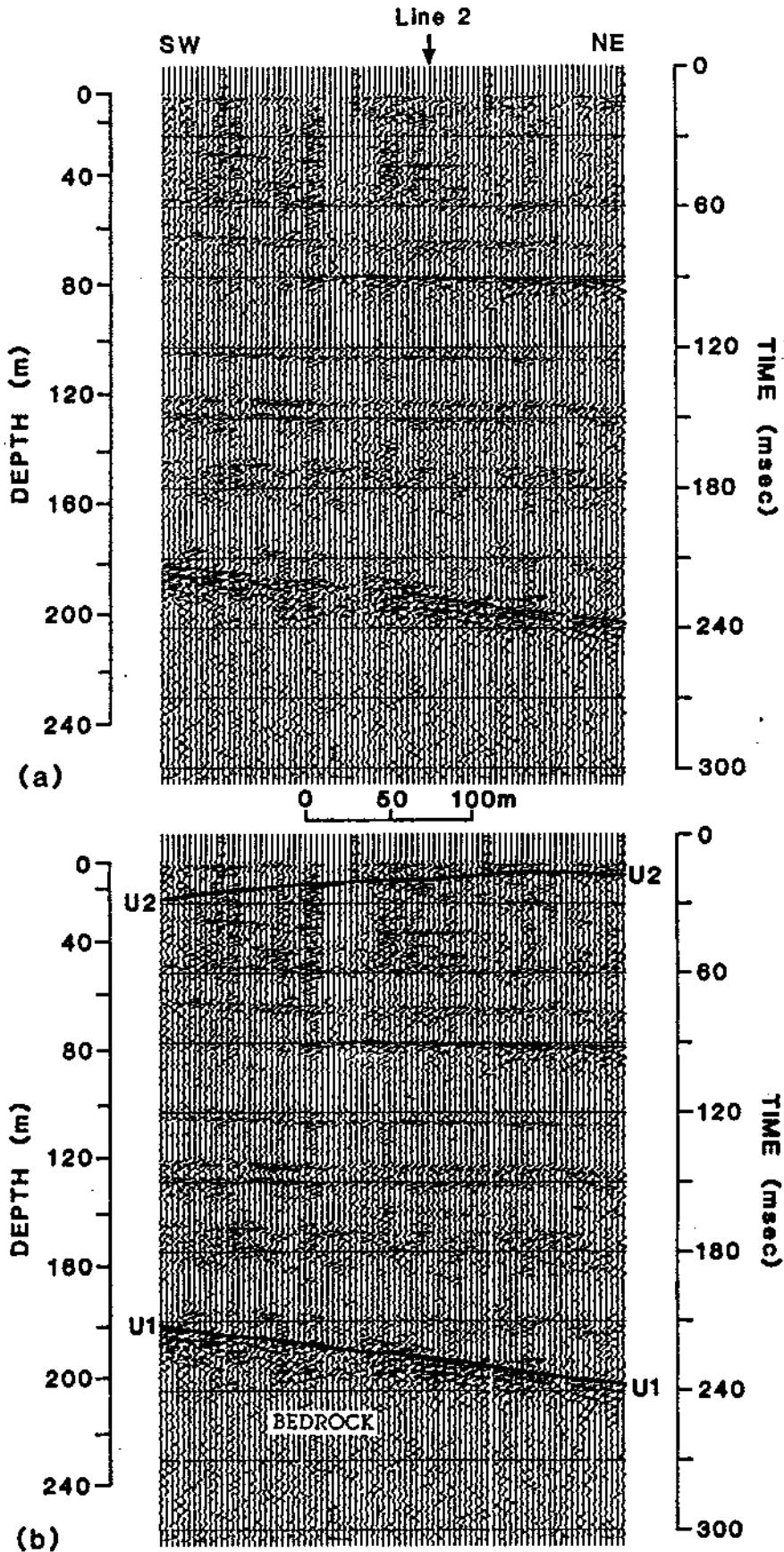


Figure 3. A. Optimum offset seismic reflection profile along Line 5.
B. Interpretation of A, showing bedrock topography and selsmostratigraphic units.

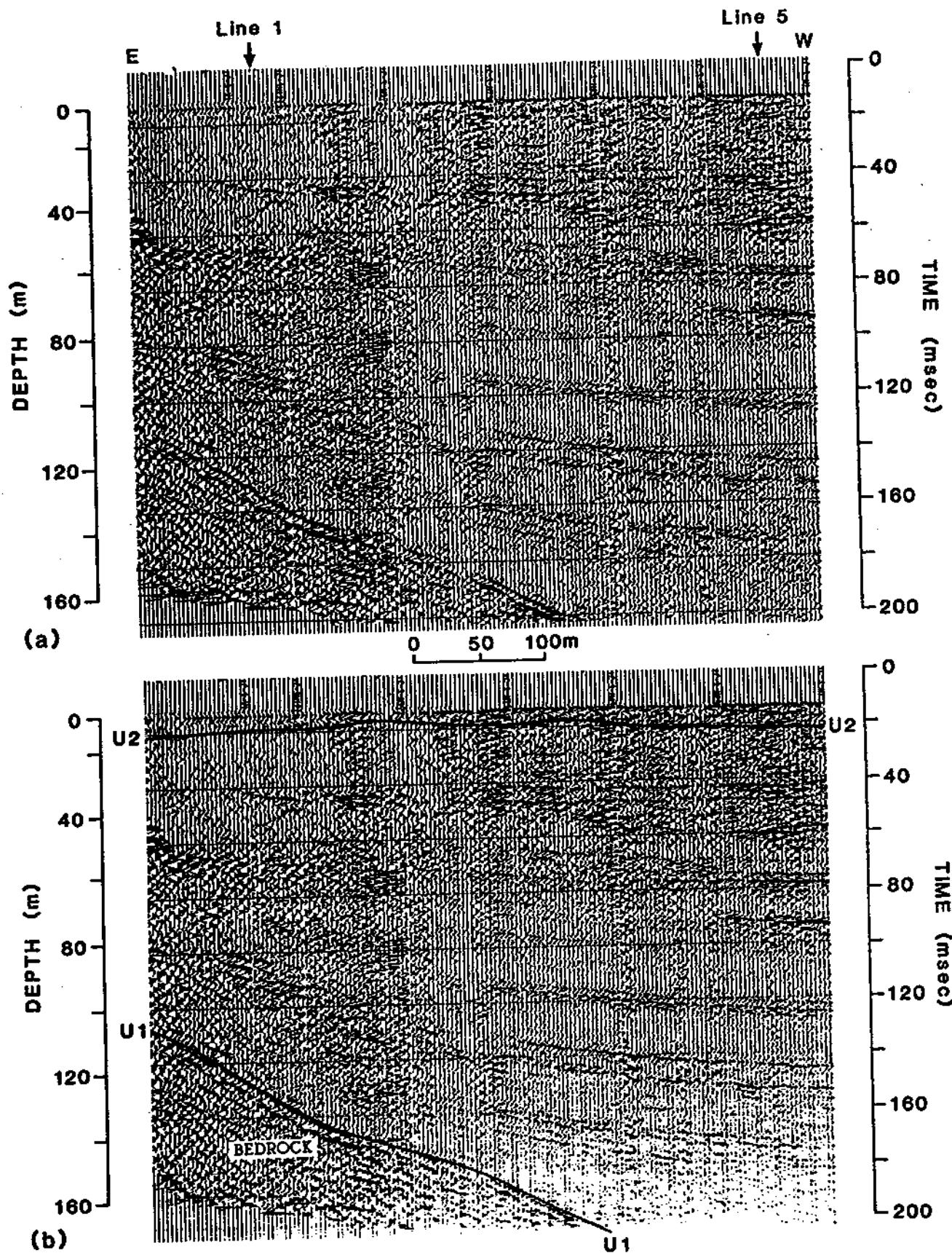


Figure 4. A. Optimum offset seismic reflection profile along Line 2. B. Interpretation of A, showing bedrock topography and seismo-stratigraphic units.

CONCLUSION

The optimum offset seismic reflection method worked well on Ile aux Coudres. Bedrock topography was delineated and the seismo-stratigraphic characteristics of the 160 m thickness of basin-fill sediments were resolved. The technique would be extremely useful for future investigations of potential CCDP drilling sites in the St. Lawrence estuary and for onshore-offshore geological correlations in the area.

ACKNOWLEDGMENTS

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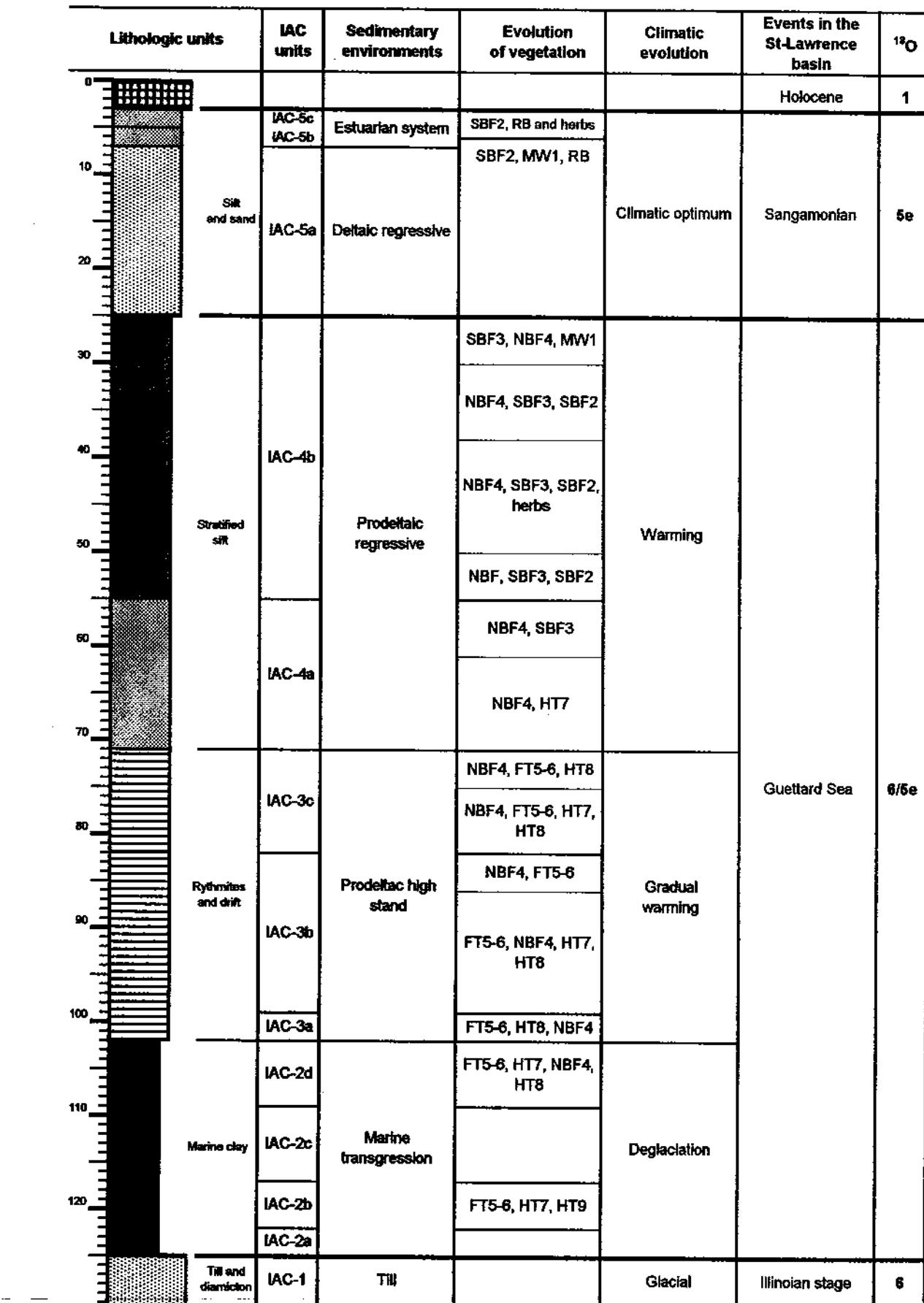


Figure 3.21 : Biostratigraphy of the drilled Ile aux Coudres Formation (from Clet-Pellerin and Occhietti, 2000).

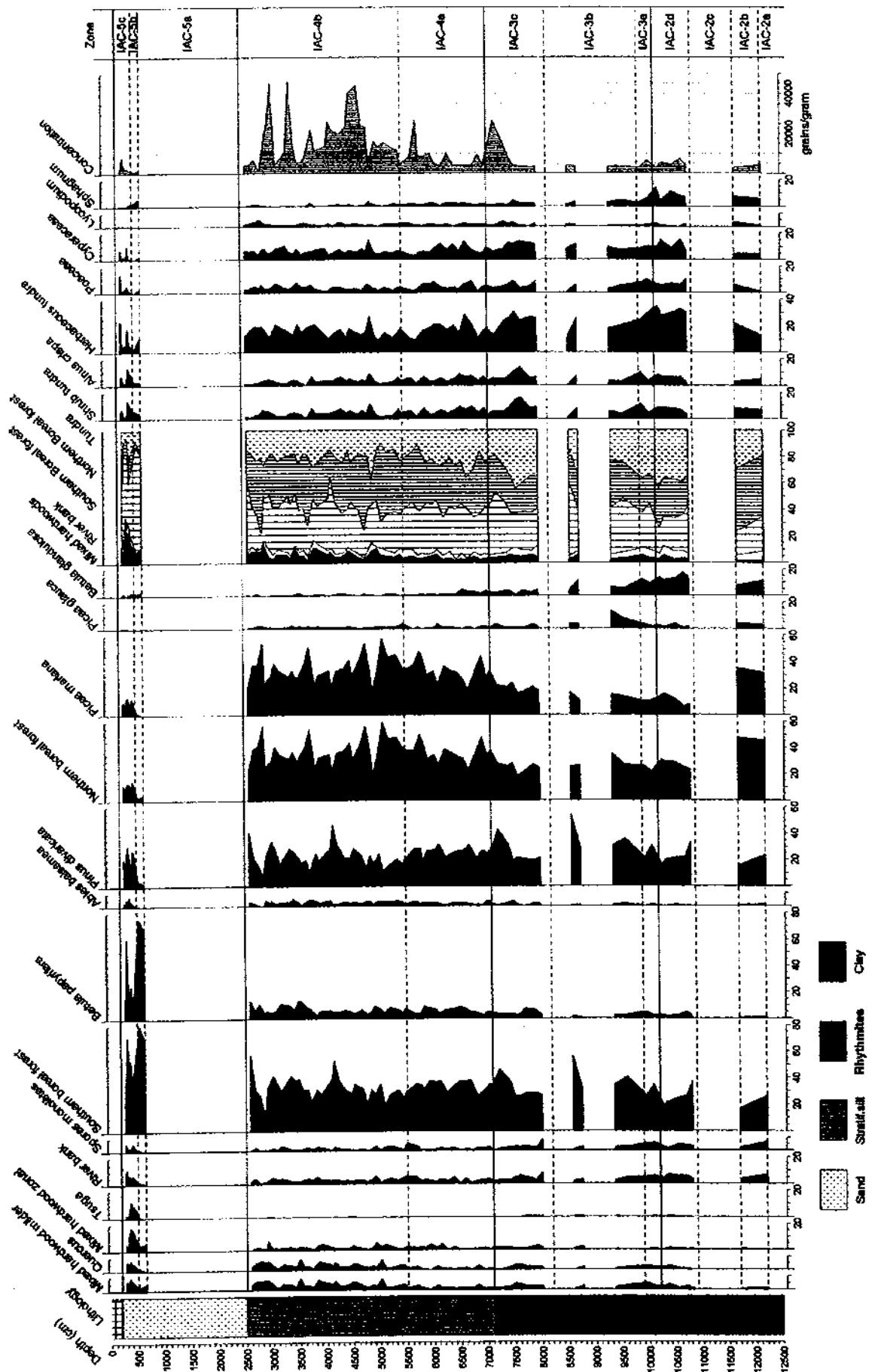


Figure 3.22: IAC-91 drilling core, pollen analysis of the île aux Coudres Formation (Occhietti et al., 1995; Clet-Pellerin and Occhietti, 2000).

Séquence de la transition Illinoien – Sangamonien : forage IAC-91 de l'Île aux Coudres, estuaire moyen du Saint-Laurent, Québec

S. Occhietti, B. Long, M. Clet, X. Boespflug et N. Sabeur

Résumé : Un groupe de dépôts pléistocènes de plus de 155 m d'épaisseur sous le niveau de la mer a été foré à l'île aux Coudres, dans l'estuaire moyen du Saint-Laurent, Québec. Ce groupe, dont la base n'est pas connue, comprend deux unités : une accumulation inférieure (-155 à -125 m) de faciès glaciaires, nommée Complexe glaciaire de Baie-Saint-Paul et corrélée à l'Illinoien (stade isotopique 6), et une séquence stratifiée nommée Formation de l'Île aux Coudres. Cette formation est subdivisée en quatre zones : argile inférieure très compacte (-125 à -102 m), rythmites à débris de schistes paléozoïques (-102 à -71 m), silts prodeltaïques et silts sableux deltaïques à foraminifères benthiques d'eaux saumâtres (-71 à -2 m). Le contenu sporopolleninique indique une toundra arbustive puis une afforestation représentée par une forêt boréale puis par une sapinière suivie d'une forêt mixte interglaciale à *Betula*, *Juglans*, *Carpinus* ou *Ostrya*, *Carya* et, au sommet, à *Betula*, *Tsuga*, *Quercus* et *Ulmus*. La Formation de l'Île aux Coudres représente une durée de sédimentation de l'ordre de 3500 ans en milieu marin initialement profond (environ 300 m) puis en contexte régressif glacio-isostatique. Elle est attribuée à une invasion marine postglaciaire, dénommée Mer de Guettard, antérieure à deux épisodes glaciaires régionaux et partiellement contemporaine de celle de la Mer de Bell dans les basses terres de la baie d'Hudson. Elle implique un influx sédimentaire postglaciaire majeur dans l'Atlantique pendant la transition Illinoien-Sangamonien et le début du Sangamonien (transition 6-5 et début du sous-stade 5e).

Abstract: A series of Pleistocene deposits extending over 155 m below sea level was drilled at Aux Coudres Island, in the middle St. Lawrence Estuary, Quebec. The series, which basis is unknown, is divided into two sedimentary units: the lower Baie-Saint-Paul Glacial Complex facies (-155 to -125 m), which is correlated with the Illinoian (isotopic stage 6), and a stratified sequence referred to as the Île aux Coudres Formation. The latter is subdivided into four zones: a very compact lower clay (-125 to -102 m), rhythmites with Paleozoic schist debris (-102 to -71 m), and prodeltaic silts and deltaic sandy silts with brackish water benthic foraminifera (-71 to -2 m). The spore and pollen content indicates a shrub tundra followed by an afforestation sequence of a boreal forest that changes to an *Abies* forest and then to an interglacial mixed forest with *Betula*, *Juglans*, *Carpinus* or *Ostrya*, *Carya*, and, at the top, *Betula*, *Tsuga*, *Quercus*, and *Ulmus*. The accumulation of the sediments of the Île aux Coudres Formation required approximately 3500 years, beginning with a deep marine environment (about 300 m) followed by shallowing waters during the subsequent glacioisostatic rebound phase of the regression. The sedimentation is assigned to a main postglacial marine invasion, referred to as the Guettard Sea, which occurred prior to two regional glacial episodes and was partly contemporaneous with Bell Sea invasion in the Hudson Bay lowlands. A major postglacial sedimentary influx in the Atlantic Ocean, during the Illinoian-Sangamonian transition and at the beginning of the Sangamonian (transition 6-5 and early substade 5e) is inferred from this marine event.

