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Seismo-Stratigraphy and Sedimentology of Holocene Sediments off Grande Rivière de la Baleine, Southeastern Hudson Bay, Québec

Stratigraphie sismique et sédimentologie des sédiments holocènes au large de la Grande rivière de la Baleine, au sud-est de la baie d'Hudson, Québec

Seismische Stratigraphie und Sedimentologie von Holozän-Sedimenten in offener See bei Grande Rivière de la Baleine, südöstliche Hudson Bay, Québec

Nicole Gonthier, Bruno d'Anglejan et Heiner W. Josenhans

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Résumé de l'article

La répartition régionale des sédiments holocènes de l'est de la baie d'Hudson, face à l'embouchure de la Grande rivière de la Baleine, a été cartographiée à l'aide d'un grille de profils de sismique réflexion (d'environ 300 km de long et d'une superficie de 800 km2) et de données provenant de sept forages par carottier à piston. Quatre unités stratigraphiques reposant sur le socle protérozoïque (unité 1) ont été définies et interprétées : un till (unité 2) déposé par un glacier progressant vers l'ouest, des argiles et silts stratifiés (unité 3) probablement déposés dans le Lac glaciaire Ojibway, des boues marines postglaciaires (unité 4) déposés dans la Mer de Tyrrell auxquelles se superposent des boues marines récentes indifférenciées et des sédiments fluvio-deltaiques distaux (unité 5) provenant de la Grande rivière de la Baleine. Les mêmes unités stratigraphiques ont été décrites sur la côte. Les analyses granulométriques et géochimiques laissent croire que les rythmites de l'unité 3 sont des varves; les couches foncées d'été ont surtout été déposées par des courants de densité s'écoulant sur le fond pendant la période libre de glace et les couches pâles d'hiver ont été transportés en suspension le long de stratifications thermiques sous un couvert de glace saisonnier. L'unité 5 couvre environ 400 km2 et forme un prisme s'étendant jusqu'à 11 km de l'embouchure de la Grande rivière de la Baleine avec des épaisseurs atteignant 30 m le long de la côte. La mise en place de l'unité 5 s'est faite entre 3500 BP et aujourd'hui et résulte de l'érosion et de l'apport de sédiments d'origine glaciaire provenant de l'amont durant l'émergence du chenal fluvial.

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SEISMO-STRATIGRAPHY AND SEDIMENTOLOGY OF HOLOCENE SEDIMENTS OFF GRANDE RIVIÈRE DE LA BALEINE, SOUTHEASTERN HUDSON BAY, QUÉBEC

Nicole GONTHIER, Bruno d'ANGLEJAN and Heiner W. JOSENHANS, respectively: Bahamian Field Station, c/o Red Aircraft, 270 SW 34th Street, Fort Lauderdale, Florida 33315, U.S.A.; Department of Earth and Planetary Sciences, McGill University, 3450, rue University, Montréal, Québec H3A 2A7; Pacific Geoscience Centre, Geological Survey of Canada, P.O. Box 5000, Sydney, British Columbia V8L 4B2.

ABSTRACT The regional distribution of Holocene sediments of eastern Hudson Bay off the Grande Rivière de la Baleine mouth was mapped using a grid of reflection seismic lines (approximately 300 km long and covering an area of approximately 800 km²) and data from 7 piston cores. Based on the seismic records and piston cores, 4 stratigraphic units overlying the Proterozoic bedrock (unit 1) were defined and interpreted: (unit 2) glacial till deposited by a westward flowing ice sheet, (unit 3) rhythmically bedded clays and silts presumably deposited in glacial Lake Ojibway, (unit 4) postglacial marine muds deposited in the Tyrrell Sea overlain by undifferentiated modern marine muds, and (unit 5) distal fluvio-deltaic sediments from Grande Rivière de la Baleine. Similar stratigraphic units have been described onshore. Textural and geochemical analyses suggest that unit 3 rhythmites are true varves; dark "summer" laminae were deposited mainly by underflows during the open water season, and light "winter" laminae were deposited by overflows-interflows along thermal stratifications under a seasonal ice cover. Unit 5 covers approximately 400 km² and occurs as a deltaic constructional wedge protruding as far as 11 km offshore of the Grande Rivière de la Baleine entrance with thicknesses reaching 30 m along the coast. It was deposited between 3500 BP and the present from remobilization of glacial sediments farther upstream due to river downcutting during emergence.

RESUMÉ *Stratigraphie sismique et sédimentologie des sédiments holocènes au large de la Grande rivière de la Baleine, au sud-est de la baie d'Hudson, Québec.* La répartition régionale des sédiments holocènes de l'est de la baie d'Hudson, face à l'embouchure de la Grande rivière de la Baleine, a été cartographiée à l'aide d'un grille de profils de sismique réflexion (d'environ 300 km de long et d'une superficie de 800 km²) et de données provenant de sept forages par carottier à piston. Quatre unités stratigraphiques reposant sur le socle protérozoïque (unité 1) ont été définies et interprétées: un till (unité 2) déposé par un glacier progressant vers l'ouest, des argiles et silts stratifiés (unité 3) probablement déposés dans le Lac glaciaire Ojibway, des boues marines postglaciaires (unité 4) déposés dans la Mer de Tyrrell auxquelles se superposent des boues marines récentes indifférenciées et des sédiments fluvio-deltaiques distaux (unité 5) provenant de la Grande rivière de la Baleine. Les mêmes unités stratigraphiques ont été décrites sur la côte. Les analyses granulométriques et géochimiques laissent croire que les rythmites de l'unité 3 sont des varves; les couches foncées d'été ont surtout été déposées par des courants de densité s'écoulant sur le fond pendant la période libre de glace et les couches pâles d'hiver ont été transportés en suspension le long de stratifications thermiques sous un couvert de glace saisonnier. L'unité 5 couvre environ 400 km² et forme un prisme s'étendant jusqu'à 11 km de l'embouchure de la Grande rivière de la Baleine avec des épaisseurs atteignant 30 m le long de la côte. La mise en place de l'unité 5 s'est faite entre 3500 BP et aujourd'hui et résulte de l'érosion et de l'apport de sédiments d'origine glaciaire provenant de l'amont durant l'émergence du chenal fluvial.

ZUSAMMENFASSUNG *Seismische Stratigraphie und Sedimentologie von Holozän-Sedimenten in offener See bei Grande Rivière de la Baleine, südöstliche Hudson Bay, Québec.* Man hat die regionale Verteilung von Holozän-Sedimenten der östlichen Hudson Bay in offener See gegenüber der Mündung von Grande Rivière de la Baleine kartographiert, mit Hilfe eines Rasters der seismischen Reflexionslinien (etwa 300 km lang und ein Gebiet von etwa 800 km² bedeckend) und der Daten aus 7 Kernen von Kolbenbohrungen. Vier über dem anstehenden Gestein des Proterozoikums (Einheit 1) liegende stratigraphische Einheiten wurden bestimmt und interpretiert: (Einheit 2) glaziales Till, das von einer westwärts fließenden Eisdecke abgelagert wurde, (Einheit 3) rhythmisch geschichteter Lehm und Schlamm, der wohl in dem glazialen Ojibwaysee abgelagert worden war, (Einheit 4) postglazialer Meeresschlamm, der in der Tyrrell-See abgelagert wurde und über dem undifferenzierter neuzeitlicher Meeresschlamm liegt, und (Einheit 5) distale Fluß-Deltasedimente von Grande Rivière de la Baleine. Ähnliche stratigraphische Einheiten sind am Strand beschrieben worden. Die Analysen von Textur und Geochemie lassen vermuten, daß Rhythmite der Einheit 3 echte Warwen sind; die dunklen "Sommer"-Schichten wurden hauptsächlich durch Unterströmungen während der Saison offenen Wassers abgelagert, und die hellen "Winter"-Schichten wurden durch Überlauf-Zwischenlauf entlang der thermalen Schichtungen unter der saisonbedingten Eisdecke abgelagert. Einheit 5 bedeckt etwa 400 km² und hat die Form eines deltaartigen Keils, der bis zu 11 km in die Mündung von Grande Rivière de la Baleine hineinragt und eine Dicke bis zu 30 m entlang der Küste erreicht.