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Introduction

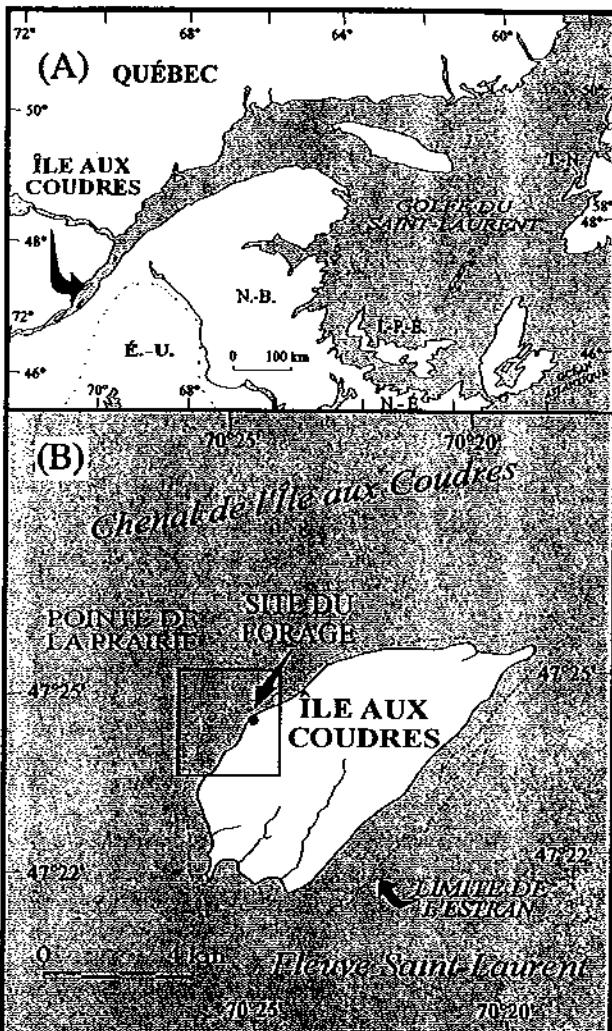
Des levés de réflexion sismique à haute résolution (Todd et al. 1991) ont révélé l'existence d'un groupe sédimentaire pléistocène non consolidé, d'au moins 160 m d'épaisseur sous le niveau de la mer, sous la rive nord-ouest de l'île aux Coudres, dans l'estuaire moyen du Saint-Laurent, au Québec (fig. 1). Ce groupe est sous-jacent à une séquence d'environ 40 m visible sur les falaises et qui comprend (fig. 2) : (i) à la base, des silts et sables stratifiés dont une zone contient jusqu'à 17% de pollen d'arbres thermophiles (en majorité de *Quercus*), (ii) un ensemble stratifié contenant deux zones de sable fluviatile et une zone intermédiaire de gravier et de

galets d'origine fluviatile ou fluvioglaciaire, (iii) des varves tronquées par un contact d'érosion, (iv) des sédiments à lits de tourbe associés aux Sédiments de Saint-Pierre, (v) des sédiments attribués au cycle glaciaire du Wisconsinien classique (Brodeur et Allard 1985; Brodeur 1987; Clet et Occhietti 1995). Les lits très riches en pollen d'arbres thermophiles de l'unité 1, échantillonnés vers +6 m, sont attribués à la fin de l'optimum climatique du dernier interglaciaire (sous-stade isotopique 5e) ou à un remaniement postérieur (Occhietti et Clet 1989; Clet et Occhietti 1995). Les unités sismostratigraphiques sous-jacentes, apparemment stratifiées, représentaient potentiellement au moins la phase de sédimentation immédiatement antérieure, c'est-à-dire le début du sous-stade isotopique 5e et la transition 6–5. Cette transition est identifiée dans les forages océaniques (Pisias et al. 1984; Martinson et al. 1987) mais restait très peu connue à l'échelle mondiale et mal documentée dans les séquences continentales. Pour cette raison, le groupe enfoui de l'île aux Coudres fut foré à la fin d'octobre 1991.

Méthodologie

Le forage de l'île aux Coudres a été exécuté avec la technique rotasonique, par J.R. Drilling Ltd. Le double tubage sur les premiers 120 m a permis d'obtenir des carottes peu perturbées, de 9 cm de diamètre, en tronçons d'environ 90 cm de long. Une profondeur de 154,8 m a été atteinte dans les sédiments non consolidés du site. La technique permet de traverser des blocs de roche précambrienne sans interrompre le forage. Les carottes ont été stockées en chambre froide à l'Institut national de la recherche scientifique (INRS) — Océanologie de Rimouski. Elles ont été analysées par scannographie (tomodensitométrie axiale) au Centre hospitalier régional de Rimouski et reconstruites numériquement à l'aide du logiciel développé par General Electric (Medical Branch International). Les images ainsi digitalisées sont analysées numériquement sur un micro-ordinateur au laboratoire de sédimentologie de l'INRS — Océanologie. Les différentes teintes de gris dépendent des propriétés d'absorption des rayons X par la matière et reflètent les variations de la densité et de la composition chimique de l'échantillon (Boespflug et al. 1994). Un échantillon a été prélevé tous les 90 cm environ et soumis à une ou plusieurs analyses (159 granulométries, 117 calcimétries, 175 mesures CHN, microfaune vérifiée dans 50 échantillons, 124 analyses polliniques). Le contenu en foraminifères est très pauvre et n'a pas permis d'obtenir un échantillon suffisant pour une datation ^{14}C par accélérateur. La description sédimentologique détaillée est actuellement en cours. Pour l'analyse pollinique, seule la fraction comprise entre 125 et 10 μm a été préparée par attaque avec HF (40%) par Téresa Novara (Université du Québec à Montréal). Un traitement informatique (Clet et al. 1991) des données d'après le logiciel G3PAL (Goeury 1988) et le dessin du diagramme à l'aide du logiciel TILIA (Eric Grimm, Illinois State Museum, Springfield) ont permis de différencier les différentes zones polliniques, de calculer les concentrations (nombre de grains par gramme de sédiment) et la diversité taxonomique des arbres, arbustes et herbacées. La reconstitution des paléoenvironnements végétaux tient compte, notamment, de ces paramètres et du pourcentage de grains de pollen d'arbres thermophiles.

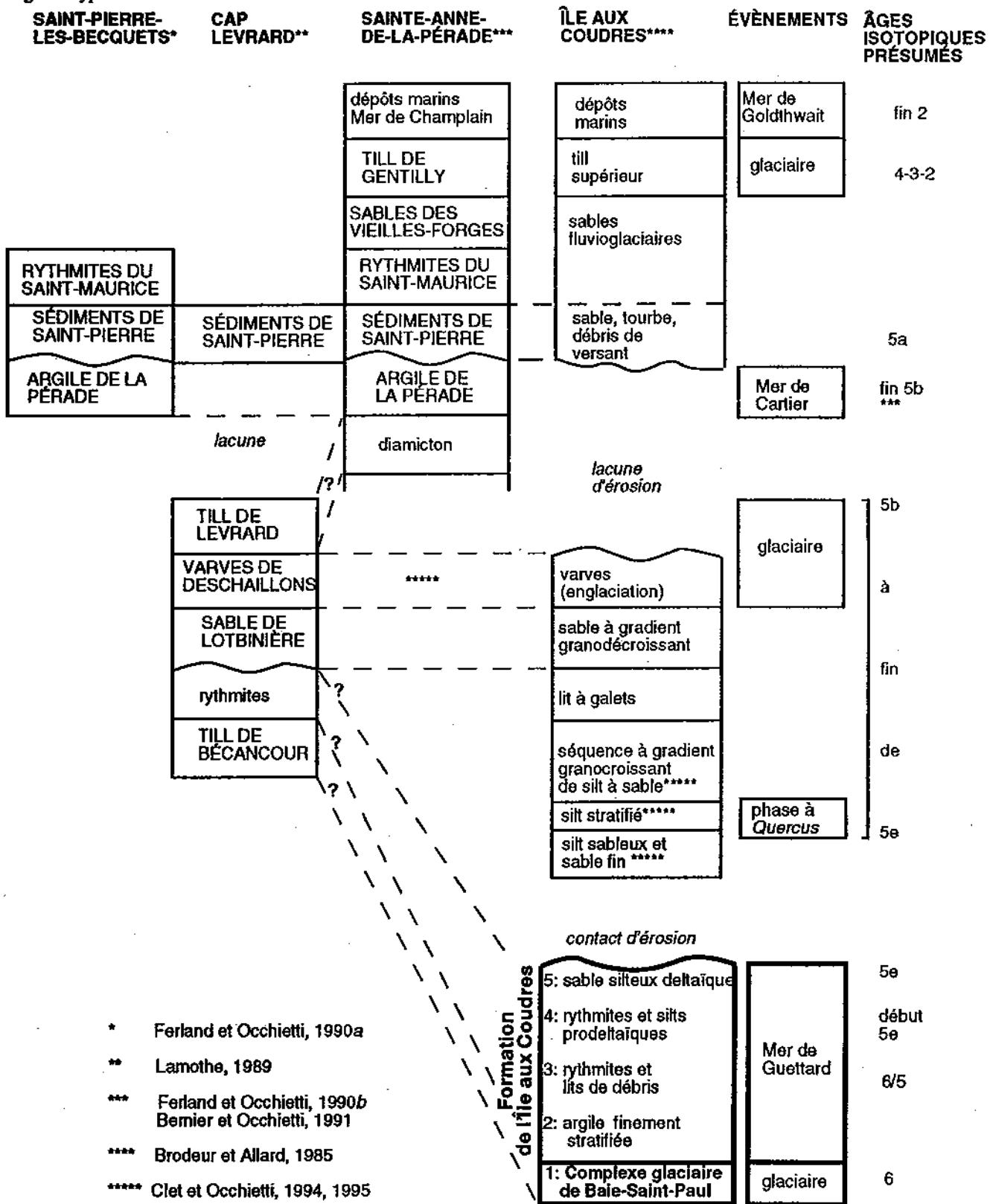
Fig. 1. Localisation du site du forage de l'île aux Coudres, estuaire moyen du Saint-Laurent, Québec.



Résultats

L'altitude de la basse terrasse sableuse supralittorale ayant servi de base au forage est à environ 4 m au-dessus du niveau moyen de la mer. Le repère de nivellement local ayant été détruit par les glaces saisonnières, les profondeurs sont mesurées par rapport à la terrasse, en attendant un nivellement rigoureux. Le fond rocheux n'a pas été atteint : le forage a dû être interrompu à cause de la rupture d'une tige de forage profonde qui fut bloquée, très vraisemblablement, par un bloc lors de la remontée du train de tiges. L'épaisseur du forage, dont il manque la partie basale, mesurée avant expansion, est supérieure de 15 m à l'épaisseur estimée par réflexion sismique (Todd et al. 1991). Cette différence, très normale, est due à la sous-estimation de la vitesse du signal sismique dans le groupe sédimentaire traversé, lequel est beaucoup plus compacté que les groupes équivalents de la Mer de Goldthwait dans l'estuaire du Saint-Laurent (vitesse de 1650 m/s, Praeg et al. 1992). Les carottes des unités non glaciaires ont subi une expansion axiale par décompression de 12 m, soit de 10% environ; l'épaisseur cumulée passant de 125 à 137 m. Afin qu'elles reflètent la géologie du forage, les profondeurs indiquées dans ce texte sont celles mesurées

Fig. 2. Hypothèse de corrélation des unités de l'île aux Coudres aux unités du Pléistocène de la vallée du Saint-Laurent.



* Ferland et Occhietti, 1990a

** Lamothe, 1989

*** Ferland et Occhietti, 1990b
Bernier et Occhietti, 1991

**** Brodeur et Allard, 1985

***** Clet et Occhietti, 1994, 1995

avant expansion. Compte tenu de la longueur des tiges de forage, 15 pi (4,57 m), une approximation théorique comprise entre 0 et 45 cm sur la profondeur réelle des échantillons prélevés ne peut être évitée, du bas au sommet de chaque groupe de carottes extraites d'une tige.

Lithostratigraphie

La séquence forée de l'île aux Coudres peut être subdivisée en deux grandes parties, un complexe glaciaire inférieur (zone 1 de la fig. 3), non distingué par la sismique à haute résolution, et un groupe stratifié apparemment continu

(zones 2 à 5 de la fig. 3). La séquence comprend les unités suivantes (fig. 3), en épaisseurs initiales, d'après la description visuelle et les autres données de tomographie, de sédimentologie et de paléontologie :

1. Complexe glaciaire inférieur

Étant donné que le complexe glaciaire inclut des bancs peu ou non cohésifs et que le forage atteignait une grande profondeur, plusieurs lithozones ont été recueillies sous forme fragmentaire. Globalement, le complexe glaciaire est composé de zones de till compact à matrice dominante silto-sableuse carbonatée (identifiées sous le nom de till dans la zone 1, fig. 3), de zones de till peu cohésif à matrice sableuse et facilement déstructuré par le forage (représentées par le symbole du sable moyen (SM), zone 1, fig. 3) et, éventuellement, de zones sans matrice silto-argileuse (zones diamicques grossières, zone 1, fig. 3). L'épaisseur minimale du complexe est de 30 m, entre le fond du forage (-154,8 m) et la base des argiles à -125 m. Le complexe glaciaire contient des blocs de granito-gneiss et d'anorthosite.

Le nom formel de Complexe glaciaire de Baie-Saint-Paul est proposé pour cet ensemble de dépôts. La limite inférieure de cette unité n'est pas connue. D'après la tige de forage perdue à la base de la carotte, il est probable que l'unité est plus épaisse et (ou) qu'une unité sous-jacente est disposée au-dessous du complexe glaciaire. Le sommet est représenté par un changement granulométrique franc entre du sable moyen compact et les argiles finement stratifiées de la base de l'unité sus-jacente.

2. Zone d'argile très compacte et finement stratifiée

De -125 à -102 m, une zone bien distincte est composée d'argile grise très compacte, carbonatée, finement stratifiée. Elle contient, à la base, quelques lits de 5 cm d'épaisseur de sable grossier composé de débris de schiste vert, de calcaire et de roches précambriques. Des petits cailloux calcaires anguleux et des lits de sable grossier sont parfois intercalés dans l'argile. Les sédiments de cette zone varient de très mal classés à mal classés. La dissymétrie est positive, ce qui implique un excès de fraction grossière caractéristique d'un système en érosion. La présence d'un kyste de dinoflagellé à -119 m, parmi de rares grains de pollen, confirme l'origine marine du sédiment.

3. Zone de rythmites grises intercalées de lits de débris de schiste vert

De -102 à -71 m, des rythmites grises compactes représentent un faciès profond. L'analyse tomographique révèle des rythmites de 40 mm d'épaisseur, subdivisées en microzones dont la disposition reflète les saisons ainsi que les périodes de marées (voir plus loin, fig. 4). Les sédiments varient de très mal à mal classés mais la distribution devient symétrique, ce qui implique que les sédiments apportés sont en équilibre.

Les rythmites sont intercalées de lits de débris de schiste vert local, entre -102 et -86 m. La taille de ces débris varie du sable au gravier. Quelques fragments de roches précambriques sont présents. Le schiste vert affleure actuellement sur la rive nord de l'île aux Coudres et fait partie des argilites cambro-ordoviciennes du Groupe appalachien de Québec (Rondot 1969).

4. Zone de silts stratifiés

Entre -71 et -25 m, un ensemble de 46 m de silts stratifiés et carbonatés s'est déposé selon un gradient granocroissant très progressif : les lits « grossiers » sont composés de silt fin à la base et de silt grossier dans la partie supérieure de cette zone. Les lits clairs réagissent plus vivement au HCl que les lits plus sombres. Deux sous-zones sont visuellement distinctes : (i) silt et silt argileux gris rougeâtre, entre -71 et -58 m, avec des taches noires dans la partie inférieure, indiquant probablement un milieu réducteur, (ii) silt gris stratifié, fin à la base et grossier vers le haut, de très compact à compact, entre -58 et -25 m. Quelques lits de sable fin sont intercalés dans la partie supérieure. D'après l'observation visuelle, une rythmite prise comme exemple vers -65 m est composée d'un lit inférieur de 7 mm de différents feuillets de couleur distincte (gris, gris rose), d'un lit finement laminé gris rose très carbonaté de 8 mm d'épaisseur et d'un lit de 22 mm de silt moyen gris et finement laminé à taches noires alignées. Les sédiments sont de mal à très mal classés et de distribution symétrique à négative. La partie supérieure est très mal classée et à dissymétrie très négative.

5. Zone de silt et de sable

À -25 m, les sédiments stratifiés deviennent sableux. De -25 à -2,2 m, la taille des sédiments varie, les lits sont silto-sableux à la base et formés de sable fin à moyen au sommet. La couleur dominante est grise; certains lits de sable sont jaunes. La stratification parallèle et la présence de foraminifères de milieux saumâtres (voir plus loin) indiquent une sédimentation en milieu estuaire, dans des eaux peu profondes. La zone 5 est mieux classée et plus grossière que la zone 4.

Le nom formel de Formation de l'Île aux Coudres est proposé pour l'ensemble des sédiments stratifiés observés par forage et disposés entre, à la base, le Complexe glaciaire de Baie-Saint-Paul identifié par forage et, au sommet, le contact d'érosion à la partie supérieure des sables silteux stratifiés de la zone 5 et sous les dépôts littoraux subactuels. Cette formation est donc composée de quatre lithozones observées par forage et différenciées par leurs caractères sédimentologiques. La limite supérieure de la Formation de l'Île aux Coudres sera probablement étendue à une ou plusieurs zones à la base des falaises du nord-ouest de l'île, à la suite de futurs travaux d'excavation. La Formation de l'Île aux Coudres semble continue. L'existence de lacunes intraformationnelles et de lacunes d'érosion ne peut toutefois être exclue. Un profil sismique perpendiculaire à l'axe du chenal de l'île aux Coudres a permis d'identifier le contact d'érosion discordant entre la Formation de l'Île aux Coudres et les sédiments de la Mer de Goldthwait (Sabeur 1994). Des levés géophysiques à maille serrée, dans le chenal de l'île aux Coudres (fig. 1) et dans le chenal nord de l'estuaire du Saint-Laurent, devraient permettre d'étendre cette surface d'érosion, de réanalyser les données sismostratigraphiques de Praeg et al. (1992) de ce secteur et d'évaluer l'extension latérale de la Formation de l'Île aux Coudres et du complexe glaciaire sous-jacent.

Micropaléontologie

Plusieurs espèces de foraminifères benthiques ont pu être extraites des faciès régressifs supérieurs (zones 4 et 5) à l'aide d'une liqueur dense. Il s'agit de formes adultes de

Fig. 3. Log et caractéristiques sédimentologiques du forage IAC-91 de l'île aux Coudres.