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INTRODUCTION

In recent years, sedimentological, stratigraphic, and geomorphological studies in southeastern Hudson Bay have provided a major insight into the deglaciation history of the Hudson Bay and adjacent regions. Precise rates of relative sea level changes, of the ice margin retreat and of postglacial uplift were obtained from the geometry and age relationships of raised beach terraces near Lac Guillaume-Delisle (Hillaire-Marcel, 1976). In the Grande Rivière de la Baleine basin, early work on regional morphology by Cailleux and Hamelin (1970) and by Portmann (1970, 1971, 1972) were followed by a stratigraphic interpretation of the postglacial sediments exposed along the lower river banks (Hillaire-Marcel and de Boutray, 1975; Hillaire-Marcel, 1976; Hillaire-Marcel and Vincent, 1980). There, lacustrine varved sediments attributed to glacial Lake Ojibway are lying above proglacial sand deposits. These sand deposits constitute a distal facies of a diamicton, interpreted as the northern extension of the Sakami Moraine by Hillaire-Marcel (1976), which is present 5 km upstream from the river mouth. The lacustrine varved sediments are overlain by Tyrrell Sea marine clays, which in turn are overlain by thick proglacial deltaic sands that record a phase of active erosion and sediment transport through the Grande Rivière de la Baleine channel during land emergence.

Offshore of Grande Rivière de la Baleine, little information was available until recently. A detailed bathymetric survey by the Canadian Hydrographic Office (Thompson *et al.*, 1985a, 1985b, 1985c) has now provided us with new insight on the sea-floor morphology in southeastern Hudson Bay. In 1987, following earlier reconnaissance work by Leslie (1964), Leslie and Pelletier (1965), and Pelletier (1966), the Atlantic Geoscience Centre of the Geological Survey of Canada initiated a multiyear geophysical and geological program in Hudson Bay, with the purpose of mapping the regional stratigraphy and the distribution of Quaternary sediments (Josenhans *et al.*, 1988; Josenhans and Zevenhuizen, 1990; Bilodeau *et al.*, 1990), and of developing a general deglaciation model.

As an addition to this regional program, this paper discusses the distribution and seismostratigraphy of the late glacial and postglacial Quaternary sediments in the region fronting the Grande Rivière de la Baleine entrance, including part of the Manitounuk Sound, between 55°10′ and 55°30′ North latitude, and between 78°20′ and 77°30′ West longitude (Fig. 1). The conclusions are based on interpretation of reflection seismic profiles and on stratigraphic control provided by piston cores. The objectives are to interpret the stratigraphic sequence offshore in terms of the processes of ice retreat and of postglacial sedimentation, to compare the offshore to the onshore stratigraphy and interpret that in terms of processes, and to relate the results to the known deglaciation and postglacial history of the region.

REGIONAL GEOLOGY AND PHYSIOGRAPHY

Hudson Bay bedrock west of the Belcher and Ottawa Islands consists of Paleozoic carbonate rocks (Shilt, 1986; Grant and Sanford, 1988) while east of those islands, where the study area is located, Precambrian formations constitute the bedrock (Shilts, 1986). The Precambrian rocks consist of Proterozoic metavolcanic and metasedimentary formations which lie unconformably on an Archean metamorphosed crystalline terrain that forms much of the Hudson Bay coastline (Shilts, 1986). The Manitounuk islands located northeast of Grande Rivière de la Baleine (Fig. 1) are NE-SW oriented cuestas formed by erosion of the westward-dipping Proterozoic rocks, which consist of dolomitic limestones, quartzose sandstones, and basaltic flows (Kranck, 1951; Biron, 1972). The bedrock in Hudson Bay is overlain by unconsolidated glacial and postglacial sediments that were deposited predominantly during and after the Late Wisconsinan glaciation (Josenhans *et al.*, 1988).

Figure 1 shows the bathymetry of the study area based on recent surveys by the Canadian Hydrographic Service (Thompson *et al.*, 1985a, 1985b, 1985c) for the bay, and by Hydro-Québec (Service des relevés techniques) for Manitounuk Sound. The general physiography offshore consists of a succession of ridges and troughs trending NE-SW with a maximum relief of approximately 120 m, generally similar to the physiography of the Proterozoic cuestas of Manitounuk Islands. The ridges form discontinuous rises, six of which have elevations to within less than 20 m below msl within 14 km of the shoreline.

To the southwest, a narrow depression reaching depths of over 160 m and cutting across the general trend of the ridges extends west-southward from the mouth of Grande Rivière de la Baleine (Fig. 1). In the remainder of the text, this feature will be referred to as the SW Trough. The average gradient through the length of the SW Trough is 3 m km^{-1}. The regional morphology apparently reflects pre-glacial erosion controlled by bedrock composition and structural trends (Pelletier, 1986).

The reconstruction by Dyke and Prest (1987) of the Laurentide Ice Sheet retreat demonstrates that deglaciation of the bay started around 8400 BP. At that time the ice sheet consisted of three large interconnected ice domes: the Labrador, the Hudson, and the Keewatin. The Hudson ice Dome was rimmed by proglacial Lake Agassiz to the southwest and Lake Ojibway to the southeast. The latter, which covered the James Bay and Hudson Bay Lowlands, extended eastward as far as the Sakami Moraine (Hardy, 1976) and northward as far as Grande Rivière de la Baleine (Hillaire-Marcel, 1976). Between 8100 BP and 8000 BP, the collapse of the ice-barrier between Lake Ojibway and the Tyrrell Sea brought about the catastrophic drainage of the lake northward, followed by marine invasion of southeastern Hudson Bay (Hillaire-Marcel, 1976). At approximately the same time, the sea reached glacial Lake Agassiz along a suture between the Keewatin and Hudson Ice domes, invading the southwestern Hudson Bay Lowlands (Dredge and Cowan, 1989).

As the ice receded, emergence due to isostatic uplift raised former marine limits to elevations above present sea level which range from 198 m south of James Bay (Hardy, 1976) to a maximum of 315 m between Petite Rivière de la Baleine and Grande RIvière de la Baleine (Hillaire-Marcel,