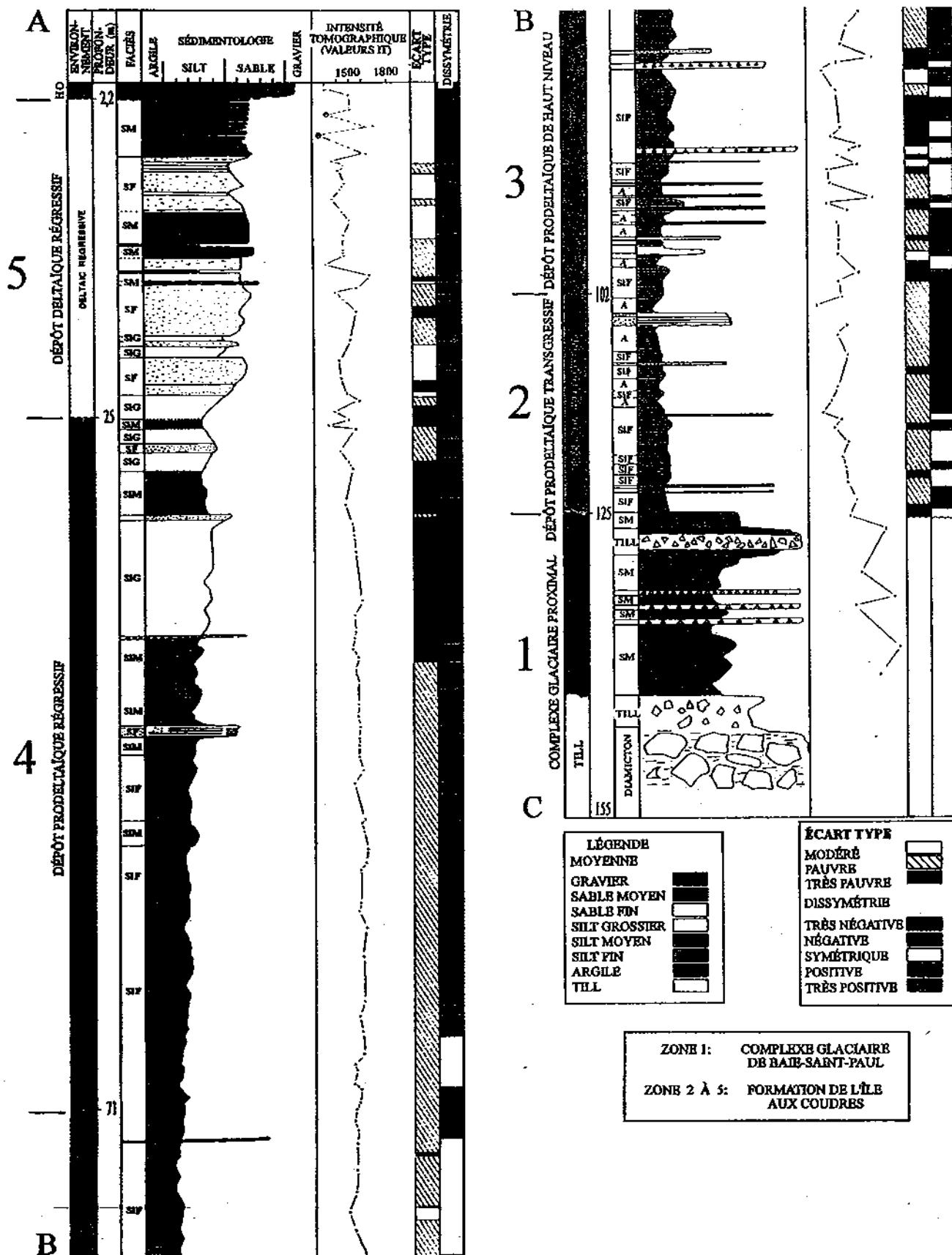


Fig. 4. Échantillon de la carotte de l'île aux Coudres, prélevé à -88 m et composé de rythmites gradées de 40 mm d'épaisseur (A). La vue agrandie et contrastée (B) révèle la structure sédimentaire de deux rythmites composées, à leur base, d'une lamine très dense (claire), puis de lamination alternées claires-sombres, devenant graduellement moins denses (plus sombres). D'après le profil des intensités tomographiques (IT) en (C), deux sous-unités apparaissent. Si une rythmite représente la sédimentation d'une année, chaque sous-unité correspond à des dépôts semi-annuels (printemps -été, automne -hiver). Chaque lamine peut refléter l'alternance des marées de vives- (VE) et de mortes-eaux (ME) ou des tempêtes barocliniques.

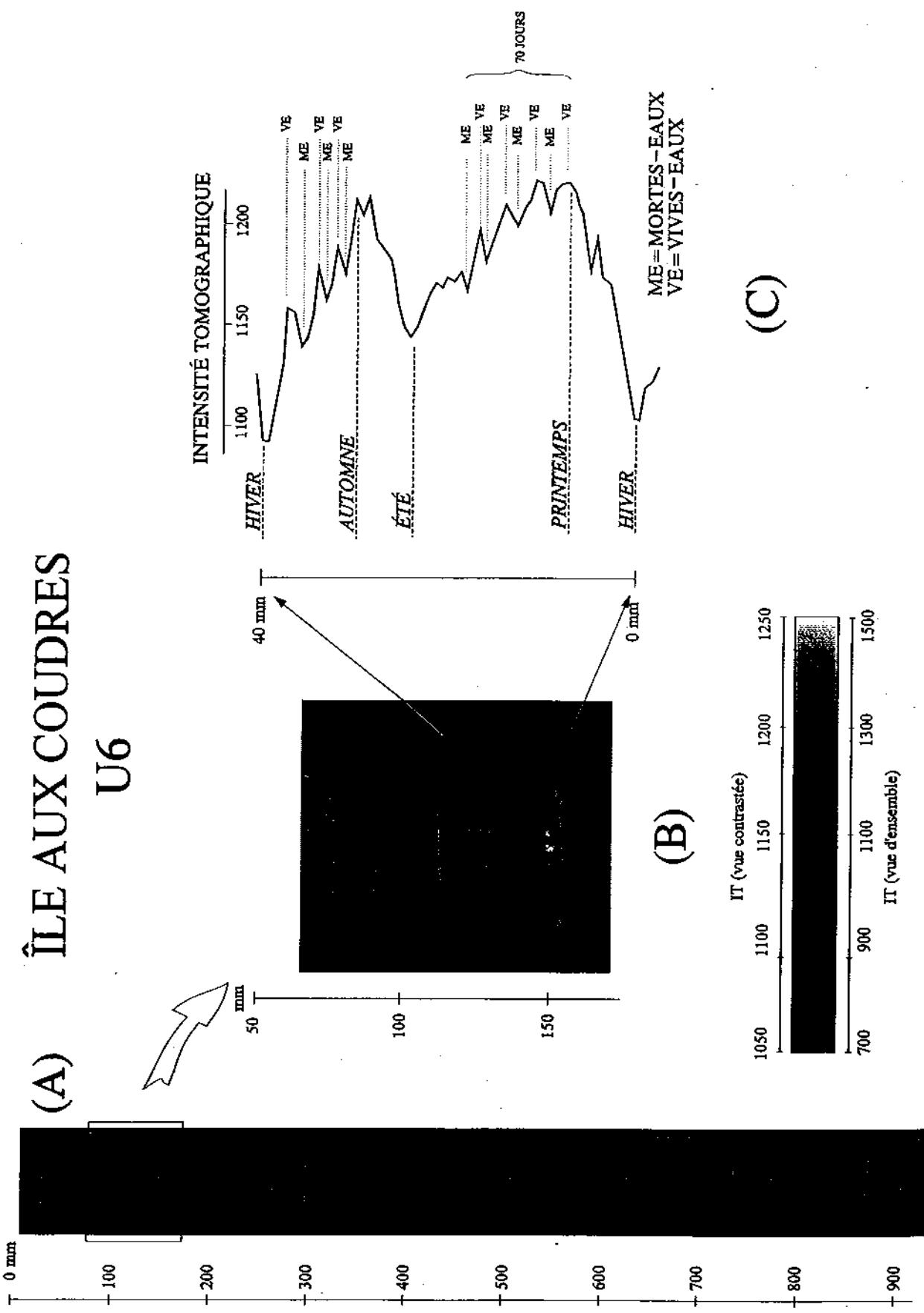


Tableau 1. Foraminifères benthiques des faciès régressifs sangamonien de l'estuaire moyen du Saint-Laurent.

	Profondeur (m)		
	-9,4	-15	-26,5
<i>Elphidium excavatum</i>	X	X	X
<i>Elphidium bartletti</i>	—	X	—
<i>Islandiella heleneae</i>	X	X	X
<i>Cibicides lobatulus</i>	X	X	X
<i>Quinqueloculina cf. arctica</i>	X	X	—
<i>Quinqueloculina cf. borea</i>	X	—	—
<i>Cassidulina reniforme</i>	—	—	X

Nota : La présence des foraminifères est indiquée par un X.

Quinqueloculina arctica, de formes juvéniles très petites (40–50 µm) d'*Elphidium excavatum* et d'*Elphidium bartletti* ainsi que de spécimens rares d'autres espèces (tableau 1). Certains spécimens sont bien conservés, d'autres sont abîmés. Ces différents degrés de conservation indiquent peut-être le mélange de tests repris par érosion et de tests pénécontemporains à la sédimentation. Les espèces identifiées indiquent un assemblage d'eaux peu profondes et saumâtres à *Elphidium excavatum*, ce qui est conforme à une sédimentation en milieu estuarien. Les sédiments silteux et sableux de la partie supérieure de la séquence furent déposés en eau saumâtre. Au-dessous de 52 m de profondeur, l'examen au binoculaire des fractions granulométriques supérieures à 64 µm semble indiquer l'absence de tests de foraminifères. Les sédiments fins contiennent parfois des débris végétaux et des exosquelettes de larves d'insectes.

Contenu sporopollinique

La séquence forée de l'Île aux Coudres est parfois apparemment stérile ou contient des grains de pollen et de spores en concentration et dans un état de conservation variables (fig. 5). Le *Picea mariana* et le *Pinus banksiana* sont généralement dominants. Le pourcentage de pollen d'arbres est compris entre 55 et 89% (fig. 6). La diversité taxonomique est dans l'ensemble faible, avec une moyenne générale de 17 taxons (fig. 5); elle est légèrement plus élevée dans la partie supérieure. Au-dessus du complexe glaciaire inférieur, le diagramme pollinique peut être subdivisé en quatre grands ensembles qui coïncident avec les lithozones de la Formation de l'Île aux Coudres (fig. 5 et 6).

IAC-1 : complexe glaciaire inférieur (-154,8 à -125 m)
Les échantillons analysés sont stériles.

IAC-2 : argile grise (-125 à -102 m)

De -125 à -122 m, les sédiments sont apparemment stériles.

De -122 à -117 m, on observe un assemblage à *Picea mariana* dominant, *Pinus* et *Betula*. Les sphagnes et les fougères puis l'*Alnus crispa*, les Cypracées et les Éricacées sont présents (fig. 6). Le mélange de plusieurs assemblages polliniques est évident. La concentration pollinique est faible (moins de 4000 grains/g de sédiment) (fig. 5). La diversité taxonomique est également faible (fig. 5). Les pourcentages de conifères fragmentés sont relativement forts (plus de 15%

à la base) (fig. 5), ce qui laisse supposer qu'il y a eu remaniement et transport de grains de pollen dans un milieu où les chocs mécaniques étaient importants.

De -117 à -109 m, les sédiments sont stériles.

De -109 à -102 m, le *Pinus banksiana* est généralement dominant et les pourcentages de *Betula* sont voisins de 20%. Les pourcentages d'*Alnus crispa* augmentent depuis la base jusqu'au sommet de cette zone. Il en va de même pour ceux des herbacées et surtout pour les cypréacées et les sphagnes.

IAC-3 : rythmites grises et silt stratifié (-102 à -71 m)

De -102 à -99 m, le *Pinus banksiana* est dominant. Les concentrations de *Betula* sont élevées. Les herbacées sont encore importantes. La concentration est toujours inférieure à 5000 grains/g. Cette zone contient les mêmes espèces que dans la zone IAC-2 entre 109 et 102 m, mais les pourcentages des espèces caractéristiques de la toundra sont en nette régression.

De -99 à -82 m, le *Pinus banksiana* présente des pourcentages oscillant entre 32 et 57%. Les pourcentages de *Picea mariana* augmentent et ceux de *Picea glauca* dépassent 14%. La diversité taxonomique est plus faible que dans les zones précédentes et la concentration est toujours inférieure à 5000 grains/g. Le taux de grains de pollen fragmentés de conifères oscille entre 4 et 10%.

De -82 à -71 m, le *Pinus* reste dominant mais ses pourcentages sont en baisse. À partir de ce niveau, les pourcentages de *Picea mariana* augmentent et l'ensemble de la végétation change. On note une forte proportion de grains de pollen dissociés de conifères. La concentration augmente et dépasse 20 000 grains/g dans la partie supérieure.

IAC-4 : Silts stratifiés (-71 à -25 m)

De -71 à -50 m, le *Picea mariana* est dominant. La concentration subit des fluctuations. Les pourcentages d'herbacées et la concentration diminuent dans les 5 m supérieurs.

De -50 à -25 m, l'*Abies* et le *Quercus* s'implantent progressivement et d'autres espèces thermophiles présentent parfois des courbes continues. La concentration est élevée puis subit de fortes fluctuations.

IAC-5 : silt et sable (-25 à -2,2 m)

De -25 à -6,4 m, les échantillons analysés sont apparemment stériles.

De -6,4 à -5 m, on observe une augmentation des pourcentages et une diversification du pollen des arbres thermophiles (*Carpinus* ou *Ostrya*, *Carya ovata* et *Juglans*) associés à 80% de *Betula*. La faible concentration pollinique et les pourcentages importants de grains de pollen dissociés impliquent toutefois un remaniement important du pollen de ces différents niveaux.

De -5 à -3 m, le pourcentage de grains de pollen de *Tsuga* atteint 8%, en association à divers arbres thermophiles (*Quercus*, *Tilia*, *Ulmus* et *Fagus*) et au *Betula*, *Pinus banksiana*, *Betula* et *Picea mariana*.

Teneurs en carbonates

Les sédiments de la carotte sont carbonatés. De -38 à -110 m, les taux de carbonates varient en général de 1 à 4% du sédiment; de -110 à -136 m, ils atteignent 17% et varient généralement entre 5 et 10%; le complexe glaciaire inférieur en contient 5% en moyenne.

Fig. 5. Assemblages polliniques, diversité taxonomique, concentrations et pourcentages sporopolliniques de la Formation de l'Île aux Coudres.

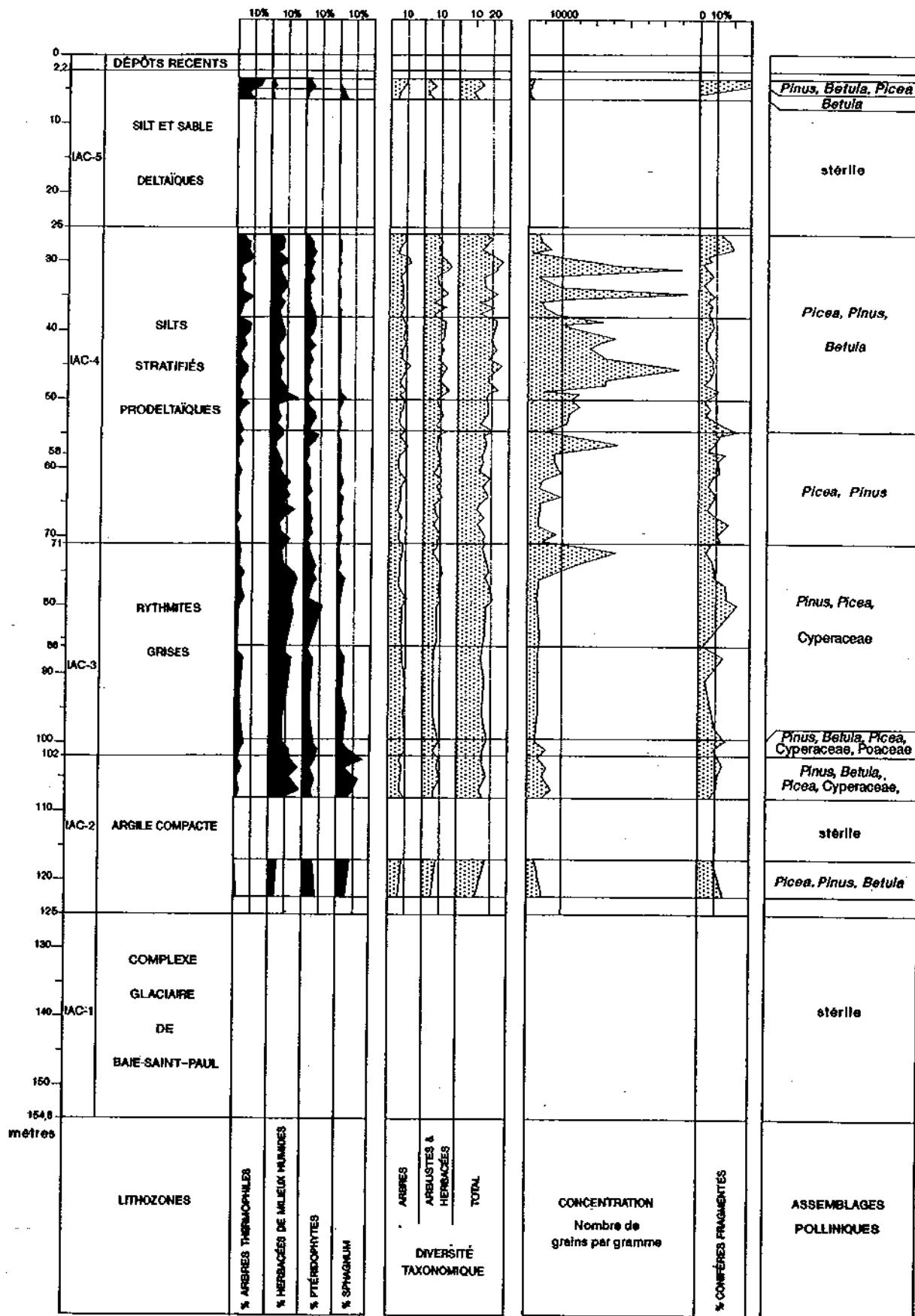
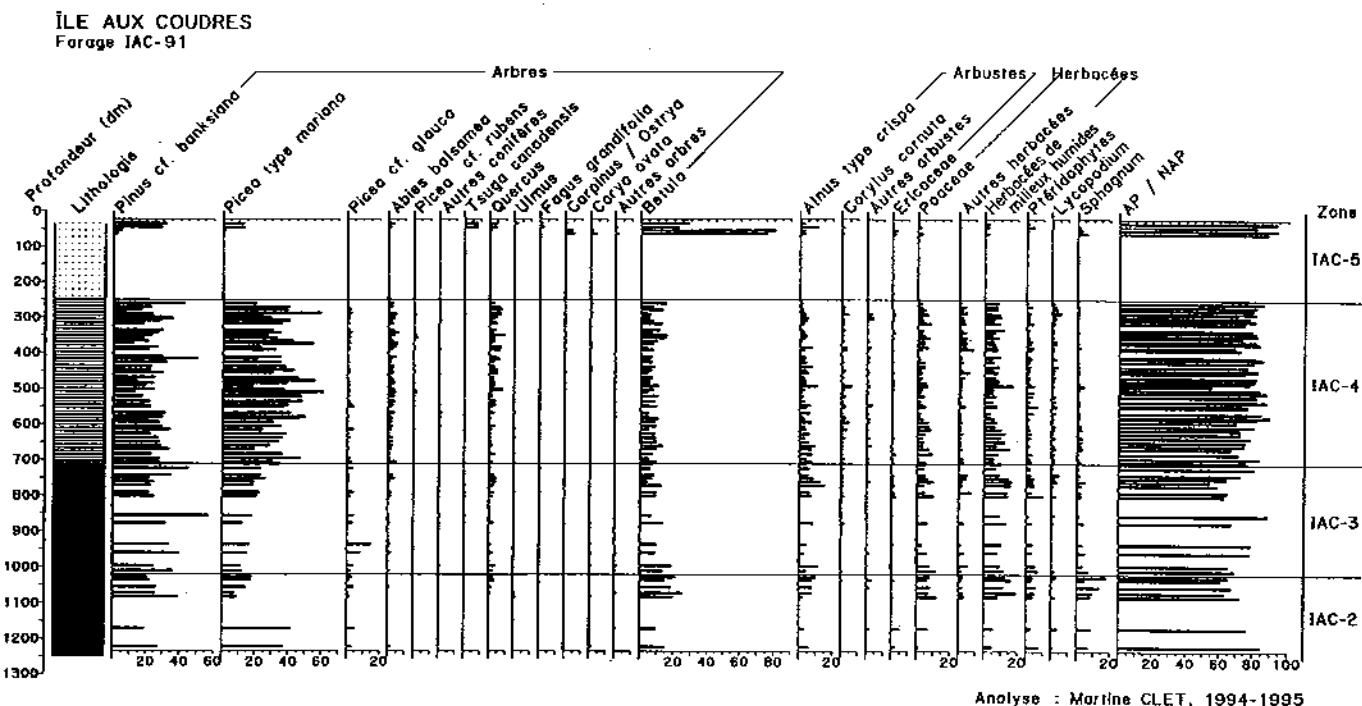


Fig. 6. Diagramme des pourcentages sporopolliniques de la Formation de l'Île aux Coudres. AP, pollen arboréen; NAP, pollen non arboréen (arbustes et herbacées).