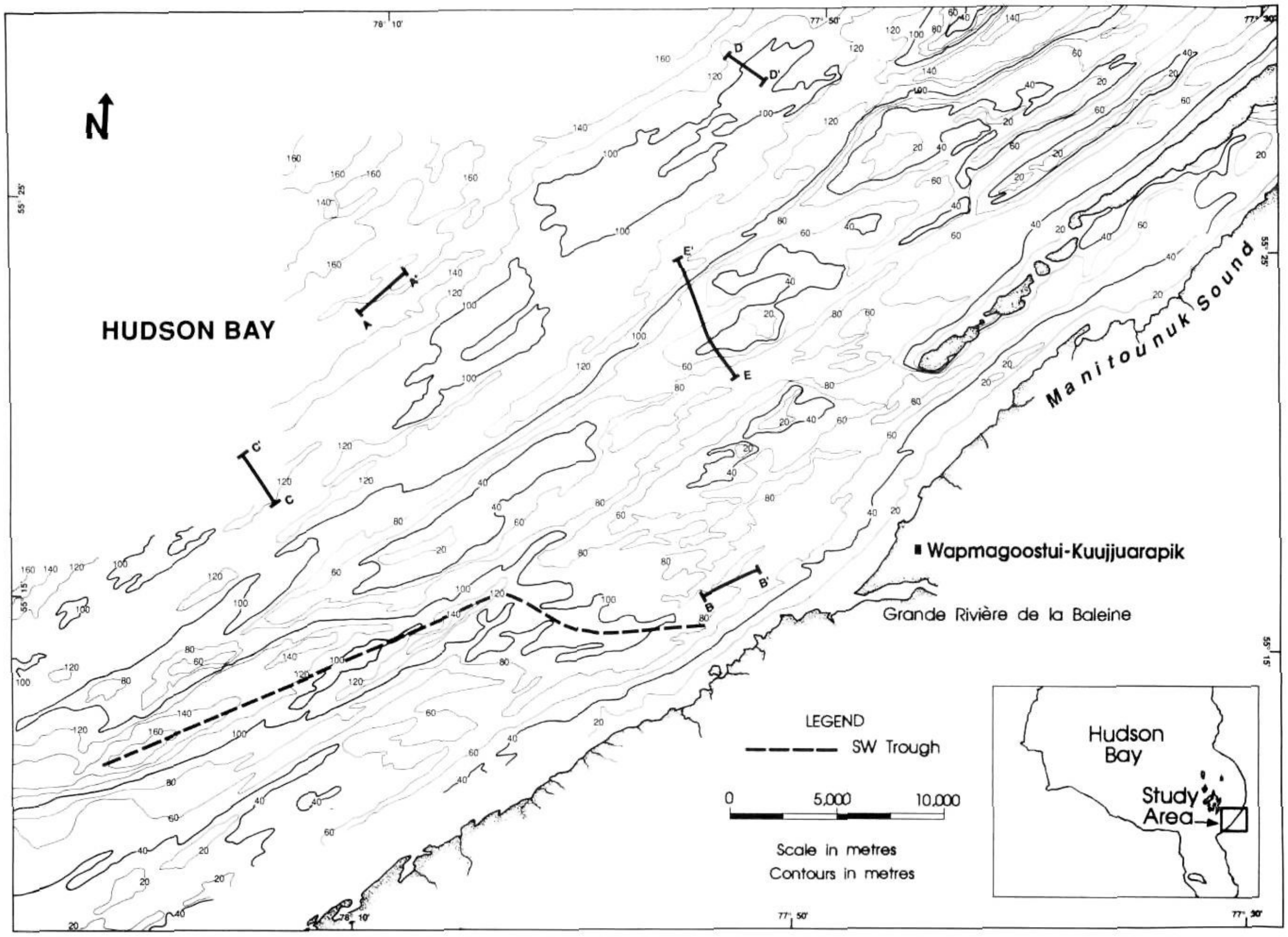

FIGURE 1. Locality map, showing generalized bathymetry of the area fronting Grande Rivière de la Baleine. Heavy dark lines indicate the positions of seismic sections refered to in the text and shown in Figures 4-7 and 18. The dotted line indicates the axis of the SW Trough.

Carte de localisation illustrant la bathymétrie généralisée de la région située face à la Grande rivière de la Baleine. Les traits continus indiquent la position des profils sismiques qui correspondent aux figures 4-7 et 18 auxquelles le texte se rapportent. Les lignes pointillées indiquent l'axe du chenal SW.

1976; Vincent *et al.*, 1987). However, north of Lac Guillaume-Delisle, elevations of the marine limit east of Povungnituk do not exceed 105 m above present sea level (Gray and Lauriol, 1985). The rate of land emergence fell from about 10 m century^{-1} at 8000 BP (Allard and Seguin, 1985) to about 1 m century^{-1} at around 2800 BP (Allard and Temblay, 1983; Vincent *et al.*, 1987). It has remained approximately constant since then (Allard and Temblay, 1983; Vincent *et al.*, 1987).

INSTRUMENTS AND METHODS

The interpretation of the regional seismo-stratigraphy presented here is based on high-resolution reflection seismic profiling and on piston coring. The main source of data is a multi-parameter grid of reflection seismic lines approximately 300 km long (Fig. 2) collected during a cruise of CSS Hudson in August 1987 (EMR CSS HUDSON 87-028/87-031 Data Report). The following seismic equipment was operated simultaneously: a) a Huntec® DTS (Deep Tow System) containing a boomer and two single channel hydrophones, one internal for maximum resolution and one external for maximum penetration; b) an airgun with a 653 cm^3 chamber fired at a 3 s rate, coupled with analog hydrophones, for intermediate penetration; c) an ORE® 3.5 kHz subbottom profiler; d) BIO 100 kHz and 75 kHz sidescan sonar systems; and e) a 12 KHz echosounder. Integration of global positioning and satellite navigation provided a positioning accuracy generally within 20 m. The Huntec® DTS and 3.5 kHz records were the principal data used in establishing the seismo-stratigraphic units and their lateral distribution. Additional seismic records were collected on a Canadian Hydrographic Service cruise aboard the CCGS Narwhal in September 1988 (Zevenhuizen and Josenhans, 1988), one line of which falls within the study area (Fig. 2). The 3.5 kHz subbottom profiler data obtained along this line were incorporated in our study.

Seven piston cores of 10 cm diameter, averaging 3.5 m in length (maximum of 7.53 m), provided stratigraphic control. The selection of these core sites (Fig. 2) was made on the basis of acoustic data in areas of condensed sections in order to sample a maximum number of stratigraphic units. The cores were split, X-rayed and subsampled for laboratory

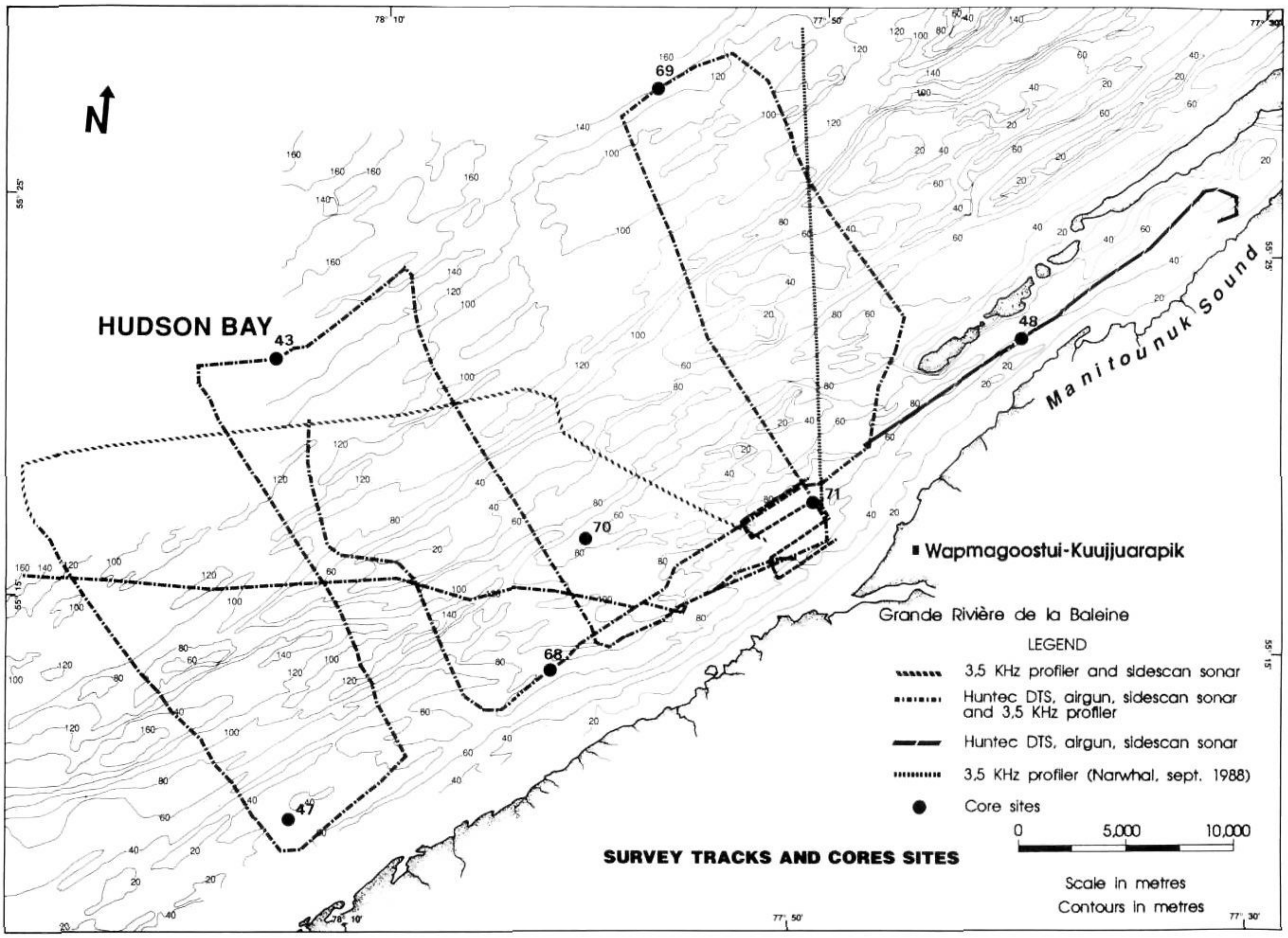

FIGURE 2. Seismic reflection tracks and core sites.