Estimation préliminaire de la durée de sédimentation marine et estuarienne

La partie stratifiée de la séquence forée, de 122,8 m d'épaisseur, est composée de couches sédimentaires dont la récurrence annuelle peut être démontrée. Par exemple, la tomographie a mis en évidence la structure fine d'une rythmite de la zone 3 (fig. 4). Les zones sombres représentent des intensités tomographiques faibles et les zones claires des intensités élevées. Dans le cas étudié, les intensités tomographiques sont corrélées à la granulométrie et à la teneur en matière organique (Boespfug et al. 1995). Ainsi, les lits sombres sont des argiles (10 Φ) relativement riches en matière organique (4%) et caractérisent les lits d'hiver. Les lits clairs sont des lits argileux (8 Φ) à faible teneur en matière organique (1,5%) et caractérisent les lits de printemps et d'automne. Les lits d'été sont caractérisés par des intensités tomographiques intermédiaires. Les lits de printemps et d'automne peuvent, de plus, être subdivisés en lamination aux intensités contrastées. Ces lamination sont associées aux marées de vives-eaux et de mortes-eaux de cycle bimensuel et à des tempêtes (Long et al. 1993), tel que déjà observé dans les sédiments actuels du golfe du Saint-Laurent (Hart et Long 1990a) et dans l'estuaire de la rivière Eastmain (d'Anglejan 1982). La valeur moyenne de sédimentation annuelle est estimée à 35 mm/an, d'après le décompte de 350 rythmiques et des mesures prises dans les différentes zones de la carotte de forage. Par conséquent, la durée de sédimentation marine et estuarienne comprise entre la déglaciation fini-illinoienne et le sommet du forage (sous la basse terrasse) est de l'ordre de 3500 ans. Cette durée est du même ordre de grandeur que celle de la phase de comblement de la Mer de Goldthwait, à la fin du Wisconsinien, entre 13 500 – 11 500 Av. P. et 10 000 – 9 000 Av. P. selon le secteur.

Interprétation

Sédimentologie

Complexe glaciaire de Baie-Saint-Paul

Dans l'état des analyses, il n'est pas possible de dire s'il s'agit d'un seul épisode glaciaire ou de plusieurs, ni de distinguer les faciès. Il est en effet difficile de distinguer en forage un till de fond, un aqua-till accumulé sous des glaces flottantes ou un diamicton compacté de délestage d'icebergs. D'après sa position topographique au-dessous de 125 m sous le niveau actuel de la mer et d'après les sondages sismiques à haute résolution qui excluent une grande épaisseur de sédiments en-dessous, il est raisonnable de penser qu'il a été mis en place sous un glacier qui s'écoulait près du substratum rocheux et, parfois, sous une marge glaciaire flottante. Cette géométrie indique soit que l'estuaire moyen n'était pas comblé avant le passage de l'inlandsis illinoien, ce qui est peu vraisemblable à cette profondeur, soit que l'inlandsis a déblayé la quasi-totalité des sédiments estuariens antérieurs, ce qui est beaucoup plus vraisemblable. Il est d'ailleurs possible que des sédiments plus anciens n'aient pas été érodés et se retrouvent latéralement à des profondeurs plus grandes.

Formation de l'Île aux Coudres

Zone d'argile très compacte et finement stratifiée : faciès d'inondation marine en eau profonde : Ce faciès d'inondation, en eau relativement profonde, témoigne d'flux grosiers probablement liés à la déglaciation et à des délestages d'icebergs. La profondeur du plan d'eau au début de l'invasion marine était de l'ordre de 300 m, en considérant : (i) la profondeur sous le niveau marin actuel de -125 m de la base des sédiments marins forés, (ii) la limite supérieure du début de l'inondation marine qui atteignait environ 200 m

d'altitude au-dessus du niveau marin actuel, si l'on accepte l'hypothèse minimale d'un enfouissement glacio-isostatique équivalent à celui du Wisconsinien final (Rondot 1974; Parent et Occhietti 1988) dans des conditions eustatiques analogues. Cette altitude relative de la limite marine à +200 m est la somme algébrique de l'altitude relative du bas niveau eustatique régional au début de l'invasion marine fini-illinoienne, qui pouvait être de 100 à 50 m sous le niveau marin moyen actuel, et l'enfoncement glacio-isostatique total contemporain, de l'ordre de 250 à 300 m. L'estimation du paléoniveau marin relatif fini-illinoien est cohérente avec les valeurs numériques de Clark et al. (1978) obtenues pour le Wisconsinien final des régions englacées.

Zone de rythmites grises intercalées de lits de débris de schiste vert : Ces rythmites représentent un faciès prodeltaïque profond, déposé au début sous environ 160 m d'eau, pendant une phase de relèvement glacio-isostatique rapide. D'après la distribution symétrique, la phase d'érosion due à l'invasion marine et les apports détritiques liés à la fonte du glacier sont terminés. Les littoraux sont stabilisés, en relation avec une remontée isostatique à peu près compensée par la remontée eustatique. Les lits de débris et les fragments de schiste vert sont probablement associés à des coulées gravitaires de débris, provenant des versants locaux immersés, et étalées sur le fond par les courants profonds. Leur abondance indique que les reliefs de l'île, qui culminent à plus de 100 m au-dessus du niveau marin actuel, commençaient à émerger ou que des courants et des tempêtes dans l'estuaire affectaient les versants submergés. Il n'est pas impossible que la sismicité active de la région de l'île aux Coudres, liée notamment à la présence de l'astroblème du Charlevoix (Rondot 1969), et accentuée par la compensation glacio-isostatique, ait favorisé ces coulées de schiste vert.

Zone de silts stratifiés prodeltaïques et régressifs : Le mauvais classement et la dissymétrie très négative du sédiment dans la partie supérieure de cette zone indiquent un excès de sédiments fins. Cet excès exprime les mouvements gravitaires le long des écailles de progradation frontale du pro-delta. Ces dépôts représentent la base des clinoformes, tel que décrit dans les séries les plus récentes de la basse Côte-Nord du golfe du Saint-Laurent (Hart et Long 1990b). L'estuaire était en voie de comblement, pendant une phase où la compensation glacio-isostatique devait être presque terminée, si l'on prend comme exemple les courbes d'émergence apparentes régionales de la fin du Wisconsinien (Dionne et Occhietti 1996).

Zone de silt et de sable deltaïques régressifs : Elle correspond à la partie sommitale des écailles de progradation (fore-set) d'un delta, conformément au modèle de Bhattacharya et Walker (1992). Les carottes de forage ne permettent pas d'évaluer l'éventuel angle de pendage, par ailleurs très faible, qui serait associé aux écailles de progradation frontale. Le faciès stratifié deltaïque de cette zone n'implique pas une exondation.

Palinologie

L'interprétation du contenu pollinique en terme de paléovégétation tient compte non seulement de la présence et de

la proportion de différents genres et espèces mais aussi de plusieurs autres facteurs. La concentration du pollen en nombre de grains par gramme dépend du taux de sédimentation et de la granulométrie des dépôts. En général de faibles concentrations sont associées à du matériel grossier ou remanié d'origine lointaine (apports éoliens ou fluviatiles) (Clet et al. 1991) et, dans le cas du faciès deltaïque de la Formation de l'Île aux Coudres, à un transport fluviatile rapide. Le pourcentage des grains de pollen fragmentés de conifères est un indice de transport par l'eau produisant des chocs mécaniques importants. La diversité taxonomique a servi de critère pour distinguer, lorsque cela était possible, le pollen de source régionale à faible diversité, du pollen de source locale à forte diversité (Clet et al. 1991; Clet et Occhietti 1994). Cependant, la diversité taxonomique a tendance à varier en fonction de la concentration.

Dans l'état actuel de l'étude palynologique, la séquence du forage indique globalement la recolonisation végétale des terres déglacées puis émergées qui étaient situées à la périphérie de l'estuaire moyen du Saint-Laurent et peut-être plus en amont. On peut y distinguer les étapes suivantes de la recolonisation végétale, dont la succession comprend plusieurs analogies avec l'afforestation postglaciaire de la fin du Wisconsinien et de l'Holocène (Richard et Poulin 1976; Richard 1993, 1994) :

Zone stérile

À la base du forage, le Complexe glaciaire de Baie-Saint-Paul semble stérile. Sa position très profonde est en faveur d'une phase glaciaire très érosive et de l'absence ou la rareté, vers l'amont, d'unités résiduelles contenant du pollen antérieur à cet épisode glaciaire. Il est donc raisonnable de postuler que le pollen sédimenté dans la Formation de l'Île aux Coudres provient de la végétation régionale ou plus distale qui succède à l'épisode glaciaire et ne contient pas ou extrêmement peu de pollen antérieur à l'Illinoien.

Toundra

Colonisation végétale des terres déglacées par la toundra, avec implantation de *Betula* et d'*Alnus crispa*, de cypéracées, d'éricacées et de tourbières à sphagne. La végétation est sans doute très disséminée. Des apports éoliens de *Picea mariana* et de *Pinus* provenant de l'amont ou du sud sont transportés et resédimentés (zone IAC-2, entre -122 et -117 m).

Toundra arbustive

Colonisation des terres émergées régionales, caractérisée par l'abondance de *Betula*, d'*Alnus crispa*, de poacées, de cypéracées et de sphagnes. Une toundra arbustive se développe avec de nombreuses zones humides. Les apports distaux ou régionaux de *Pinus banksiana* et de *Picea mariana* restent importants (zone IAC-2, entre -109 et -102 m; zone IAC-3, entre -102 et -99 m).

Forêt boréale

L'installation d'une forêt boréale à *Picea mariana* accompagné de *Pinus banksiana* et de *Picea glauca* indique une forte influence maritime, d'après la répartition actuelle de *Picea glauca* à la périphérie méridionale du golfe du Saint-Laurent, en Gaspésie et sur la côte est de la baie d'Hudson.

(Payette et Filion 1975; Payette 1976, 1993; Ritchie 1987).

La forêt boréale évolue ensuite progressivement. On note une tendance à la diminution relative de *Picea glauca*, de *Betula*, de poacées, de cypéracées, de ptéridophytes et de *Sphagnum*, ainsi qu'une augmentation lente d'*Abies* et de *Quercus* (IAC-3 et IAC-4). Le *Picea mariana* augmente jusqu'au milieu de la zone IAC-4 pour fluctuer ensuite dans la partie supérieure de cette zone. La présence discontinue de rares grains d'arbres thermophiles (*Tsuga*, *Tilia*, *Ulmus*, *Carya*, *Carpinus* ou *Ostrya*) est attribuée à des apports distaux, provenant vraisemblablement de l'amont du bassin de drainage du Saint-Laurent. Ils indiquent l'existence d'une forêt mixte ou décidue en position plus méridionale et contemporaine de la pessière régionale.

Forêt à Picea, Abies et Quercus

Une forêt régionale à *Picea*, *Abies* et *Quercus* est la source principale de l'apport pollinique pendant la sédimentation prodeltaïque de la moitié supérieure de la zone IAC-4. On note en effet les plus fortes concentrations de pollen (jusqu'à 40 000 grains/g) et la plus forte diversité taxonomique (jusqu'à 25 taxons) dans les sédiments de cette phase sédimentaire. Cette paléovégétation régionale se rapproche de la végétation actuelle de l'île aux Coudres et de la rive sud de l'estuaire moyen du Saint-Laurent (sapinière à érable rouge, épinette et bétulaie, Richard 1987). La végétation actuelle sur la rive sud est nettement plus diversifiée que la pessière des Basses Laurentides qui colonise actuellement la rive nord de l'estuaire moyen du Saint-Laurent. Il est probable que les conditions climatiques de la fin de la phase prodeltaïque étaient de même type que les conditions climatiques actuelles.

Forêt mixte

Les indices d'une forêt à *Betula* associée à des arbres thermophiles tels que le *Carpinus* ou l'*Ostrya*, le *Juglans* et le *Carya*, puis d'une forêt mixte à *Pinus banksiana*, *Betula*, *Picea mariana*, *Tsuga* et *Quercus*, *Ulmus* et *Fagus*, sont présents au sommet des sédiments deltaïques de la zone IAC-5. Le transport fluviatile du pollen est attesté par la diversité taxonomique peu élevée, l'abondance des fragments de grains de pollen de conifères, la faible concentration pollinique et, probablement, par la forte variabilité taxonomique du pollen. Le contenu pollinique du sommet de l'unité deltaïque IAC-5 ne reflète pas nécessairement la végétation régionale; il peut représenter, dans une proportion non déterminée, la végétation en amont du moyen estuaire. Toutefois, le pourcentage notable (4%) du pollen d'*Abies*, reconnu comme peu transportable, laisse à penser que le pollen observé ne provient pas non plus de zones très éloignées. Compte tenu de la proportion des arbres thermophiles égale ou supérieure à 10% et de la diversité taxonomique exceptionnelle, il est possible d'affirmer que le sable deltaïque au sommet du forage de la Formation de l'Île aux Coudres est contemporain d'une forêt régionale décidue et (ou) d'une forêt mixte développées pendant un optimum climatique plus chaud qu'aujourd'hui.

Un assemblage aussi diversifié en arbres thermophiles n'est jamais observé ni dans les dépôts fluviatiles ou deltaïques sus-jacents présents dans les falaises de l'île aux Coudres (Clet et Occhietti 1995) ni dans les unités de la vallée du Saint-Laurent (Terasmae 1958; Clet et Occhietti 1988, 1994; Clet et al. 1991), à l'exception de la zone à

Carya de la Formation de Pointe-Fortune, à l'ouest-nord-ouest de Montréal (Anderson et al. 1990), associée à l'optimum climatique du Sangamonien. Par rapport aux sédiments actuels de l'estuaire du Saint-Laurent étudiés par Giroux (1990) et de Vernal et Giroux (1991), les deux échantillons sommitaux de la Formation de l'Île aux Coudres ont un assemblage pollinique très proche de l'assemblage moyen de sites actuels de la rive sud de l'estuaire maritime du Saint-Laurent composé notamment de *Pinus* ($24,9 \pm 4,2\%$), *Betula* ($24,1 \pm 3,8\%$), *Picea* ($16,2 \pm 4,6\%$), *Quercus* ($3,8 \pm 1,1\%$), *Tsuga* ($3,2 \pm 1,9\%$). Par rapport aux sédiments de la fin du Wisconsinien et de l'Holocène, le contenu pollinique du sommet de la Formation de l'Île aux Coudres est également très proche de l'assemblage à *Pinus* – *Tsuga* des sédiments de l'optimum thermique de l'Holocène identifié dans les sédiments d'une carotte de forage prélevée dans le détroit de Cabot (de Vernal et al. 1993) et d'assemblages holocènes de tourbières du Québec (Richard 1993, 1994). Ces analogues polliniques actuels et récents ainsi que la diversité taxonomique confirment le caractère interglaciaire de la zone supérieure de la Formation de l'Île aux Coudres.

Évolution paléoenvironnementale

La séquence pollinique du forage de la Formation de l'Île aux Coudres révèle une évolution apparemment continue des paysages végétaux qui est caractérisée par une recolonisation végétale postglaciaire évoluant d'une toundra à une forêt mixte tempérée associée à l'optimum climatique du Sangamonien. Cette évolution végétale confirme la continuité de la séquence sédimentaire de remplissage du moyen estuaire du Saint-Laurent mise en évidence par la sédimentologie. La durée de sédimentation de cette succession de faciès, de 3500 ans environ, est cohérente avec la durée d'une phase de réchauffement climatique de transition interglaciaire–glaciaire. Elle implique un influx sédimentaire rapide et continu, compatible avec un contexte de retrait d'inlandsis et de remobilisation de sédiments associés à ce retrait glaciaire. Elle implique également l'exondation rapide d'un bassin de 125 m de profondeur. Par analogie avec le contexte de déglaciation et d'inondation marine à la fin du Wisconsinien et au début de l'Holocène, la Formation de l'Île aux Coudres est une succession de faciès d'inondation marine puis de régression en contexte prodeltaïque distal, proximal puis en contexte deltaïque en milieu estuarien. Cette succession est interprétée comme une succession transgressive instantanée et régressive forcée. La transgression est due à l'invasion instantanée des eaux atlantiques dans un bassin libéré par le glacier illinoien, puis la régression a été forcée par le relèvement glacio-isostatique postglaciaire dans un contexte de remontée du niveau eustatique par fonte glaciaire généralisée. La zone deltaïque supérieure correspond probablement à une phase de stabilisation du niveau relatif de drainage, avec un niveau eustatique relativement stable, à part d'éventuelles fluctuations métriques telles qu'observées pendant l'Holocène (Dionne 1988), et avec une rééquilibration glacio-isostatique terminée ou à taux de compensation très faible. D'autres modèles de sédimentation pourraient être envisagés pour expliquer le comblement et l'exondation rapide, dans cette région à mouvements tectoniques verticaux mineurs. Ils contredisent toutefois les données régionales : (i) le comblement d'un bassin en contexte régressif général par abaisse-

ment du niveau eustatique impliquerait, au Pléistocène, un refroidissement climatique qui ne concorde pas avec les données polliniques régionales, (ii) le comblement du bassin en contexte de stabilité eustatique implique une stabilité du volume des glaciers continentaux en contradiction avec le contexte postglaciaire et l'afforestation de la région; (iii) le comblement du bassin pendant une phase de remontée eustatique sans rééquilibrage glacio-isostatique est inconcevable dans le contexte postglaciaire régional, même si l'on ne peut plus observer les paléorivages perchés du début du Sangamonien. Les conditions de compensation glacio-isostatique et de vitesse de déglaciation, de remontée eustatique et d'influx sédimentaires des phases postglaciaires fini-illinoienne et fini-wisconsinienne sont essentiellement comparables.

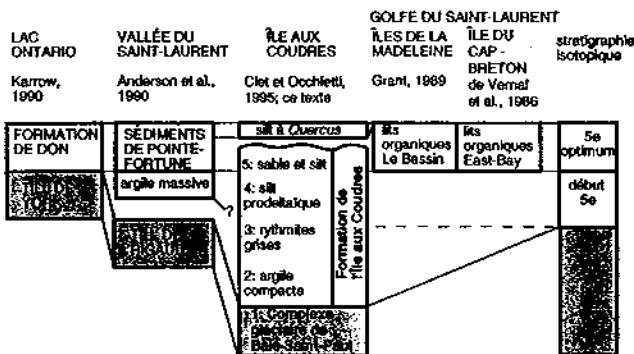
Position stratigraphique et âge

La séquence forée est sous-jacente (fig. 2) à la succession stratigraphique observée en continu depuis +6 m dans la coupe de la Calvette (Occhietti et Clet 1989; Clet et Occhietti 1995) et aux autres unités en affleurement décrites par Brodeur et Allard (1985) dans l'île aux Coudres. La séquence forée est donc plus ancienne que les lits à 17% de *Quercus* de la coupe de la Calvette (la phase à *Quercus* de la fig. 2) attribués à la fin de l'optimum climatique du Sangamonien (sous-stade 5e) ou à un remaniement immédiatement postérieur. Elle est également antérieure à deux unités impliquant deux phases glaciaires distinctes, représentées respectivement par des varves d'englaciation suivies d'une lacune d'érosion et par un till supérieur (fig. 2). Cette position stratigraphique, la position altitudinale sous le niveau de la mer et le contenu pollinique démontrent que les zones argileuses et silteuses de la séquence forée précèdent nécessairement la phase de plaine alluviale associée à l'optimum climatique du sous-stade 5e au cours de laquelle le niveau eustatique était plus haut que l'actuel. Le complexe glaciaire inférieur de la séquence forée représente un épisode glaciaire majeur, mono- ou multi-phased, antérieur au Sangamonien, c'est-à-dire l'Illinoien sensu lato (stade 6). La Formation de l'Île aux Coudres représente une inondation marine postglaciaire immédiatement postérieure, en majeure partie d'origine glacio-isostatique (fin du stade 6, transition 6–5 et début du sous-stade 5e). L'hypothèse que ces unités soient encore plus anciennes est peu plausible. L'ampleur des processus glaciaires et sédimentaires représentés par ces unités et leur contexte stratigraphique écartent également l'hypothèse d'une mise en place pendant et à la fin de l'un des deux épisodes modérément froids (5d ou 5b) du stade isotopique 5. La séquence forée n'a pas les caractéristiques d'un stade bref suivi d'une invasion de début d'interstade.