Traces de sismique réflexion et sites de carottage.

analyses to determine geotechnical and physical properties (Marsters, 1988) as well as textures and geochemical properties (Henderson, 1989). Microfaunal and palynological analyses were made only on core 69 (Fig. 2 for location) by Bilodeau *et al.* (1990). Slabs of sediment 25 cm long and 1 cm thick were then taken from cores 43, 48, and 69 following the method described by Mosher and Asprey (1986). They were X-radiographed in a Picker (Mini-shot II) X-Ray machine. The sample to source distance was 53 cm and the exposure varied from 50 to 60 kV at 3 mA for a period of 50 s. Two of the slabs, one from each of core 43 and 48, were then subsampled for various analyses. Grain-size analyses were performed with a Coulter counter model TA, on small samples collected every 3 mm along the slabs. These samples were prepared by suspension in an isotonic solution and dispersion in an ultrasonic bath for 15 to 20 s. The suspensions were then passed through a 70 μm aperture tube, which can determine particle size between 1 μm and 32 μm.

Samples of individual dark and light laminae from the same two slabs were also taken and oven-dried. A fraction was ground and analyzed by X-ray fluorescence on a Philips PW 1400 unit to determine the following major and trace elements: SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O, P_2O_5, Co, Cr_2O_3, Cu, Ni, and Zn. All analyses were done on fused beads prepared from ignited samples. Measurement precisions are of less than $\pm$ 1% for SiO_2; less than $\pm$ 5% for Na_2O and MgO; less than $\pm$ 2% for the other major elements; and less than $\pm$ 5% for the trace elements. Another fraction was used to determine carbon and sulphur concentrations in a LECO induction furnace with a gravimetric absorption bulb for the CO_2 analysis and an Alpha sulphur titrator for the SO_3 analysis. The precision of the analyses was 0.01% for C and 0.2% for S. Finally, an aliquot of three samples from core 48, suspended in distilled water and mounted on a glass slide (Gibbs, 1965), was analyzed by X-ray diffraction on a Siemens® unit, model D500. CuKa radiation was used with the following setting: 40 KV; 20 mA; chart speed 2° 2 Θ/min; at 1000 cps. All laboratory analyses were performed at the Department of Geological Sciences of McGill University.

ACOUSTIC AND LITHOSTRATIGRAPHIC CHARACTERISTICS OF THE UNITS

Five seismo-stratigraphic units were identified on the basis of their acoustic character as defined by the high resolution Huntec DTS, 3.5 kHz, and airgun surveys (Fig. 2). They were established at several characteristic sections,

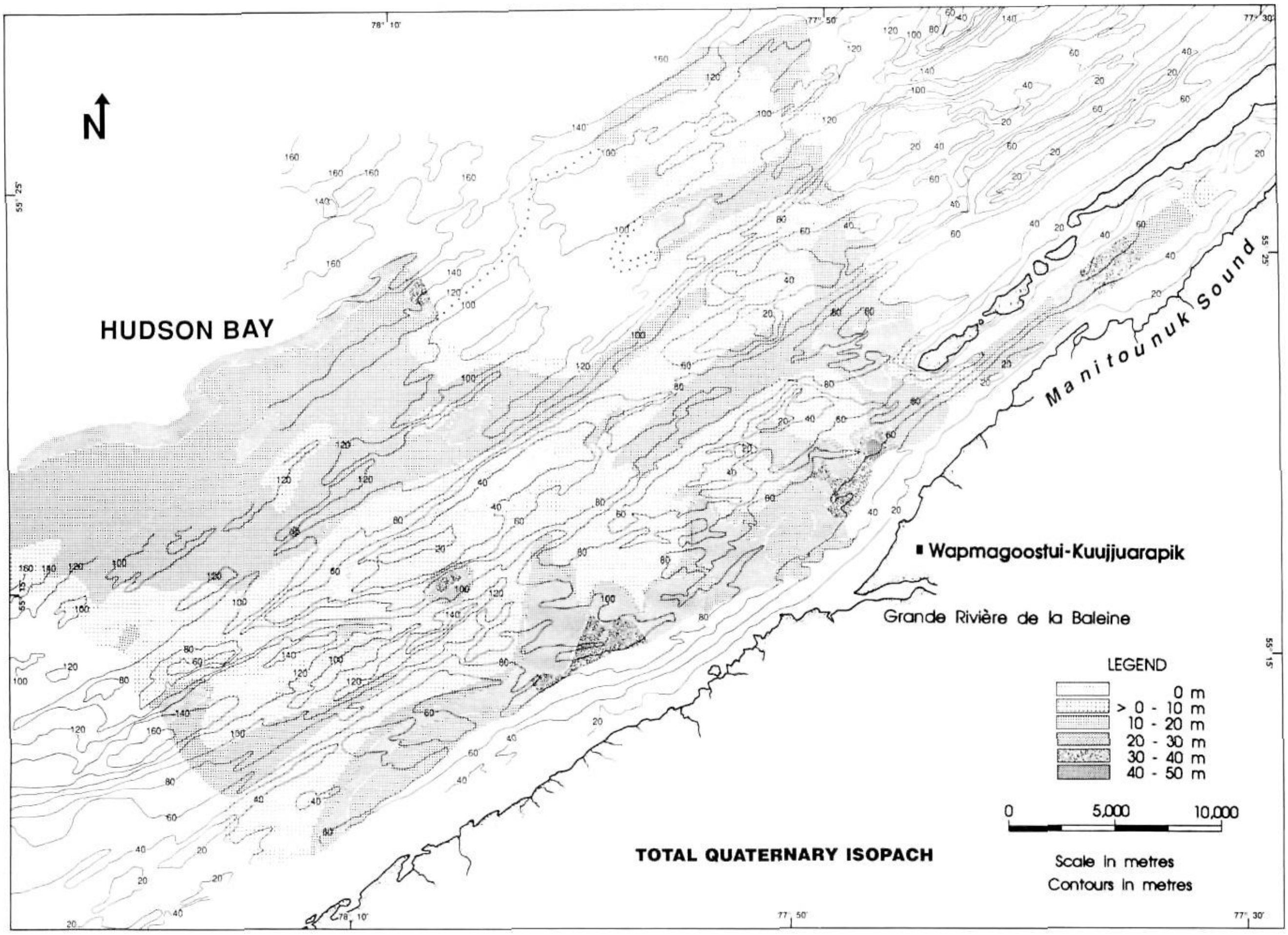

FIGURE 3. Total Quaternary sediment isopach map.

Carte de l'épaisseur totale des sédiments quaternaires.

then traced laterally to establish a regional stratigraphy. During this process, variations in definition of the acoustic attributes, geometry, or bedding style of the different units were often encountered and required interpretation of stratigraphic and facies relationship.

Isopach maps of the total Quaternary sequence and of each of the individual acoustic units were made based on the acoustic coverage shown in Figure 2. The isopach map of the total Quaternary sequence (Fig. 3) shows that the sediment cover is generally thick nearshore (10 to 42 m), and that two distinct lenses are present, one on each side of the Grande Rivière de la Baleine entrance. Offshore the sediment cover thins out over the ridge-and-trough topography, to generally less than 10 m, but increases to 10-30 m seaward of the 100 m contour. Within the surveyed outer region of Manitounuk Sound, sediment thicknesses vary between 0.5 m and 38 m. Regional variations in thickness of the total Quaternary sequence reflect the changing styles of sedimentation across the study area.

The sediment distribution over the ridge-and-trough topography as described above was also observed on underwater photographs obtained during the 1987 CSS Hudson cruise by a towed near-bottom video camera system of the Bedford Institute of Oceanography. They show smoothed out topography in troughs and rock debris on ridges.

Examination of seismic profiles led to the recognition of four distinct units overlying the Proterozoic bedrock (unit 1). These four units were interpreted on the basis of their similarity to units established in other similar areas; *i.e.* Hudson Bay (Josenhans *et al.*, 1988; Josenhans and Zevenhuizen, 1990), Labrador Shelf (Josenhans *et al.*, 1986). Scotian and mid-Norwegian Shelves (King *et al.*, 1991), and Gulf of St. Lawrence (Syvitski and Praeg, 1989).They are designated as: ice contact sediments (unit 2), rythmically bedded clays and silts (unit 3), postglacial marine muds (unit 4) and, distal fluvio-deltaic sediments (unit 5). Each unit represents a particular stage in the deglaciation and the postglacial evolution of this region.

These interpretations are supported by the piston core stratigraphy. Of the 7 cores collected (Fig. 2), 4 intersected more than one unit. Core 47 is the only one that sampled the complete nearshore stratigraphic sequence, which consists of a sandy diamicton (unit 2) at the base, overlain by rhythmically banded sediments (unit 3), followed by a short section (14 cm) of dark grey silty clay sediments (unit 4), and finally at the top by an olive grey silty clay sediment (unit 5). In core

48 the sequence is incomplete as unit 5 lies directly over unit 3; the two units being separated by an erosional surface. Core 69 may show the complete stratigraphic sequence farther offshore, which consists of a till (unit 2) overlain by rhythmites (unit 3) and by silty clays (unit 4). Core 43 intersects only units 3 and 4.