Corrélations

Sur le plan des corrélations (fig. 7), le Complexe glaciaire de Baie-Saint-Paul est l'équivalent régional du Till de Rigaud observé au site de Pointe-Fortune (Anderson et al. 1990), du Till de York situé sur la marge nord du lac Ontario (Karrow 1989) et probablement des tills les plus anciens de la vallée moyenne du Saint-Laurent (Till de Bécancour, Lamothe 1989, fig. 2; Till de Portneuf, Bernier et Occhietti 1991; zone inférieure du Till de Donnacona, Clet et al. 1991). La zone supérieure forée, sableuse et à grains de pollen d'arbres thermophiles, de la Formation de l'Île aux Coudres est en

Fig. 7. Hypothèse de corrélation, dans l'axe de drainage du Saint-Laurent, des unités du forage de l'île aux Coudres aux unités de l'Illinoien et de l'optimum climatique du Sangamonien.



corrélation avec les dépôts associés à l'optimum climatique de l'Interglaciaire Sangamonien, respectivement les Sédiments de Pointe-Fortune et la Formation de Don (Ontario). La Formation de l'Île aux Coudres est une nouvelle unité, intercalée en grande partie entre la nappe de tills illinoiens et ces dépôts interglaciaires.

Potentiellement, la Formation de l'Île aux Coudres et des faciès latéraux devaient s'étendre dans toutes les dépressions de la vallée du Saint-Laurent et des basses terres adjacentes, ce qui ouvre d'intéressantes perspectives de recherche. Ce vaste corps sédimentaire a été tronqué et il ne reste actuellement que des témoins sous certaines rives de l'estuaire et au moins sous le chenal de l'île aux Coudres (affleurements du Phare in Clet et Occhietti 1995; profil sismique de Sabeur 1994). En amont de l'estuaire moyen, les rythmites identifiées par forage (Lamothe 1989) ou observées à marée basse (Besré et Occhietti 1990; Bernier et Occhietti 1990) sous le Sable de Lotbinière, dans le secteur de Deschaillons, peuvent être en corrélation avec la Formation de l'Île aux Coudres ou d'une partie de celle-ci (fig. 2). Cette hypothèse est géométriquement plausible mais reste à démontrer. En aval de l'estuaire, d'après l'ampleur des dépôts marins et prodeltaïques de la Formation de l'Île aux Coudres, un influx sédimentaire majeur, associé à la déglaciation fini-illinoienne, devrait être enregistré dans le cône sous-marin à la sortie du golfe du Saint-Laurent et à sa périphérie, dans l'Atlantique Nord. Le forage de l'île aux Coudres constitue un élément important de corrélation continent-océan au cours de la transition de l'Illinoien au Sangamonien.

Par la position stratigraphique, l'épaisseur, l'altitude et les caractéristiques sédimentologiques, la séquence marine et prodeltaïque du forage de l'île aux Coudres est distincte (fig. 2) de l'Argile marine interstadiaire de la Pérade identifiée immédiatement sous les Sédiments de Saint-Pierre dans le haut estuaire du Saint-Laurent (Ferland et Occhietti 1990b). L'Argile de la Pérade est en effet peu épaisse (3–8 m), en position interstadiaire au-dessus de deux unités glaciaires, d'altitude supérieure au niveau actuel de la mer et à contenu pollinique indiquant une recolonisation végétale de type interstadiaire. La séquence stratifiée inférieure de l'île aux Coudres représente donc la troisième invasion marine distincte identifiée dans l'axe de drainage du Saint-Laurent. Le nom de Mer de Guettard est proposé pour cette mer intergla-

ciaire, d'après le premier naturaliste qui a publié des travaux sur la géologie de la vallée du Saint-Laurent (Guettard 1752). À la fin de la glaciation du Wisconsinien, la rive nord du moyen estuaire du Saint-Laurent où est localisée l'île aux Coudres a été déglacée et envahie par les eaux atlantiques (Mer de Goldthwait) vers 11 700 – 11 500 Av. P. (Dionne et Occhietti 1996) tandis que la baie d'Hudson a été déglacée et envahie par la Mer de Tyrrell vers 8000 Av. P. (Craig 1968). Par analogie avec ce décalage chronologique de l'ordre de 3500 ans, lié à une déglaciation plus tardive vers les hautes latitudes, le début de l'invasion de la Mer de Guettard dans l'estuaire du Saint-Laurent est probablement légèrement antérieur à l'invasion marine post-illinoiene de la Mer de Bell dans les basses terres méridionales de la baie d'Hudson, représentée par le faciès marin à la base de la Formation de Missinaibi (Skinner 1973). La Formation de l'Île aux Coudres est également l'analogie des unités marines interglaciaires de la Nouvelle-Angleterre et de l'État de New York, aux États-Unis, telles que les Argiles de Gardiners (Schafer et Hartshorn 1965) et les Sables de Sankaty (Oldale et al. 1982).

Conclusions : implications de la séquence du forage de l'île aux Coudres

(i) Les unités pléistocènes situées sous le niveau de drainage actuel du Saint-Laurent sont localement plus épaisses que les unités en affleurement. Cette dissymétrie était déjà explicitement reconnue dans l'estuaire supérieur (Occhietti 1990). Cette conclusion est en conformité également avec les épaisseurs obtenues par géophysique de Syvitski et Praeg (1989) dans l'estuaire inférieur du Saint-Laurent et de Praeg et al. (1992) dans l'estuaire moyen, même si l'interprétation sismostratigraphique proposée par ces auteurs doit être révisée à la lumière du forage de l'île aux Coudres.

(ii) L'estuaire moyen du Saint-Laurent fut le lieu d'une invasion marine et d'un comblement prodeltaïque et deltaïque continu qui a pu durer environ 3500 ans, à la fin de l'Illinoien et au début du Sangamonien. Cette invasion marine est analogue à l'invasion, à la fin du Wisconsinien, de la Mer de Goldthwait – Mer de Champlain dans l'estuaire et la vallée du Saint-Laurent.

(iii) Le Complexe glaciaire de Baie-Saint-Paul, identifié à la base du forage, indique le débâlement très poussé des chenaux de l'estuaire moyen du Saint-Laurent par l'*Inlandsis laurentidien* au cours de l'Illinoien. Cet indice d'une glaciation plus marquée que celle du Wisconsinien est conforme aux données géologiques connues (p. ex. Alam et Piper 1977). Au contraire, la glaciation wisconsinienne a préservé de vastes accumulations pléistocènes dans l'estuaire moyen du Saint-Laurent, notamment la Formation de l'Île aux Coudres et la séquence exposée sous le till supérieur dans les falaises de l'île aux Coudres. Les dépressions axiales qui constituent les chenaux nord du moyen estuaire (d'Anglejan et Brisebois 1974; Praeg et al. 1992) représentent, par conséquent, un piège sédimentaire épicontinentale d'unités pléistocènes.

(iv) La séquence marine et estuarienne fini-illinoiene et du début du Sangamonien de la Formation de l'Île aux Coudres implique que le moyen estuaire du Saint-Laurent a été entièrement comblé, au moins jusqu'à l'île aux Coudres et vraisemblablement jusque vers les hauts-fonds proches de

l'embouchure du Saguenay, avant l'optimum climatique du sous-stade isotopique 5e. La plaine alluviale contemporaine du début du Sangamonien devait s'étendre dans toute la vallée et le moyen estuaire du Saint-Laurent.

(v) La présence de sédiments stratifiés et stratiformes sangamoniens et présangamoniens de signature géophysique analogue (à la vitesse de propagation près) à celle des sédiments fini-wisconsiniens et holocènes du moyen estuaire du Saint-Laurent (Todd et al. 1991; Praeg et al. 1992) ouvre la voie à de nouvelles interprétations sismostratigraphiques à l'échelle de l'ensemble du bassin de drainage du Saint-Laurent et probablement dans le Saguenay. Une partie des unités sismostratigraphiques attribuées aux sédiments de la Mer de Goldthwait par Praeg et al. (1992) dans le moyen estuaire et par Syvitski et Praeg (1989) dans l'estuaire inférieur est certainement attribuable à des unités plus anciennes dont, en particulier, la Formation de l'Île aux Coudres.

(vi) Des analyses sédimentologiques, tomographiques et palynologiques plus détaillées de la carotte de l'île aux Coudres devraient permettre de préciser davantage l'évolution climatique et environnementale de la transition Illinoien–Sangamonien (transition 6–5), actuellement rarement présente dans les séquences sédimentaires épicontinentales et continentales. Il sera intéressant de comparer la séquence de l'estuaire du Saint-Laurent aux séquences du Danemark (Seidenkrantz 1993a, 1993b; Seidenkrantz et Knudsen 1994) et aux carottes de glace du Groenland (Dansgaard et al. 1993).

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STOP 1.8 ILE AUX COUDRES : MICMAC SHORELINE AND MITIS TERRACE

The field trip will stop on the road from the Calvette Section to Les Voitures d'Eau Hotel.
(Jean-Claude Dionne)

The twenty-foot terrace and sea-cliff described by J.W. Goldthwait (1911) and discussed by D.W. Johnson in *The New England-Acadian Shoreline* (p. 223-233) is a complex feature common to both shores of the St. Lawrence Estuary. As described long ago, the Micmac shoreline is composed of three distinct units: 1) a former cliff cut into both bedrock and marine clay, which extends most continuously from Québec City to Sainte-Anne-des-Monts (Gaspé Peninsula), and discontinuously from Québec to the Saguenay River, on the north shore of the St. Lawrence Estuary; 2) a low accretion terrace, a few hundred meters wide, built at the foot of the cliff; and 3) a shore platform cut alternatively in shales or clay, which extend into present day intertidal zones. In addition, the three units present many morpho-sedimentological variations from place to place.

Detailed investigations of each unit in various areas have been made recently in order to determine how and when these characteristic features were produced, and what is their respective significance. Based on 62 radiocarbon dates from 19 localities, the low accretion terrace (commonly called the Mitis terrace) was built between 2.8 and 1.5 ka, with a median age of 2030 ± 50 y. B.P.

Consequently, at that time the relative sea level was about 4.5 to 3.5 m higher than at present. Where the cliff and the adjacent intertidal platform are cut into marine clay, they are mid- to late- Holocene features, pre- or post-dating the construction of the low terrace. The rock cliff and related shore platform are inherited features of pre-Wisconsin age, which were only slightly modified by shore processes during the Holocene. To avoid confusion, there is a necessity to distinguish the sequence of events when referring to the Micmac shoreline.

CHAPTER 4
DESCRIPTION OF FIELD STOPS
Sunday June 3, 2001

8 h - 8 h 20		Ferry from Isle aux Coudres to Saint-Joseph de la Rive
9 h 55		Arrival at the Whale watching boarding point, Baie-Sainte-Catherine
10 h 20 - 10 h 30		Ferry to Tadoussac. Collation
10 h 30 - 11 h 30	Stop 2.1	Tadoussac delta and St. Narcisse readvance, marine fan at the mouth of the Saguenay
11 h 40 - 12 h		Ferry to Baie-Sainte-Catherine
12 h 10 - 13 h 30	Stop 2.2	Walk to Pointe aux Alouettes: ice contact deposits with shell fragments dated at 35 ka BP Lunch (The whale watchers will be taken by car)
13 h 40 - 14 h	Stop 2.3	View of the Rivière aux Canards Section: glaciomarine stony clay (St. Narcisse event) interbedded in marine clays
14 h 20 - 14 h 30	Stop 2.4	St. Narcisse Moraine at Saint-Siméon and marine clay in valleys of the Laurentians
15 h 15		View stop 2.5 Morainic ridges of the St. Narcisse complex
15 h 35 - 16 h		Optional touristic stop at Baie-Saint-Paul Collation
17 h		Return to the Quartier Hotel End of the FOP 2001 excursion

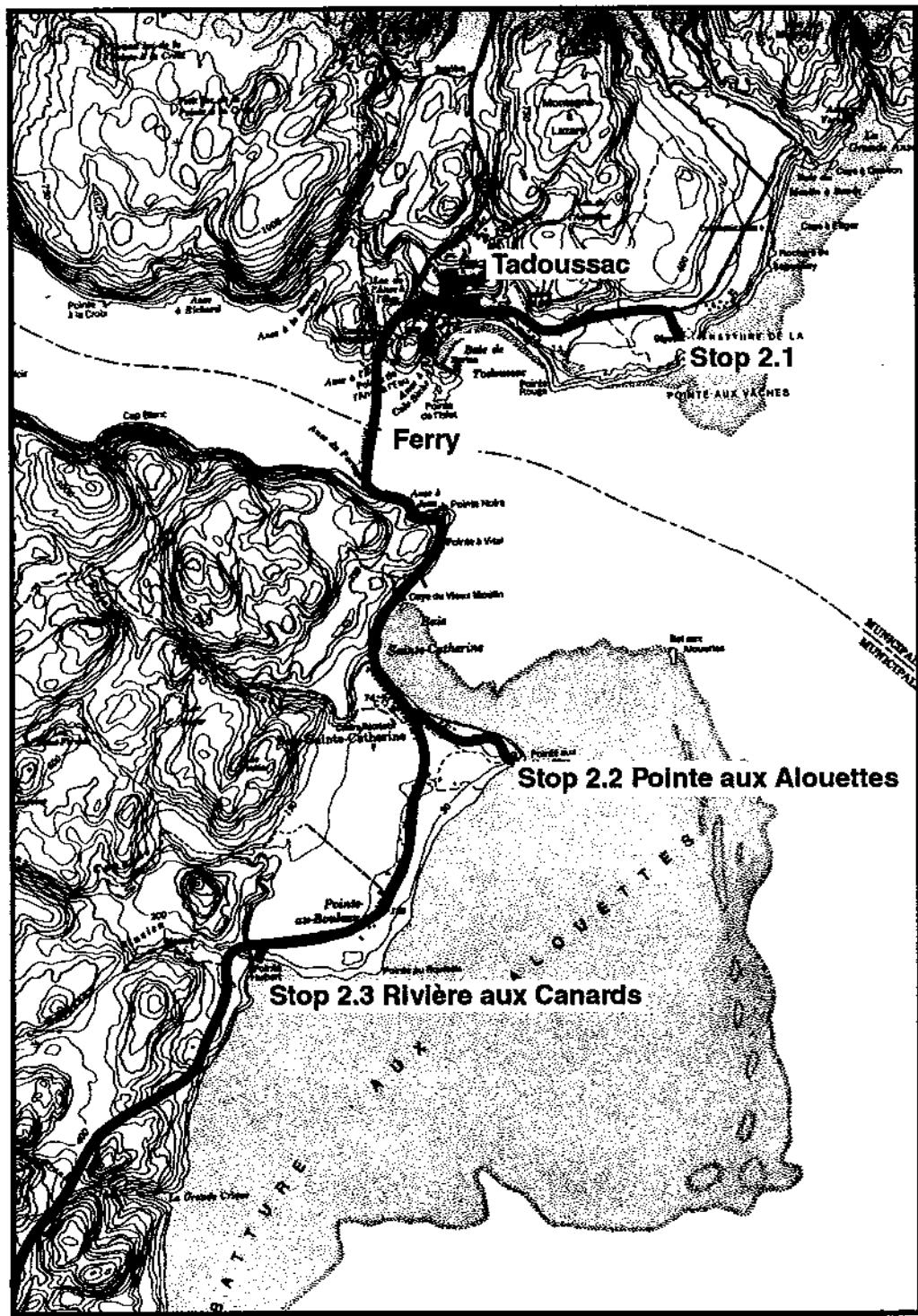


Figure 4.1 Stops : 2.1, 2.2 and 2.3 in the Saguenay area: Tadoussac Delta, Pointe aux Alouettes and Rivière aux Canards. (1:50 000 topographic map 22C/4)

STOP 2.1 : TADOUSSAC DELTA

From the center of Tadoussac, take the road to the East, toward the Batture de la Pointe aux Vaches for 2.5 km.

Outline of the Quaternary geology of the Tadoussac area (Jean-Claude DIONNE et Serge OCCHIETTI) (see the annexed reprint Dionne and Occhietti, 1996)

Introduction

The Saguenay is the only classic fjord of southern Québec. It is a major river draining a watershed of 88,100 km² which includes the Lake Saint-Jean Basin. During the Wisconsinan, this large valley has influenced the ice flow. A main ice stream flowed SE until the St. Lawrence Valley and then was deflected to the NE. Until recently little was known about the Quaternary of the lower Saguenay area, particularly the area of Tadoussac located at the fjord entry.

Geographic and geologic setting

Tadoussac is located on the north shore of the St. Lawrence Estuary, approximatively 225 km downstream from Québec City. The Saguenay is at the frontier between the middle and the lower St. Lawrence Estuary. The area of Tadoussac is characterized by three main physiographic units: 1) the Laurentide Shield forming a plateau at a mean elevation around 500-600 m; 2) a series of terraces including wide tidal flats on both sides of the Saguenay mouth; and 3) submarine units with a relatively complex topography and a submarine drainage channel.

The highlands are made of Precambrian igneous and metamorphic rocks forming a series of rounded massive hills mostly devoided of drift. The terraces are made of Late Pleistocene and Holocene unconsolidated fine to coarse grained deposits. The wide Alouettes tidal flat, a unique feature of the St. Lawrence Estuary, is made of fine-grained stratified deposits several meters thick, and also of older buried deposits. The thickness of the unconsolidated deposits underlying the tidal flat is estimated to exceed 200 m.

Ice flow direction

Ice flow direction in the Lower Saguenay region is relatively well known since a field survey made at the beginning of 1970 was completed recently (Dionne, unpublished map). The main ice flow is from NW to SE, with direction between 100° and 140°. Near Tadoussac, the ice flow was mainly 120°-140°. At a few sites, there is also an ice flow NNW-SSE around 170°. Along the shoreline and away from the Saguenay fjord entry, an ice flow to the NE has been also recognized. Although there is no data allowing to date the various ice flow directions, we suggest that the NW-SE direction is older than the NNW-SSE and SW-NE ice flow directions which are more closely related to deglaciation.

The maximum level reached by the Goldthwait Sea was not well known. The Glacial map of Canada (Prest et al., 1970) reported 465 feet (approx. 124 m) for the Tadoussac area, while Vincent (1989) and Occhietti (1989) in the Quaternary Geology of Canada referred to 167 and 150 m respectively. According to our data, we think that the Goldthwait Sea maximum level was about 140 m in the vicinity of Tadoussac and 150 m in the area of Sacré-Cœur-de-Saguenay, a locality about 15 km NW, and 180 m in the southern part of the Lake Saint-Jean Basin.

Quaternary deposits and Pleistocene-Holocene stratigraphy

1. Grandes-Bergeronnes area

At Grandes-Bergeronnes, a locality approximately 20 km NE of Tadoussac, the 20-m terrace is composed of the following units from the bottom to the top (Fig. 5, in Dionne and Occhietti, 1996). The first unit is a brownish calcareous stiff clay which outcrops at the base of the cliff, throughout the intertidal zone. Thickness and age of this clay are not known. It is overlain by a grey calcareous till including several striated clasts of Trenton limestone and Proterozoic dolostones. Fossiliferous marine stratified sand and gravel (beaches) deposits overlie the till. The till overlying the brownish clay is up to 20 m thick. In the estuary of Petites-Bergeronnes, approximately 3 km to the west, an erosion surface is cut into Goldthwait Sea clay and covered by an intertidal deposit dated at 6 to 6.3 ka from clams (*Mya arenaria*) in living position.

2 Baie-Sainte-Catherine complex

The Baie-Sainte-Catherine complex is characterized by a peninsula 3.5 km long and 2.5 km wide, formed by Quaternary deposits, and located at the foot of the Laurentides escarpment. This landform is cut into by several terraces, particularly at the elevations of 6, 15, 20, 30 and 40 m. It is also fronted by a large tidal flat up to 6 km wide and 12 km long. This sedimentary complex is made of various deposits including: a) littoral sand and gravel at surface; b) Goldthwait Sea marine silty-clay dated 8.3 to 10.7 ka; c) silt-clay prodelta marine rhythmites, dated 11.3 to 11.7 (?) ka; d) diamictite or till; e) fluvioglacial gravel; f) an old fossiliferous marine coarse sand deposit dated circa 35 ka; g) and a late Holocene muddy-clay tidal deposit dated 1.1 to 2.1 ka. (see STOPS 2.2 and 2.3).

3. Tadoussac complex

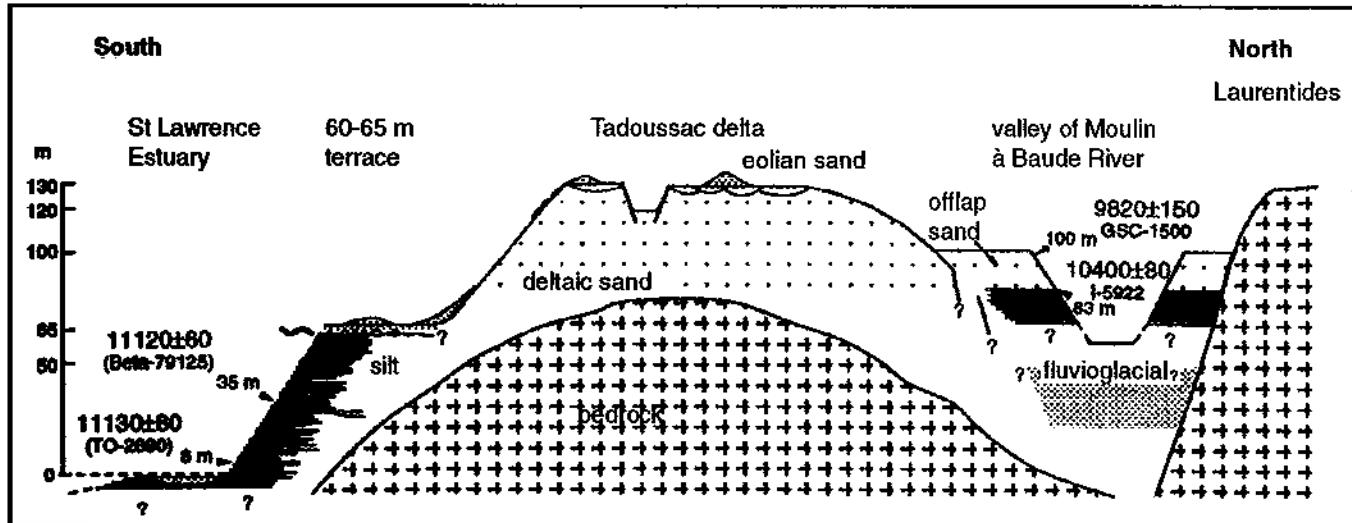


Figure 4.2 : The Tadoussac raised proglacial delta. The delta is related to the St. Narcisse ice front readvance.

The Tadoussac area is characterized by thick surficial deposits associated to a series of terraces and escarpments. One major sequence is exposed in the cliff and gullies cut into the 60 m terrace at Pointe aux Vaches. This terrace is composed of the following units. On the surface are sand and gravel deposits about 2 m in thickness. These beach deposits overlie a 60-m thick sequence of stratified grey fine sand and silt, and silt and clay with massive bodies of medium to coarse sand. These prodelta deposits are slightly fossiliferous and dated at 11.1 - 11.5 ka.

Above the 60-m terrace is a raised sand and gravel delta, at 125-130 m a.s.l. The presence of a few kettles at the surface suggests an ice-marginal deposition. Since the delta overlies the 60-m terrace, it is younger and most likely related to the St-Narcisse event dated circa 10.8-10.6 ka. Another small delta at the same altitude is also found on the right side of the Saguenay, west of Pointe-Noire.

The Micmac shoreline

At Pointe aux Alouettes, the Micmac shoreline of Goldthwait (1911) is cut into the 20-30 m terrace, at an elevation of 6 m. The shoreline extends between Pointe aux Alouettes and Pointe au Bouleau, and has been severely eroded for many years. Only a small portion remains today. The following sections are representative of the back portion of the terrace near its contact with the Micmac cliff. Marine silt-clay rhythmites dated 11.4 ka are exposed at the base of the cliff. They are truncated by an erosion surface overlain by an intertidal silty-clayey deposit (1 to 2 m thick) dated from 2.1 to 1.1 ka. The tidal deposit is covered locally by sand and gravel beaches dated at 1.3-1.1 ka, or by peat dated 910 to 1,050 years BP. In addition, the surface is locally covered by mudflow deposits, 1 to 2.5 m thick, which contains tree trunks and peat dated between 690 to 1,260 years BP.

In the area near Pointe aux Alouettes, the low terrace is more sandy, but the tidal unit is present everywhere and the surface is usually covered by clay colluvium 30 to 50 cm in thickness. There is an archeological site in this area dated 880-890 y. BP.

Land emergence and Holocene relative sea level

A series of about 30 radiocarbon ages from the Quaternary deposits and a series of more than 40 ages from the Micmac shoreline are now available in the area of Tadoussac. They allow us to suggest the following land emergence or fluctuation of the relative sea level during the Holocene.

Assuming 140-150 m for the maximum level of the Goldthwait Sea at about 11.5 ka, the isostatic recovery has been relatively rapid. By 6-6.3 ka, the sea level was close to the present level. It subsequently rose circa 2 ka and cut back the Micmac Cliff into the silty-clay 30 m terrace and built the Mitis Terrace. The median age (N-16) of the tidal deposit of the Mitis Terrace is 1.4 ka. Along the St. Lawrence Estuary, the median age of the Mitis Terrace, based on 26 radiocarbon dates from 15 localities, is $2,080 \pm 60$ BP (Beta-33922). It is close to the median age (N-23) of the lower terrace at Petite-Rivière, which is $2,000 \pm 50$ BP (Beta-38605).

Conclusion

In summary, there is evidence that the sea reached the area of Tadoussac before Late Wisconsinan. The fossiliferous sand deposit is a relict deposit of a deglaciation phase. According to amino-acids analysis, the radiocarbon age of 34.5 ka is probably a minimum age for the relict sand deposit of Pointe aux Alouettes.

The age of the brownish calcareous clay overlain by a calcareous till in the area NE of Tadoussac is not known, but is older than the till, and the overlying Goldthwait Sea silt-clay dated between 12 and 11 ka.

The prodelta complexes of Tadoussac and Baie-Sainte-Catherine were built at a time when an ice tongue still occupied the Saguenay fjord. This ice probably remained at that position until the St-Narcisse event during which the raised delta at Tadoussac was built circa 10.8 - 10.6 ka.

The Saguenay fjord was deglaciated quite rapidly, the postglacial submergence of the upper Saguenay area occurred soon after 10 ka. As the ice retreated, the depressions on both sides of the Saguenay were submerged and filled mainly with sand, silt and clay. However, many depressions were also partly filled with glaciomarine stony clay and grey calcareous till containing striated clasts of Trenton limestone and Proterozoic dolostone. Further investigations are necessary to reconstruct all the geologic events which occurred during the Quaternary in the Tadoussac area.

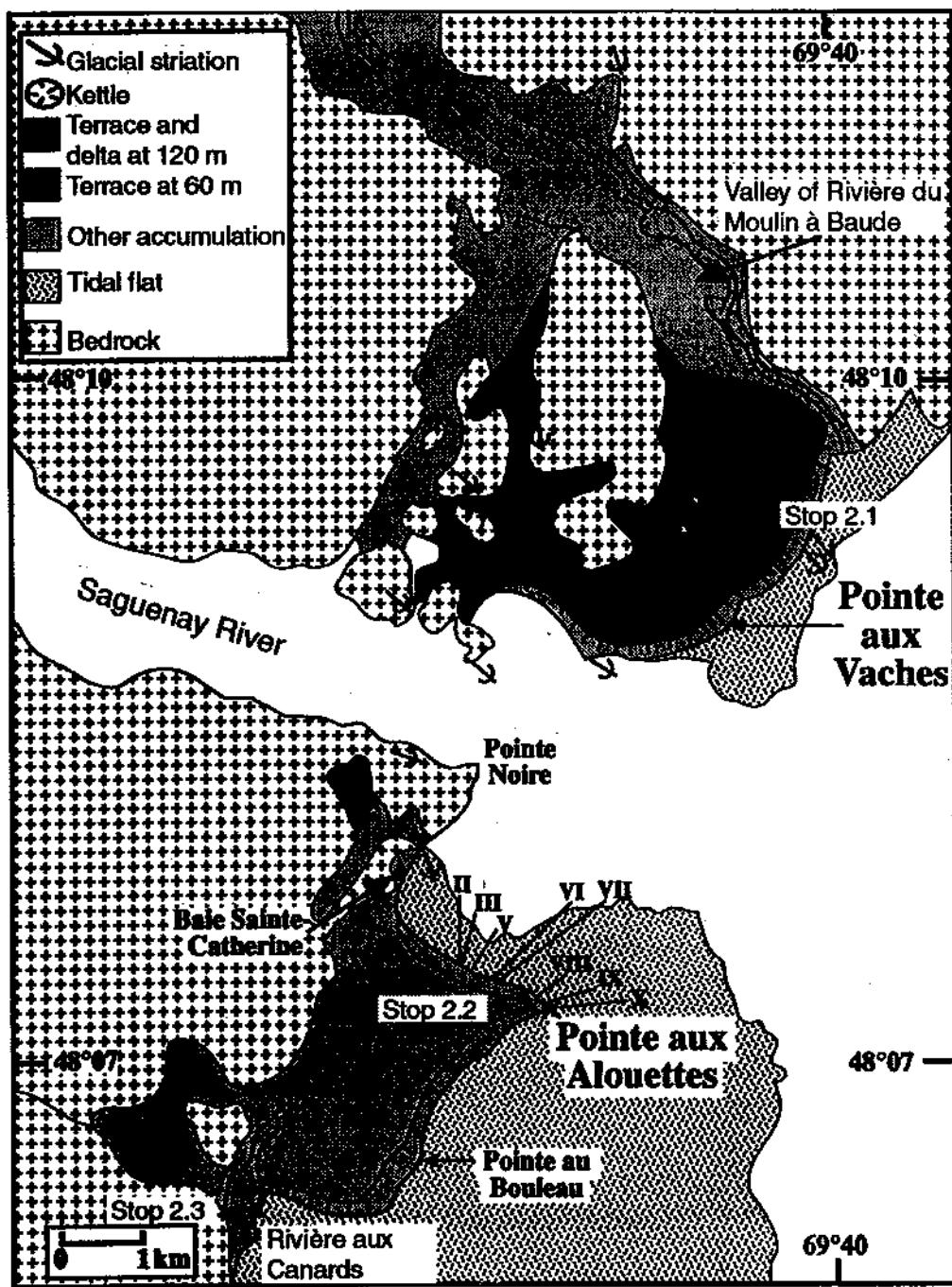


Figure 4.3 : Location of sites and sections in the Tadoussac area. Note the extent of the tidal flats.

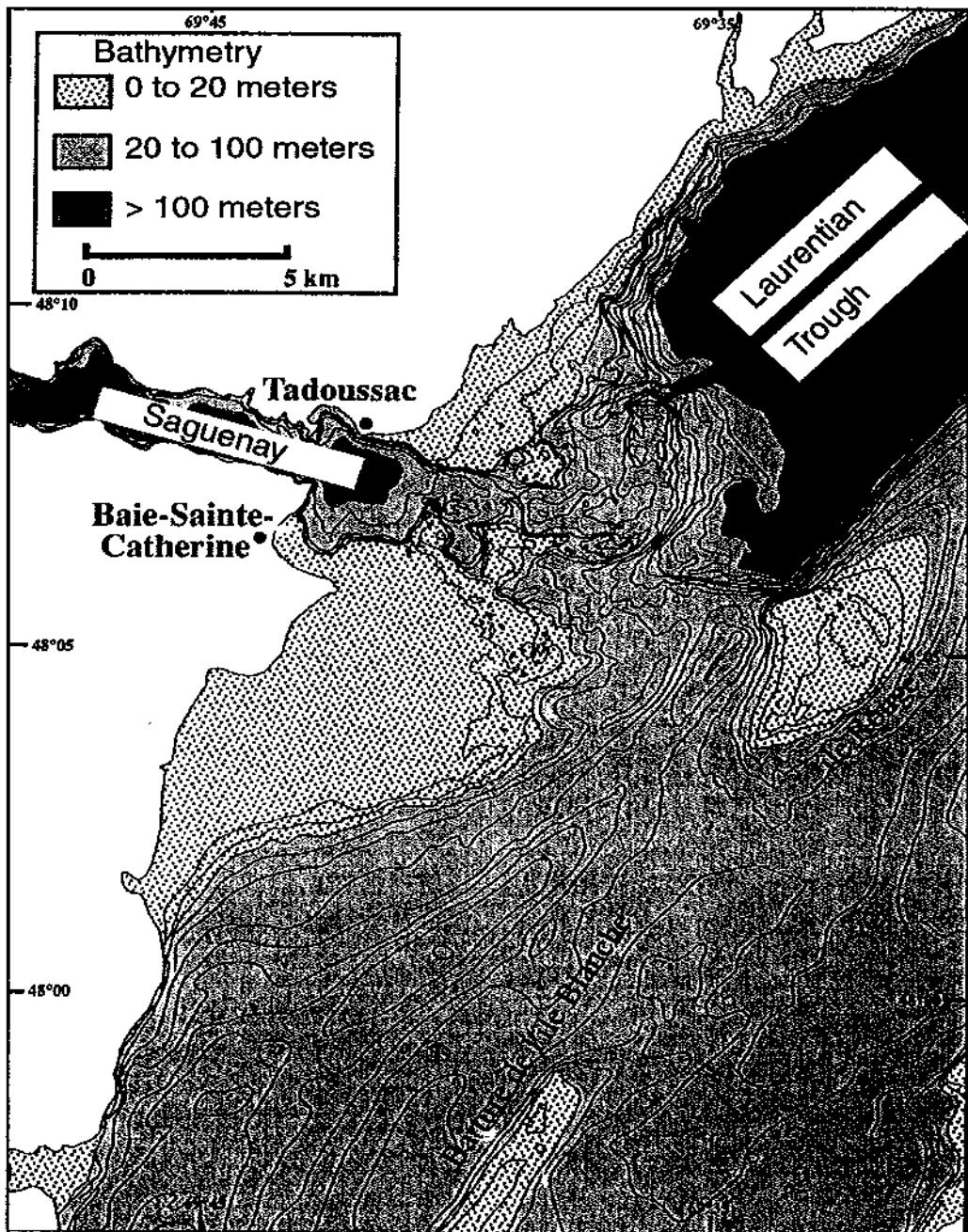


Figure 4.4 : Bathymetry at the mouth of Saguenay River (from Dionne and Occhietti 1996).

STOP 2.2 : POINTE AUX ALOUETTES

From Road 138, private road on the east side, in front of the gas station of Baie-Sainte-Catherine. The Pointe aux Alouettes is located 1200 m ($\frac{3}{4}$ mile) from the gate.

Pointe aux Alouettes 20-30 m terrace. (Jean-Claude Dionne and Serge Occhietti)

Along the 20-30 m terrace between Pointe aux Alouettes and Baie-Sainte-Catherine, many exposures show various deposits of interest (Sections I to X, Fig. 4.3). The outer limit of Pointe aux Alouettes is made of coarse sand and gravel, on the lower half of the cliff. The coarse well graded sand contains small fragments of shells, mainly barnacles (*Balanus* sp.) and mussels (*Mytilus* sp.) dated 34.9 ka. This old deposit is overlain by several meters of coarse sand and cobble interpreted as a fluvioglacial or an ice-marginal deposit in a marine environment. The surface of the deposit is reworked by Holocene beaches and contains a few marine shells. In other exposures, the fossiliferous coarse sand deposit, which is often thicker than at Pointe aux Alouettes, is overlain by silt-clay rhythmites with diamict layers and is locally covered by an upper aqua-till. To the north, the basal fossiliferous sand deposit disappears and is replaced by Goldthwait Sea fine grained stratified deposits capped by a tidal unit and by sandy beach deposits. The marine and tidal units of the 20-30 m terrace in this section are dated 8.3 to 10.7 ka. The 20-m terrace, in front of Baie-Sainte-Catherine village, is apparently composed entirely of sand and gravel. The junction between the 20-30 m terrace of Pointe aux Alouettes and the 20-m terrace of Baie-Sainte-Catherine is complex. The surface unit is a beach sand about 2 m thick. This unit overlies about 3 m of fine grey sand (a shallow water or an intertidal deposit), which covers 2-3 m of stratified marine silt-clay. These Goldthwait Sea and Holocene marine-estuarine units are encased into a gravelly fluvioglacial deposit.

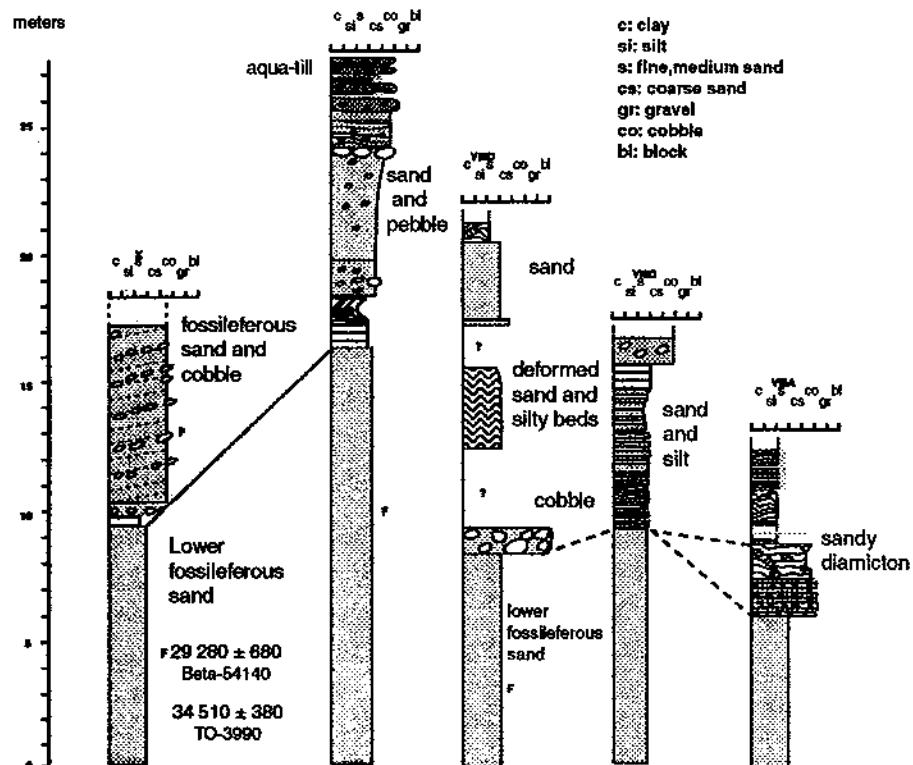


Figure 4.5 : Sections VIII, IX and X at Pointe aux Alouettes from Dionne and Occhietti (1996). Outcrops of marine sand and cobble are related to a mid-Wisconsinan interstadial episode.