The 3 remaining cores (68, 70, 71) intersect the upper part of unit 5 without reaching its base. The acoustic and physical characteristics of each unit are presented below.

UNIT 1: BEDROCK

The bedrock surface is identified by a relatively well-defined reflector characterized by variable relief and very limited penetration of energy from the acoustic profiling system (Figs. 4 and 5). It can be traced across most of the record, except in some areas where it is hidden by the first multiple (surface reflection on Huntec) or where resolution is poor due to thick overburden. Outcrops of bedrock observed in the seismic sections are limited.

The topography of the bedrock surface is generally rough (Figs. 4, 5, 6). Cuesta ridges, dipping to the NW, which is characteristic of the Proterozoic terrain in this area, can be observed at some sites (Fig. 6).

UNIT 2: ICE-CONTACT SEDIMENTS

Unit 2 is the lowermost unconsolidated layer. It is characterized by a uniformly dark grey tone, lack of coherent reflectors and an undulating upper surface (Figs. 4 and 5). It discontinuously overlies the bedrock and commonly occurs as fill in topographic depressions (Figs. 4 and 5) or locally forms mounds or ridges (Fig. 7). The upper contact is always sharp. However, the lower contact with the bedrock is sometimes hard to define because the acoustic impedance of the two units is similar and also because there is probably a reduction in seismic energy as it passes through the till.

The isopach map of this unit (Fig. 8) indicates that it is generally thin (average: 5 m) and is missing locally. Thicker patches reaching a maximum thickness of 30 m are found scattered throughout the area. The occurrence of these deposits as a fill in topographic depressions suggests that they have been formed by processes of abrasion and accumulation similar to those operating under a land-based glacier flowing over rough surfaces as described by Boulton (1975). The acoustic character (uniform tone with no internal reflectors, undulating surface, and strong surface reflector) of this unit are characteristic of glacial till (Josenhans *et al.*, 1986; Josenhans *et al.*, 1988; King *et al.*, 1991). This interpretation is confirmed by the piston cores.

Unit 2 is penetrated by core 47 (Fig. 9). Cores 69 and 48, and possibly core 43, seem to have bottomed out on the upper surface of unit 2. The base of core 69 (Fig. 10) has been partially disrupted during the coring process but the dark grey mud observed within the lower 18 cm is similar to

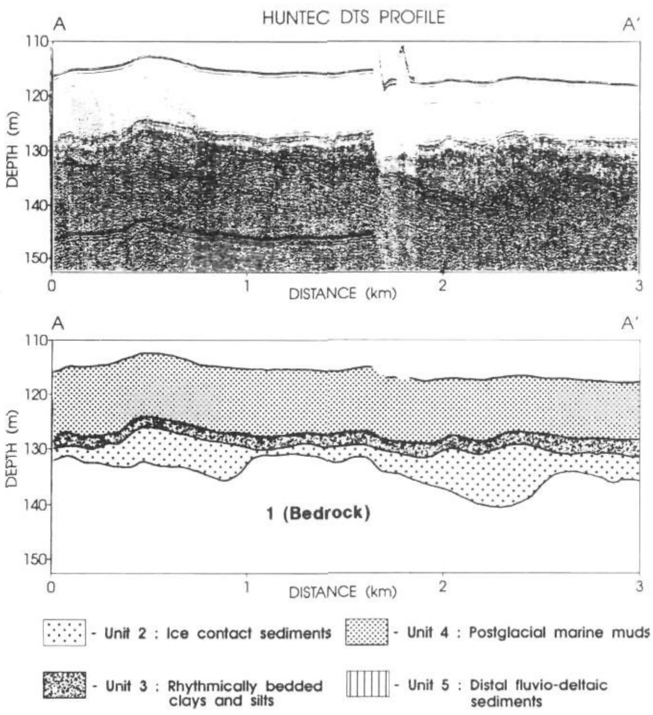

FIGURE 4. Seismic profile A-A' (Fig. 1), showing the acoustic character of units 1, 2, 3, and 4. Legend applies to Figures 4-7 and 18.

Profil sismique A-A' (fig. 1) illustrant les caractéristiques acoustiques des unités 1, 2, 3 et 4. La légende s'applique aux figures 4-7 et 18.

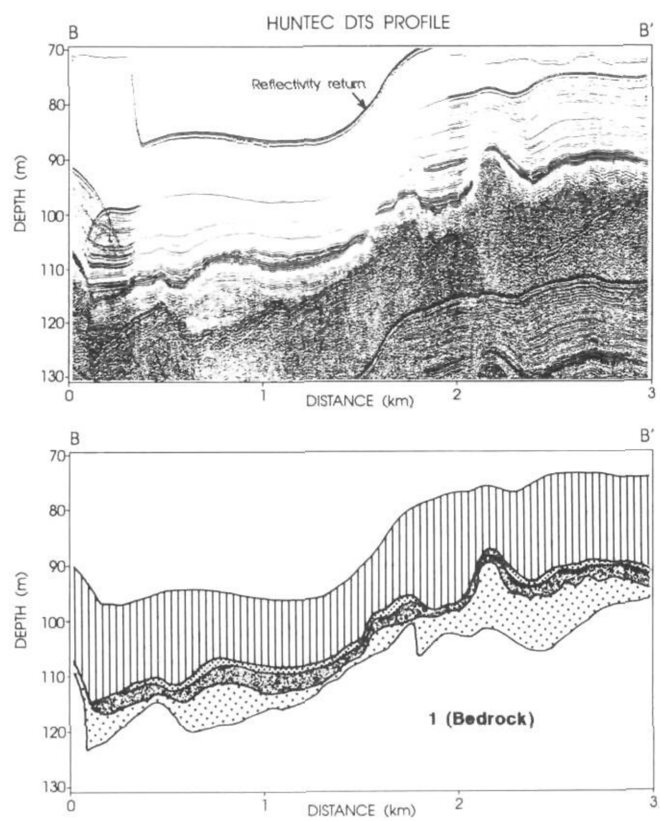

FIGURE 5. Seismic profile B-B' (Fig. 1), showing acoustic character of units 1, 2, 3, 4, and 5 (Fig. 4 for legend).

Profil sismique B-B' (fig. 1) illustrant les caractéristiques acoustiques des unités 1, 2, 3, 4 et 5 (légende à la fig. 4).

the glacial sediments observed in core 47. It is therefore possible that the lower 18 cm of core 69 also consist of till. As for core 48, geotechnical data show a marked near-bottom increase in both sound velocity and bulk density, as well as a sharp drop in water content, characteristics that are commonly observed at the upper contact of unit 2 (Marsters, 1988).

Unit 2 in core 47 consists of an unstratified, dark grey (Munsell colour code 7.5YR 4/0), gravelly mud with sand (Fig. 9). The gravel fraction (2-5.6 mm) is composed mainly of crystalline (62 to 64%) and Proterozoic carbonate rock fragments (31 to 34%) (Henderson, 1989). The unstratified and poorly sorted nature of the sediment and the presence of exotic rock fragments confirm the interpretation as basal till.

UNIT 3: RHYTHMICALLY BEDDED CLAYS AND SILTS

Unit 3 occurs within the seismic section as an acoustically well-stratified unit with strong and closely spaced reflectors. It is relatively thin, with an average thickness of 2 m and a maximum of 5 m. Where present, it occurs as a conformable deposit draped over the bedrock substrate or over the ice contact sediments (unit 2) (Figs. 4 and 5). Occasionally, where unit 2 (till) forms a ridge, unit 3 onlaps both flanks, but is missing on top (Fig. 7). It is distributed throughout the entire study area except on topographic highs and in the SW Trough (Fig. 11). It is acoustically similar to the ice proximal glaciomarine sediments described by Josenhans *et al.* (1986), Josenhans *et al.* (1988), and King *et al.* (1991). However, core analysis suggests that the sediments were deposited in a glaciolacustrine rather than a glaciomarine environment as discussed below.

Unit 3 was penetrated by four cores; 47 (thickness: 0.46 m; Fig. 9), 69 (thickness: 1.38 m; Fig. 10), 48 (thickness: 0.98 m; Fig. 12), and 43 (thickness: 2.60 m; Fig. 13). It consists of rhythmically bedded clays and silty clays marked by dark and light laminations of varying colour and thickness. The lower contact with unit 2, as seen in core 47, is sharp, which is consistent with the distinct basal seismic reflector in the seismic record.

Couplets of dark and light laminae in the unit generally thin upward. The light laminae (dark grey brown to olive grey; Munsell colors 2.5Y 3/2 to 5Y 4/2) have thicknesses that do not vary significantly throughout the unit (3 mm to 2 cm). However, the dark laminae (dark grey to very dark grey; Munsell colors 5Y 4/1 to 5Y 3/1) get much thicker toward the bottom of the unit, with thicknesses increasing from 3 mm at

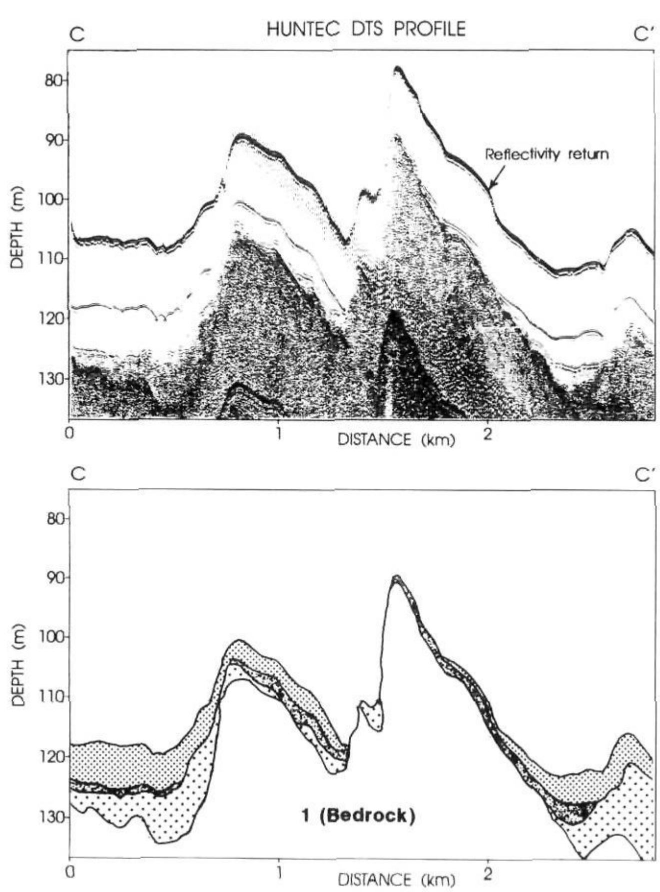

FIGURE 6. Seismic profile C-C' (Fig. 1), showing the cuesta topography of the bedrock (Fig. 4 for legend).

Profil sismique C-C' (fig. 1) illustrant la topographie en forme de cuestas du socle rocheux (légende à la fig. 4).

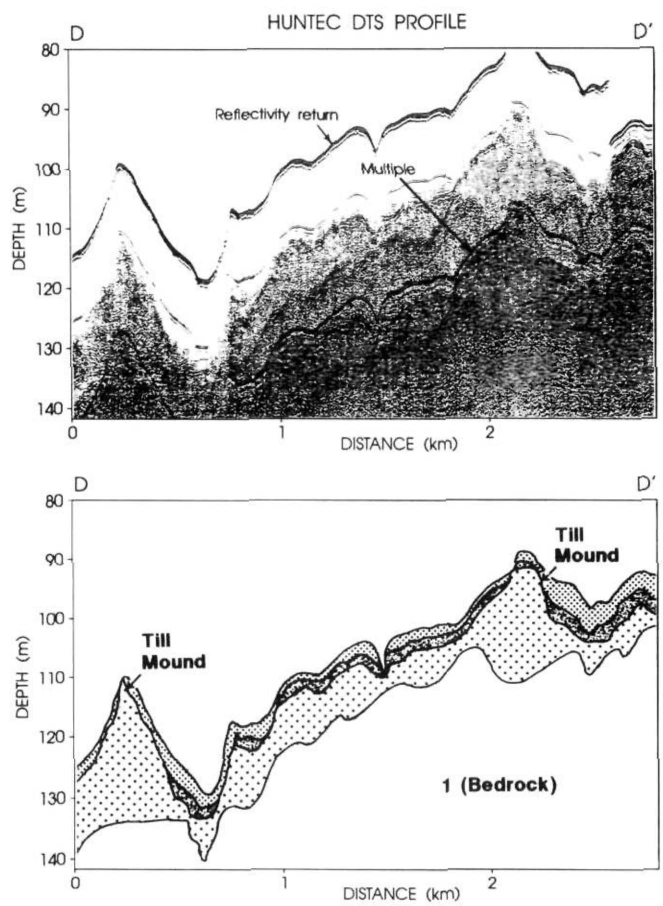

FIGURE 7. Seismic profile D-D' (Fig. 1), showing mounds formed by unit 2. Unit 3 onlaps each side of the ridges and is absent on their crests (Figure 4 for legend).

Profil sismique D-D' (fig. 1) illustrant la forme en monticules de l'unité 2. L'unité 3 chevauche les flancs des crêtes, mais est absente sur les sommets (légende à la fig. 4).

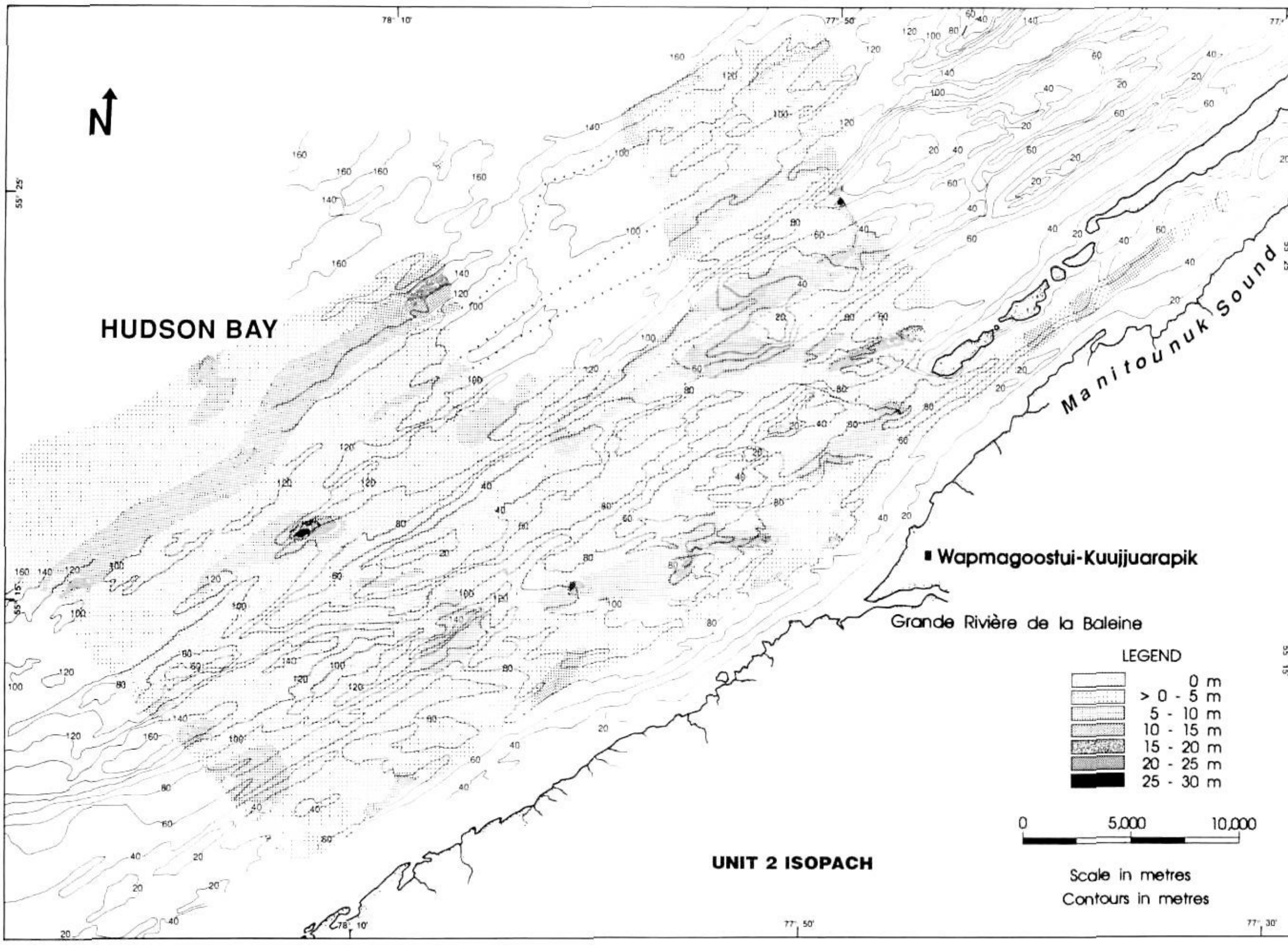

FIGURE 8. Isopach map of unit 2 (ice-contact sediments).