Table 4.1: Alle/ile ratios (total amino acids) of Pleistocene - Holocene marine shells from temperate to sub-arctic areas

Areas/ Events	Species	Age ka or stages	Alle/ile (Total)
Tadoussac ¹	<i>Balanus hameri</i>	35 ka	0.260 ± 0.060
Goldthwait Sea ¹	<i>Mytilus edulis</i>	8.8 ka	0.08 ± 0.012
	<i>Balanus hameri</i>	8.8 ka	0.094 ± 0.050
Cartier Sea ²	<i>Nucula</i> sp.	about 100 ka	0.333 ± 0.039 N: 0.268 ± 0.031
Champlain Sea ²	<i>Nucula tenuis</i>	11.1 -11.3 ka	0.087 ± 0.019
	<i>Hiatella a.</i>	10.3 ka	0.070 ± 0.010
	<i>Mya truncata</i>	11.25 ka	0.071 ± 0.020
		9.5 ka	0.048 ± 0.010
Hudson Bay ³			
-Bell Sea	<i>Hiatella a.</i>	6/5 or older?	0.200 ± 0.03
-intermediate event	id.	5a or older?	0.140 ± 0.02
-intermediate event	id.	35 ± 10 ka	0.065 ± 0.009
-Tyrell Sea	id.	7 - 8 ka	0.036 ± 0.015
St. Lawrence Gulf ⁴			
-Nova Scotia	<i>Mercenaria m.</i>	stage 5	0.212 ± 0.010
North Sea (Denmark, Germany, Netherlands) ⁵			
-Eemian	moderate rate	substage 5e	0.18 ± 0.02
-late Weichselian	sp, id,	10-12 ka	0.06 ± 0.01

¹Dionne and Occhietti, 1996

²Occhietti et al., 1996

³Andrews et al., 1983

⁴Stea et al., 1992

⁵Miller and Mangerud, 1985

STOP 2.3 : RIVIERE AUX CANARDS SECTION

On Road 138, on the south side of the bridge over the Rivière aux Canards.

The 20-30 m terrace of Rivière aux Canards (Jean-Claude Dionne and Serge Occhietti)

On both sides of the Rivière aux Canards mouth, the 20-30 m terrace is well exposed because of continuous active erosion. On the south side (Pointe Hubert), the terrace is composed mainly of silt-clay rhythmites including several thin layers of diamicts and occasionally more massive bodies of diamicts. The rhythmites are slightly carbonated, contain many dropstones, and are poorly fossiliferous. At about 8 m below the surface, a continuous 1 m thick layer of sandy diamicton is interstratified in the marine rhythmites. The diamicton, related to the St. Narcisse episode, contains striated clasts of Trenton limestone and Proterozoic dolostone with and without stromatolites. The last 4 m below the surface of the terrace is made of stratified silt and fine sand. Two ^{14}C ages of 10.8 and 11.3 were obtained on marine shells.

This thick fine-grained sequence with diamicts inclusions and dropstones is interpreted as an ice-marginal submarine fan. It is linked to a till which builds up a point located 500 m to the south (the Diamicton Point).

On the north side towards Pointe au Bouleau, the 20-30 m terrace is entirely composed of poorly fossiliferous silt-clay rhythmites with a few dropstones; they were dated 11.4 to 11.7 ka.

Since mid-Holocene, this area has been severely affected by landslides and mudflows. Basal peat and wood in a depression on the floor of a large landslide have released ^{14}C ages of 4.2 and 4.5 ka.



Figure 4.6 : Rivière aux Canards Section: a 1m-thick diamicton is interstratified in ice marginal submarine rhythmites. The diamicton is related to the St. Narcisse readvance.

Un kame sur la batture aux Alouettes, près de l'embouchure du Saguenay, Québec

Jean-Claude Dionne¹

Division de la science des terrains

Dionne, J.-C., 1996 : *Un kame sur la batture aux Alouettes, près de l'embouchure du Saguenay, Québec; dans Recherches en cours 1996-C; Commission géologique du Canada, p. 177-182.*

Résumé : Contrairement à la majorité des îles du Saint-Laurent estuaire, la petite île du Chafaud aux Basques, à l'extrême sud de la vaste batture aux Alouettes, à l'embouchure du Saguenay, est entièrement constituée de matériaux meubles sablo-graveleux stratifiés avec des couches diamictiques caillouteuses. Il s'agit d'un kame sis à la limite des basses mers et reposant sur un estran silto-argileux au pied de l'escarpement du Bouclier laurentidien. Essentiellement précambriens, les matériaux proviennent de l'arrière-pays. L'écoulement glaciaire dans l'anse du Chafaud aux Basques est orienté 95°-105°. À peine modifié par les eaux de la Mer de Goldthwait, ce kame résiduel indique fort probablement la position du front glaciaire dans ce secteur de la côte nord lors de la récurrence de Saint-Narcisse, datée de 11 -10,6 ka.

Abstract: Although most islands in the St. Lawrence estuary are rocky, the islet called Île du Chafaud aux Basques, located at the southern end of the large tidal flat aux Alouettes, at the mouth of the Saguenay fjord, is composed entirely of unconsolidated stratified sand and gravel with bouldery diamict layers. This islet is a true kame occurring at low tide level on a silty-clayey flat that extends from the foot of the Laurentides Shield escarpment. Rock debris are essentially from the inland Precambrian substrate. Late glacial flow directions in Chafaud aux Basques cove are 95°-105°. Slightly modified by wave action during the Goldthwait Sea episode, this relict kame most likely indicates the ice front position during the St. Narcisse event dated at 11-10.6 ka in the area.

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INTRODUCTION

Aucun exemple de kame sur les rivages du Saint-Laurent, en aval de Québec, n'étant connu, il s'avère utile de signaler celui de l'anse du Chafaud aux Basques découvert récemment (Dionne, 1994a) et de proposer une interprétation préliminaire.

OBSERVATIONS

L'île du Chafaud aux Basques est située en face de l'anse du même nom ($69^{\circ}45'50''W$, $48^{\circ}01'30''N$), soit à l'extrême sud de la vaste batture aux Alouettes, sise du côté sud-ouest de l'embouchure du Saguenay (fig. 1), à une vingtaine de kilomètres de Pointe-Noire. A cet endroit, on trouve une petite anse découpant la ligne de rivage taillée à même le grand escarpement rocheux du Bouclier laurentidien.

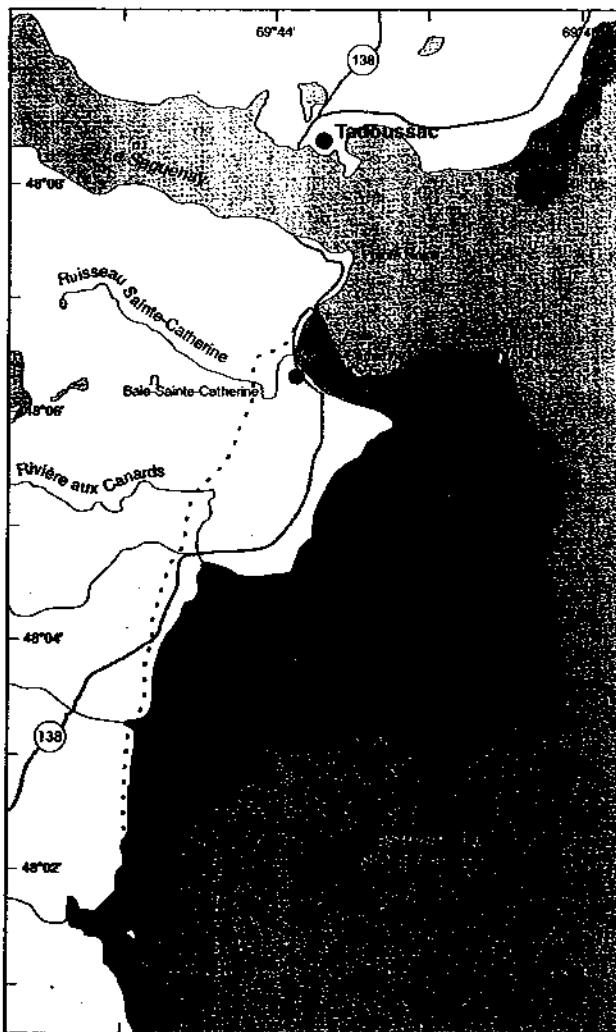
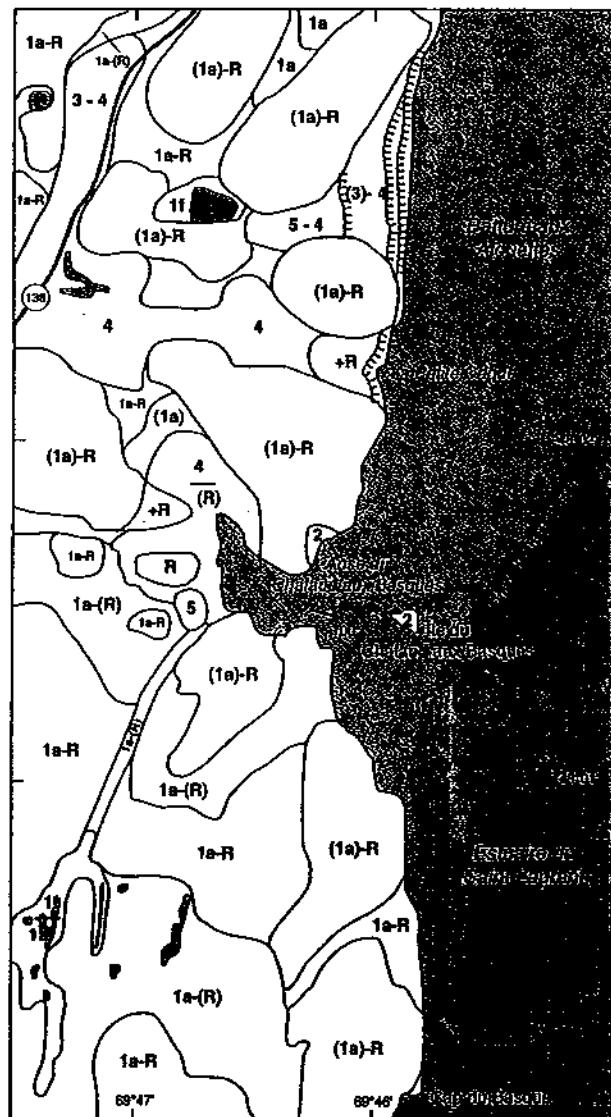


Figure 1. Carte de localisation et noms de lieux

Située à la limite des basses mers (fig. 2), la petite île, de forme triangulaire et cônique, s'élève à 25 m environ au-dessus de l'estran environnant. Elle se trouve dans le prolongement de la ligne du rivage rocheux, de part et d'autre de l'anse. Elle mesure environ 150 m de longueur (axe a) et 90 m de largeur (axe b). Elle est caractérisée par des pentes escarpées mais rarement taillées en falaise vive, car elle est ceinturée par un



R	: Substrat rocheux : roches précambriques	2	: Fluvio-glaciaire
(1a)-R	: Till très mince sur roc	3	: Sédiments ittoraux (Mer de Goldthwait)
1a-R	: Till mince sur roc	4	: Sédiments fins (Mer de Goldthwait)
1a-(R)	: Till sur roc	5	: Tourbe
(1a)	: Till relativement épais	TTTTTTT	: Talus d'érosion
II	: Till délavé	→	: Striae glaciaires

Figure 2. Extrait de la carte des formations meubles de Tadoussac (Dionne, 1972), dans le secteur de l'anse du Chafaud aux Basques.

cordon de gros blocs (fig. 3). Du côté est, exposé aux vagues, les blocs sont presque tous de taille métrique, les plus gros excédant 2 m (L). Les cailloux représentent diverses lithologies ignées et métamorphiques du Bouclier laurentien d'âge précamalien, situé à proximité (Miller, 1973). Du côté de la mer, on observe un beau replat d'érosion vers 15 m d'altitude. Le sommet de l'îlot est relativement plat.

Sur la photo aérienne prise en 1976 (fig. 4), l'îlot est entièrement boisé. Il y avait alors un beau couvert de résineux et de feuillus comprenant des épinettes (*Picea sp.*), des sapins (*Abies sp.*) et des bouleaux (*Betula papyrifera*). Lorsque nous avons visité l'îlot pour la première fois en 1989, le couvert végétal arborescent avait été détruit par une colonie de cormorans à aigrettes (*Phalacrocorax auritus*). Des reprises d'érosion à quelques endroits sur les versants escarpés ont alors permis d'examiner la nature du dépôt.

Le dépôt comporte essentiellement des matériaux détritiques grossiers (rudites et arénites) stratifiés avec des couches de galets et des blocs, les couches ayant un pendage général vers l'est, c'est-à-dire vers la vallée du Saint-Laurent. Sont associés aux sédiments fluvioglaciaires des masses de diamicton sableux de tailles variées. L'analyse granulométrique d'un échantillon de diamicton provenant de la partie sommitale du côté sud de la butte a révélé que la matrice contenait 19 % de petit gravier, 68,9 % de sable, 9,5 % de silt et 2,6 % d'argile. Le tri est faible, l'indice de Trask étant de 2,984. La teneur en carbonates (calcite) est à peu près nulle : 0,3 % seulement. On n'y a observé aucun cailloux carbonaté (calcaire de Trenton ou dolomie du Protérozoïque). Il n'y en a pas non plus sur le haut de plage au pied du rivage rocheux environnant. Les premiers éléments carbonatés sur le rivage actuel ont été observés après la Petite Crique, à plus de 3,5 km au nord (Dionne, 1994b).



Figure 3. Vue générale du kame de l'anse du Chafaud aux Basques, à marée basse. À remarquer le couvert forestier détruit par les cormorans et les cicatrices d'érosion apparues par la suite. La butte, d'environ 25 m de hauteur, est ceinturée par un cordon de gros blocs précambriens (6-10-89).

Le cordon de gros blocs ceinturant l'îlot atteste de l'abondance des blocs dans la butte, ce qui indique la présence d'une source située à faible distance ou encore d'un agent de transport puissant lors de leur dépôt.

Une belle flèche en queue de comète (fig. 4), constituée de sable et de petit gravier, s'est formée du côté ouest de l'île du Chafaud aux Basques, c'est-à-dire du côté abrité. Ce cordon d'environ 250 m de longueur sur une quinzaine de mètres de largeur se prolonge vers le fond de l'anse, en direction d'un îlot rocheux. Ce dernier montre un façonnement glaciaire bien conservé avec une surface polie et striée indiquant un écoulement de la glace selon une direction de 95°-105°, soit grossièrement parallèle à l'axe central de l'anse. Cette direction se retrouve ailleurs dans la région de Tadoussac (Dionne et Occhietti, 1996).

L'estran ceinturant la butte est constitué essentiellement de silt et d'argile stratifiés de couleur gris pâle. À proximité de l'îlot, la surface de l'estran est en grande partie masquée par de minces placages de sable et gravier et des blocs épars. À certains endroits, cependant, la surface argileuse affleure. La flèche en queue de comète repose d'ailleurs sur l'argile. Fait intéressant à signaler, le poids de la masse sédimentaire provoque une surcharge, de sorte que l'argile sous-jacente injectée vers le haut forme des bourrelets diapiriques en bordure de la flèche. La grande batture, qui s'élargit jusqu'à 5,5 km en direction nord vers l'embouchure du Saguenay (fig. 1), est elle aussi, du moins en surface, composée de silt et d'argile stratifiés (Dionne et Occhietti, 1996).

Sur la rive nord, à la sortie de l'anse du Chafaud aux Basques, on a observé un petit dépôt résiduel de type diamictique grossier accroché au versant rocheux. Le matériau sablo-graveleux contient beaucoup de cailloux dont plusieurs de taille métrique. Il s'agit vraisemblablement d'un dépôt apparenté au kame.

Dans les environs de l'anse du Chafaud aux Basques, les collines rocheuses dominent partout et sont en grande partie dénudées. Plutôt mince, le till est concentré dans les dépressions (fig. 2). À l'instar de la dépression de la Petite Crique, au nord, la dépression qui entaille le bouclier à la tête de l'anse du Chafaud aux Basques a un fond rocheux couvert d'une mince couche de till et de sédiments fins silto-argileux laissés par la Mer de Goldthwait; cette dernière a atteint une altitude maximale d'environ 140-145 m dans le secteur. Il ne semble pas y avoir eu de communication entre les deux dépressions.

INTERPRÉTATION

Première interrogation : s'agit-il vraiment d'un kame? Si on se fonde sur les caractéristiques du dépôt, la butte de l'anse du Chafaud aux Basques correspond exactement à la définition d'un kame offerte dans l'ouvrage «Vocabulaire de la géomorphologie» (Conseil international de la langue française, 1979, p. 110): «Dépôt hydro-glaciaire dont les matériaux sont semblables aux moraines d'ablation, mis en place dans des dépressions d'obturation soit entre des lobes d'un glacier, soit en position juxtaglaciaire». La butte de

L'anse du Chafaud aux Basques correspond aussi à la définition d'un kame offerte dans le Glossary of Geology (Bates et Jackson, 1987, p. 354). Il s'agit bien d'un dépôt juxtaglaciale.

Le deuxième aspect concerne la signification précise du kame de la batture aux Alouettes. D'une part, s'agit-il d'un fragment de moraine frontale appartenant à une langue glaciaire (glacier de piedmont) canalisée dans la dépression de l'anse du Chafaud aux Basques et étalée sur le rivage en face, ou s'agit-il plutôt du front de l'Inlandsis laurentidien formant un grand arc à l'embouchure du Saguenay (Dionne et Occhietti, 1996)? D'autre part, à quel événement se rattache

cette butte résiduelle? S'agit-il d'une butte mise en place au Wisconsinien supérieur ou antérieurement ou bien d'un dépôt frontal lié à la récurrence de Saint-Narcisse au tardiglaciale?

En raison de l'échelle, les cartes de Prest (1969) et de Dyke et Prest (1987) retracant les fronts glaciaires de l'Inlandsis laurentidien sont peu utiles pour résoudre le problème. La série de cartes de la position du front glaciaire de LaSalle et al. (1977) montre le tracé de l'Inlandsis laurentidien dans le secteur de l'embouchure du Saguenay entre 11 et 10,5 ka (fig. 5). Sur la figure 5A, on constate que vers 11,3-11 ka, le front de l'Inlandsis laurentidien, sur la rive nord du moyen

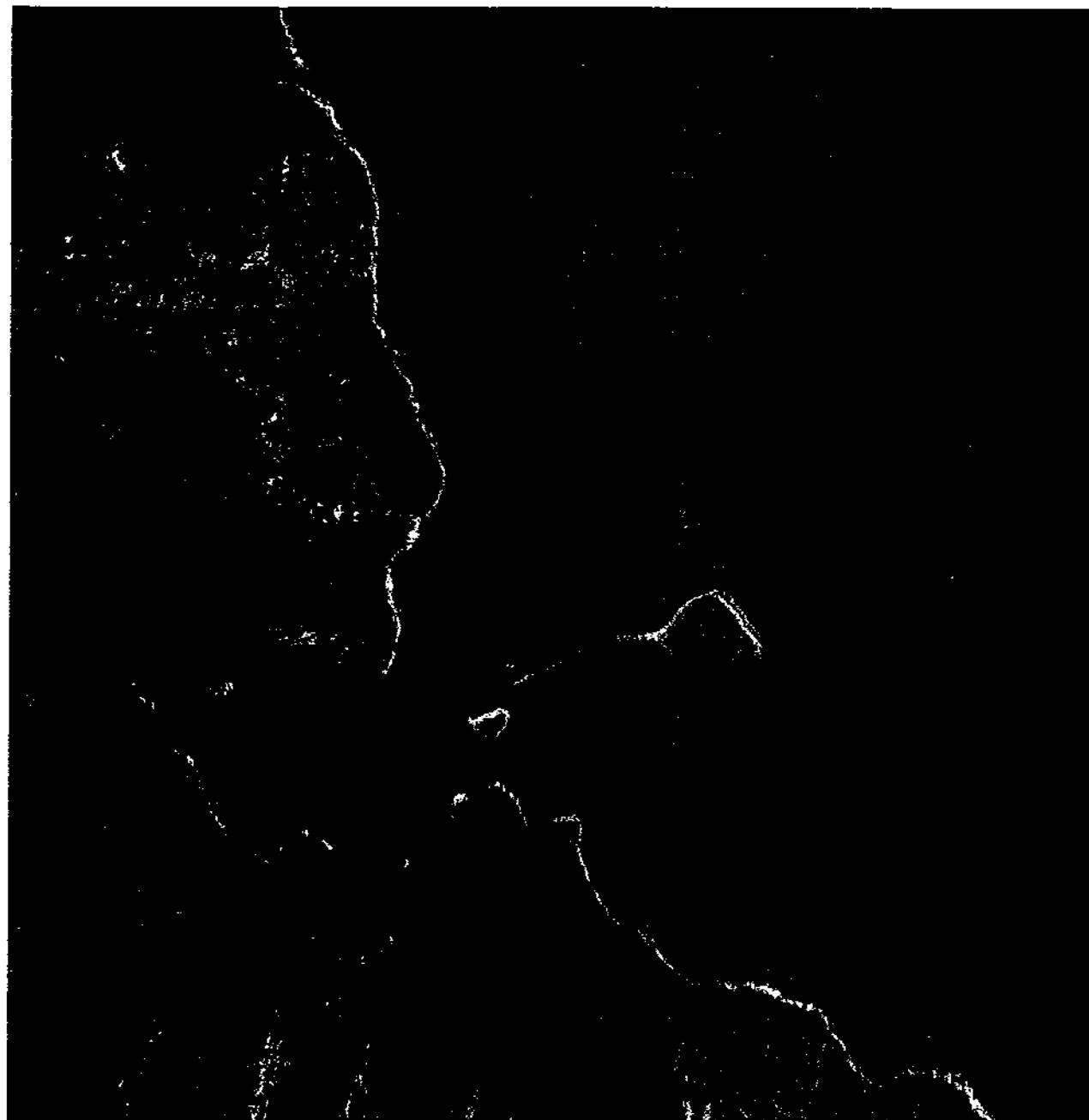


Figure 4. Vue aérienne verticale de l'île et de l'anse du Chafaud aux Basques, littoral est de Charlevoix (Photo aérienne Q76317-66; échelle 1:10 000; Photocartothèque du Québec).

estuaire, occupait une position à l'intérieur des terres légèrement méridionale par rapport au tracé de la moraine de Saint-Narcisse. Toutefois, dans le secteur oriental du moyen estuaire, on note qu'une langue glaciaire occupait la vallée de La Malbaie et s'étalait en un lobe arrondi (glacier de piedmont) dans le Saint-Laurent au droit du banc des Anglais. Cet événement avait d'ailleurs été mis en évidence par Poulin (1977, voir sa carte hors texte en particulier). Plus en aval, le front glaciaire, à la même époque, occupait encore la moitié du chenal Nord entre Saint-Siméon et Tadoussac. La batture aux Alouettes était donc entièrement recouverte par le glacier.

La figure 5B (LaSalle et al., 1977) présente la position du front glaciaire lors de la récurrence de Saint-Narcisse entre environ 11 ka et 10,5 ka. L'ensemble de la rive nord du Saint-Laurent entre Québec et Saint-Siméon était alors déglaçé et le rebord du Bouclier laurentidien était submergé par les eaux de la Mer de Goldthwait.

À l'embouchure du Saguenay, cependant, la masse de glace avait changé de configuration, prenant la forme d'un lobe circulaire étalé sur la plate-forme continentale jusqu'aux hauts-fonds de l'île Rouge (Dionne et Occhietti, 1996). La batture aux Alouettes et l'anse du Chafaud aux Basques étaient donc sous la glace à cette époque. Nous ignorons sur quels éléments de terrain LaSalle et al. (1977) se sont basés pour établir le tracé du front glaciaire entre Saint-Siméon et Tadoussac, car ils ne mentionnent pas la seule carte des formations meubles (Dionne, 1972) existant à l'époque pour le secteur en question.

L'âge exact de l'accumulation du kame de l'anse du Chafaud aux Basques n'est pas connu. En première approximation, nous pensons que cette butte a été édifiée par un lobe local lié à la réavancée de Saint-Narcisse, soit entre 11 et

10,6 ka, d'après la chronologie établie pour la région de Tadoussac (Dionne et Occhietti, 1996). Or, il subsiste des questions qu'il convient d'évoquer brièvement.

D'une part, nous ignorons la nature du substrat sur lequel repose le kame. Repose-t-il vraiment sur la surface silto-argileuse environnante ou y est-il enfoui, sa base reposant plutôt sur un substrat de nature inconnue mais peut-être morainique? Si le kame surmonte le dépôt argileux, il lui est forcément postérieur; il correspondrait alors aux événements de Saint-Narcisse, car une partie des sédiments silto-argileux de la batture aux Alouettes semble attribuable à une phase précoce de la Mer de Goldthwait antérieure à la récurrence de Saint-Narcisse. Toutefois, comme l'ont évoqué ailleurs Dionne et Occhietti (1996), la vaste batture aux Alouettes pourrait avoir un âge pré-goldthwaitien. D'autre part, ce kame peut-il être corrélé avec la butte de till de la pointe du Diamicton ou encore avec le dépôt sableux relique de la pointe aux Alouettes qui remonte à environ 35 ka (Dionne et Occhietti, 1996)? Dans l'état actuel des connaissances, il est difficile de répondre de façon satisfaisante à ces interrogations.

Il faut donc poursuivre les recherches sur le Quaternaire du secteur de l'embouchure du Saguenay, qui jusqu'à récemment avait été largement négligé. Des travaux de géophysique et même un sondage par carottier permettraient de connaître la nature et l'épaisseur des formations meubles de la batture aux Alouettes, qui occupe une position étrange à l'embouchure du fjord du Saguenay. La découverte récente à la pointe aux Alouettes d'un dépôt fossilifère relique qui date d'au moins 35 ka permet de penser qu'il subsiste dans le secteur de Tadoussac des traces d'événements géologiques survenus au cours du Wisconsinien moyen ou inférieur. Cela revêt donc une importance majeure pour reconstituer la stratigraphie et l'évolution de la vallée moyenne du Saint-Laurent.

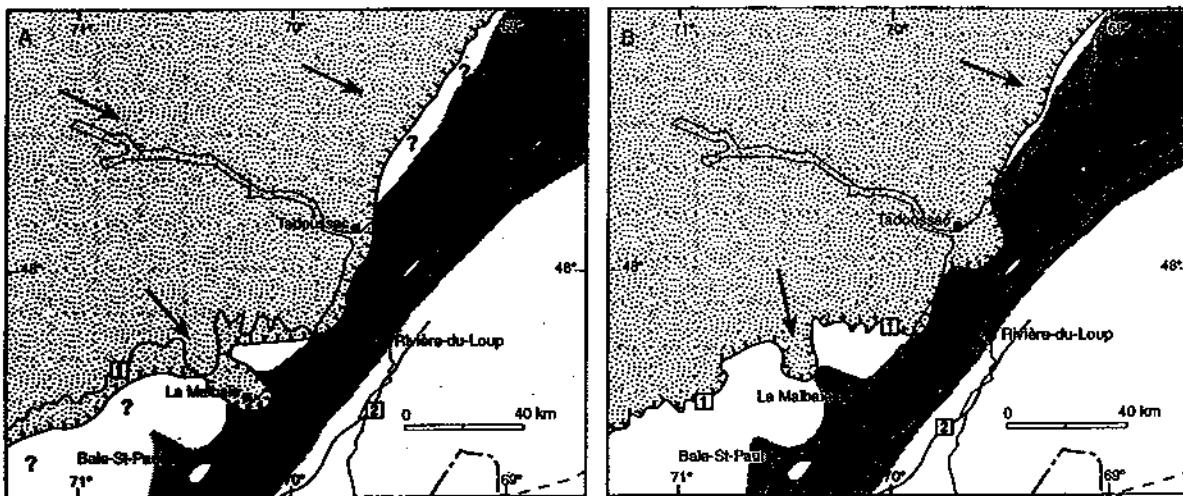


Figure 5. Tracé du front de l'*Inlandsis laurentidien*, entre Baie-Saint-Paul et le Saguenay, d'après LaSalle et al. (1977); A) front glaciaire vers 11,3-11 ka; B), front glaciaire entre 11 et 10,5 ka.

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Cette contribution s'inscrit dans un projet de recherche sur le Quaternaire du Saguenay subventionné par la Commission géologique du Canada. Deux anciens étudiants du Département de géographie de l'Université Laval (Stéphen Poitras et Robert Bonenfant) nous ont accompagné à l'île du Chafaud aux Basques, en 1989 et 1991. Les figures au trait ont été réalisées au Laboratoire de cartographie du Département de géographie, Université Laval. L'analyse granulométrique de l'échantillon du diamicton a été effectuée à la Commission géologique du Canada (Ottawa).

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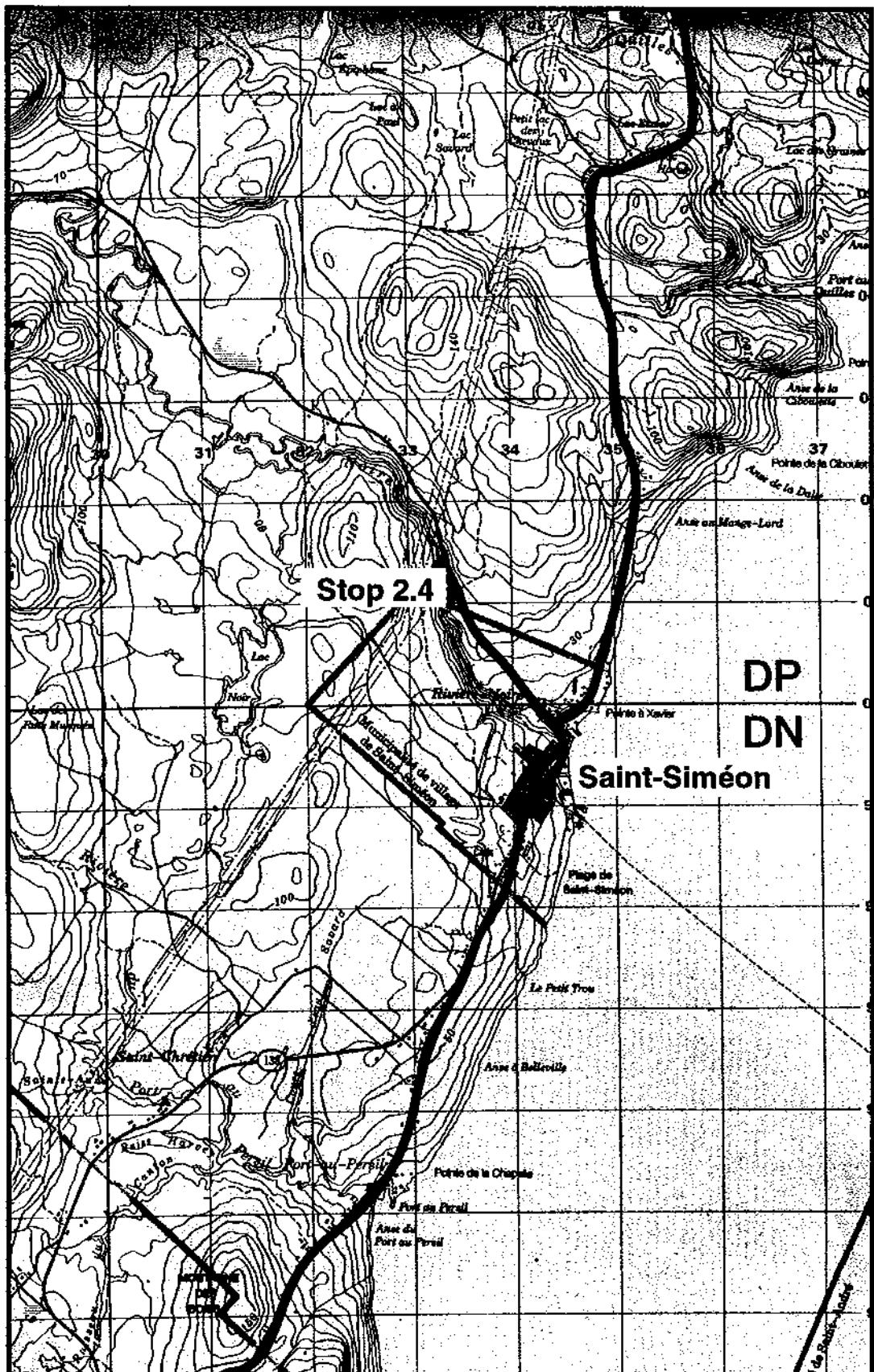


Fig 4.7 Stop 2.4 Saint-Siméon (1:50 000 topographic map 21N/13)

STOP 2.4: SAINT-SIMÉON

From Road 138, turn right to Road 170 toward Chicoutimi, drive for 2.5 km or 1.6 mile.
(Occhietti, from the MSc thesis of Hardy, 1970)

Hardy (1970) described the St. Narcisse morainic system in north Charlevoix. He distinguished an external zone of ice disintegration, 11 km (7 miles) wide, interpreted as a stable phase of the ice front.

The outline of the internal continuous main ridge is influenced by topography, with local minor lobes in the valleys. The ice front gradient is a variation of level of about 300 m (1000 feet) for 5 km (3 miles). In lower areas, the ridge becomes a hummocky moraine.

A second inner discontinuous ridge, at about 3 to 8 km (2 to 5 miles) from the main ridge, represents the northern limit of the St. Narcisse morainic system.

In the Noire River Valley, at about 2 km from Saint-Siméon, coarse gravel and cobble deposits overlie Goldthwait Sea clay. The ice front readvanced locally.

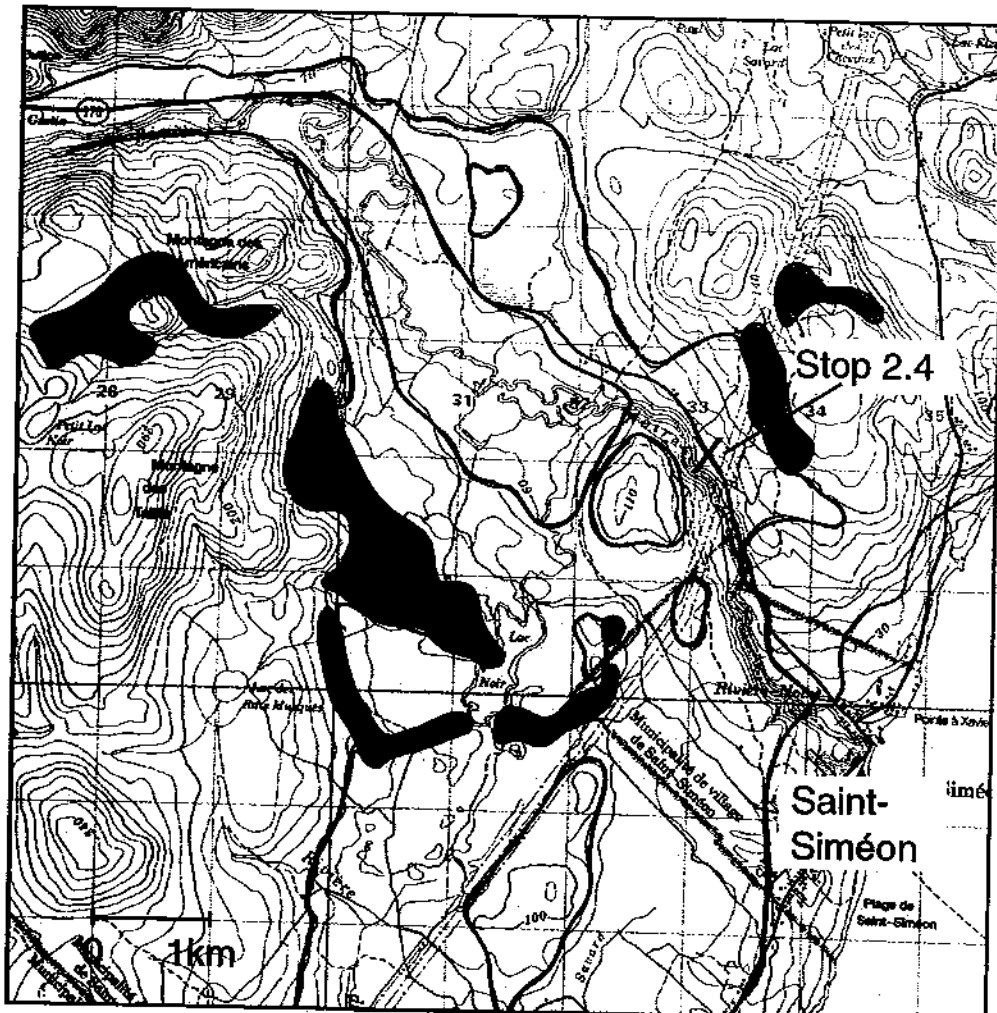


Figure 4.8 : Ice front features of the St. Narcisse Moraine and Goldthwait Sea deposits mapped by Hardy (1970).

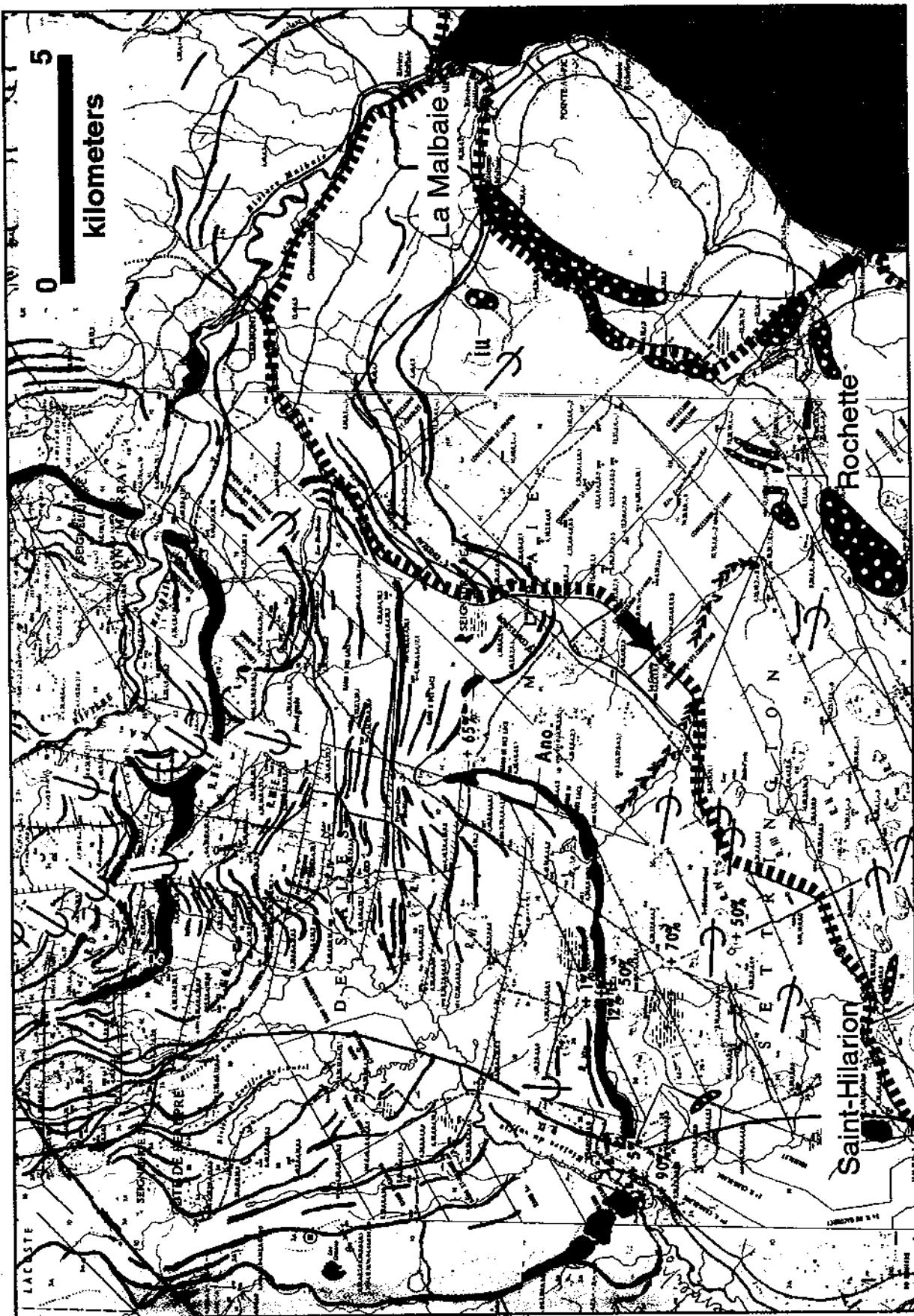


Figure 4.9 : View stop 2.5, on ridges of the St. Narcisse morainic complex (map by Rondot, 1974)

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