Carte isopaque de l'unité 2 (sédiments de contact glaciaire).

the top to a maximum of 14 cm at the bottom. The thicker laminae often contain white intra-microlaminations. The rhythmites are often interrupted by fractures. Each core, with the exception of core 48, contains an interval (core 69 has two), 12 to 48 cm thick, in which the mud has fragmented into irregular lumps, although traces of original (disturbed) bedding remain discernable.

Unit 3 is mainly composed of clay (7-96%) and silt (2-61%) usually with little sand and gravel (Henderson, 1989). The variations in grain-size, obtained by Coulter counter measurements within individual laminations in a section of core 43 (Fig. 14) and of core 48 (Fig. 15), show that the fine-grained laminae (2-6 μm in core 43 and 1-5 μm in core 48), which correspond to low values in the graph, are light-colored, while coarse-grained laminae, which correspond to peak values, are dark-colored. Contacts between successive laminations are sharp as shown by the abrupt changes in grain size across the interface. The light fine-grained laminae show a possible normal grading in core 48 section, while a reversed grading is noticed in the dark coarser-grained laminae of core 43. Comparison of X-ray diffractograms made in core 48 indicates that the finer laminae contain relatively more clay minerals (chlorite and illite), and less quartz and feldspar than the coarse laminae.

Geochemical analysis made on both core sections (core 43, Table I; core 48, Table II) indicates that the coarse dark-colored laminae contain significantly higher amounts of SiO_2, CaO and Cu, and lower amounts of Al_2O_3, Fe_2O_3, Na_2O, K_2O, MgO, TiO_2, MnO, Zn, Ni, and Co than the fine light-colored laminae. In addition, concentrations of total carbon expressed as $\%CO_2$ by weight are higher in the coarse dark layers than in the fine light layers of core 43 (Gonthier, 1992). This seems to be caused by differences in inorganic C, which is more abundant in the dark laminae than in the light ones. In contrast to core 43, core 48 total carbon content tends to be higher in the light laminae than in the dark ones, but no trend is observed in the distributions of inorganic C or organic C. Total sulphur values (as $\%SO_3$) for both cores are equivocal.

Geotechnically, the unit shows a general trend toward an increase in bulk density and a decrease in water content downward, indicating a normally consolidating sequence (Marsters, 1988). The bulk density varies from 1.52 to 2.07 $g{\cdot}cm^{-3}$, and water content ranges from 99.6 to 25.5% of dry

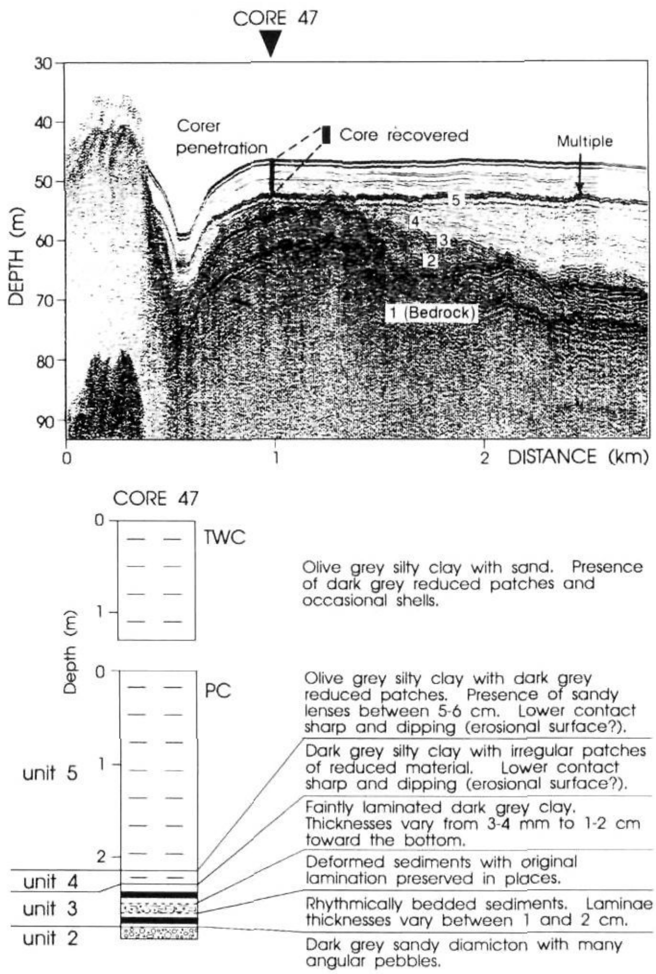

FIGURE 9. Lithostratigraphy of core 47 and its approximate position and penetration on the seismic section. Core description is from Henderson (1989). See Figure 2 for core locality. TWC = trigger weight core. PC = piston core.

Lithostratigraphie de la carotte 47, avec son emplacement et la profondeur de pénétration. La description de la carotte est tirée de Henderson (1989). Voir la figure 2 pour la localisation de la carotte. TWC = carottier déclencheur; PC = carrottier à piston.

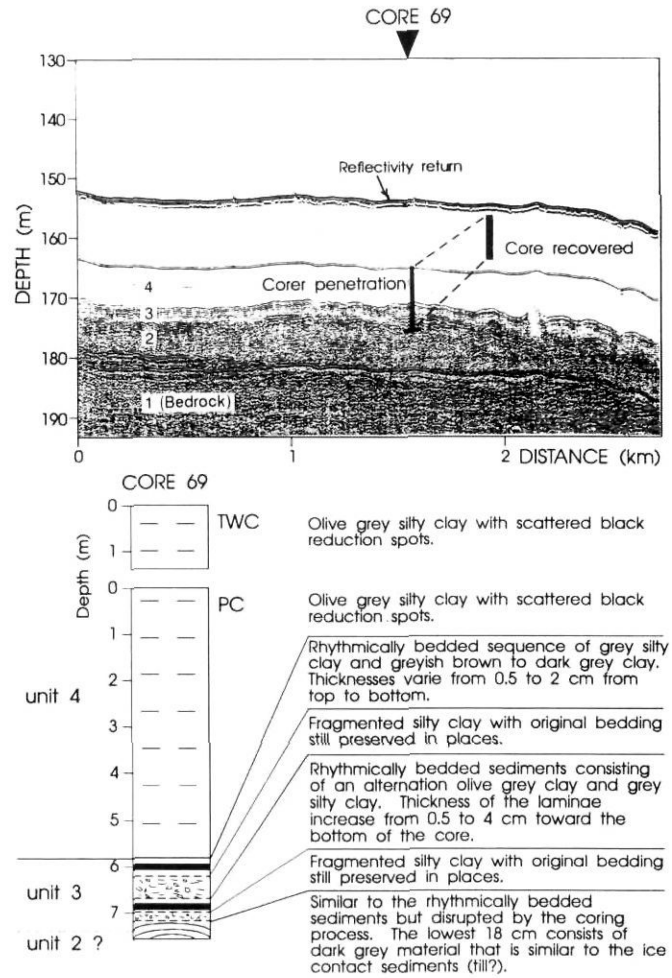

FIGURE 10. Lithostratigraphy of core 69 and its position and penetration on the seismic section. Core description is from Henderson (1989). See Figure 2 for core locality. TWC = trigger weight core. PC = piston core.

Lithostratigraphie de la carotte 69, avec son emplacement et la profondeur de pénétration. La description de la carotte est tirée de Henderson (1989). Voir la figure 2 pour la localisation de la carotte. TWC = carottier déclencheur; PC = carrottier à piston.

weight (Marsters, 1988). Shear strength values are between 4.4 and 15.0 kPa (Marsters, 1988).

Micropaleontological examination of the unit in core 69 indicates a very sparse microfauna consisting only of badly preserved ostracods possibly of lacustrine origin (Bilodeau *et al.*, 1990). Sparse pollen assemblages characteristic of open tundra are also found (Bilodeau *et al.*, 1990).

UNIT 4: POSTGLACIAL MARINE MUDS

This facies is characterized by very weak acoustic stratifications (Figs. 4 and 5). It occurs as a conformable deposit over the rhythmically bedded muds of unit 3 or sometimes over the ice contact sediments (unit 2) or the bedrock (unit 1). As explained below, that part of unit 4 within 11 km of the shoreline is overlain by unit 5, but farther offshore unit 4 grades upward into recent marine muds. The recent muds cannot be differentiated acoustically from unit 4 because the environment of deposition has not changed substantially.

The isopach map of unit 4 (Fig. 16) indicates thicknesses of less than 5 m nearshore. Farther offshore, at depths below 120 m in the northwest region of the study area, thicknesses range between 5 to 16 m. The average thickness over the entire study area is about 3 m. As with unit 3, this unit is absent on top of some topographic highs and in the SW Trough. Its acoustic character is similar to those of the postglacial sediments described by Josenhans *et al.* (1988).

This unit, observed in core 47 (thickness: 0,14 m; Fig. 9), core 69 (thickness: 6,71 m; Fig. 10), and core 43 (thickness: 3,69 m; Fig. 13), is a bioturbated olive grey (Munsell colour code 5Y 4/2) to dark grey (Munsell colour code 5Y 4/1) silty mud with black sulphide mottling. In all cores, the lower contact is sharp. No observable contact exists near the upper

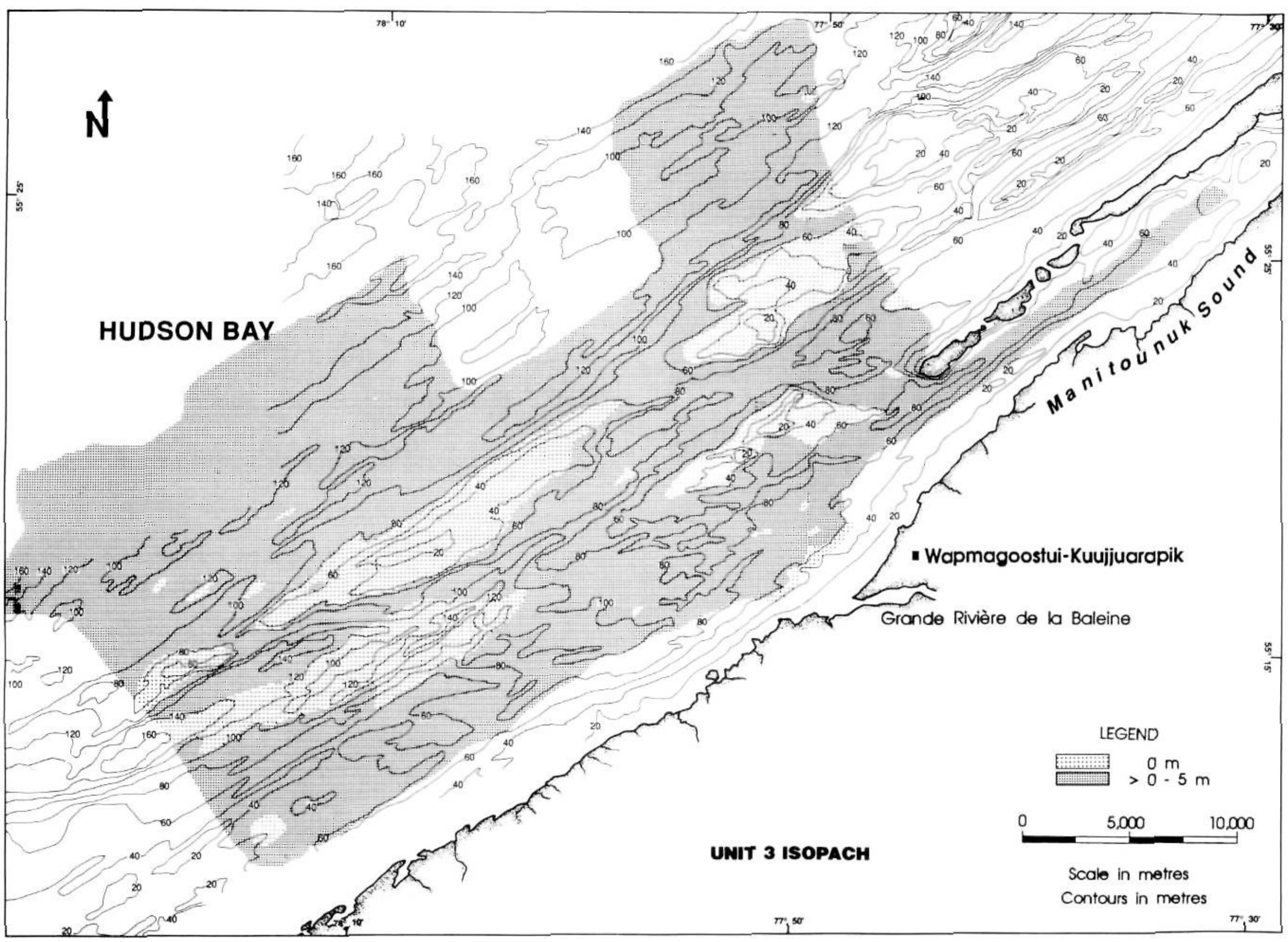

FIGURE 11. Isopach map of unit 3 (rhythmically bedded clays and silts).

Carte isopaque de l'unité 3 (silts et argiles stratifiés).

part of unit 4 that would allow the differentiation of modern muds from the remainder of the unit. The unit consists mainly of clay-size material, with percentages ranging between 60% and 73% of the sediment by weight. Scattered patches, higher in gravel or sand content, have clay-size fractions ranging from 38% to 49%. Silt forms most of the remainder (20-38%), with little sand (0-23%) and gravel (0-20%) (Henderson, 1989). As unit 3 above the unit shows a general trend toward an increase in bulk density and a decrease in water content downward, reflecting a normally consolidating sequence (Marsters, 1988). It has a shear strength of approximately 3-14 kPa, a water content of 79-104% of dry weight, and a bulk density of 1.50-1.70 $g \cdot cm^{-3}$ (Marsters, 1988).

Unit 4 contains a diverse microfauna dominated by tests of foraminifera indicative of cold water and near normal seawater salinities (Bilodeau *et al.*, 1990). Changes in pollen and spore assemblages within the unit indicate an environmental change from early postglacial vegetation (*ca.* 8000-6500 BP) to regionally widespread open spruce woodland vegetation (<6500 BP) (Bilodeau *et al.*, 1990).

UNIT 5: DISTAL FLUVIO-DELTAIC SEDIMENTS

The isopach map (Fig. 17) indicates that unit 5 is present only nearshore and in the Manitounuk Sound. It is characterized by strong and dense acoustic stratifications with a sharp reflector at its base, and has a slightly undulating upper surface (Fig. 5). Where present, unit 5 conformably overlies unit 4. However, at some sites, it was found to lie directly on either the rhythmically bedded muds, the ice contact sediments, or the bedrock.

Unit 5 is acoustically similar to the paraglacial deltaic unit described by Syvitski and Praeg (1989) in the St. Lawrence Gulf, but is of different origin as it postdates by a long period the retreat and disappearance of the ice sheet (see below). It occurs as a constructional deltaic wedge built outward from the mouth of Grande Rivière de la Baleine. Immediately offshore from the river mouth, the unit thins to less than 10 m in the axis of the river channel, whereas north and south of the axis, 10 to 30 m thick sediment lobes are present (Fig. 17). Seaward, beyond 5 km from the shore, thicknesses remain below 10 m, except for scattered patches which may reach 20 m (Fig. 17). The area covered by the sediments of unit 5 is approximately 400 km^2 (10 km × 40 km) in the offshore area adjacent to the Grande Rivière de la Baleine area. With an average thickness of 15 m, this unit represents approximately 6×10^9 m^3 of sediments. It is absent on two topographic highs northwest of the Grande Rivière de la Baleine mouth, and also in some of the deeper parts (>120 m) of the SW Trough (Fig. 17).

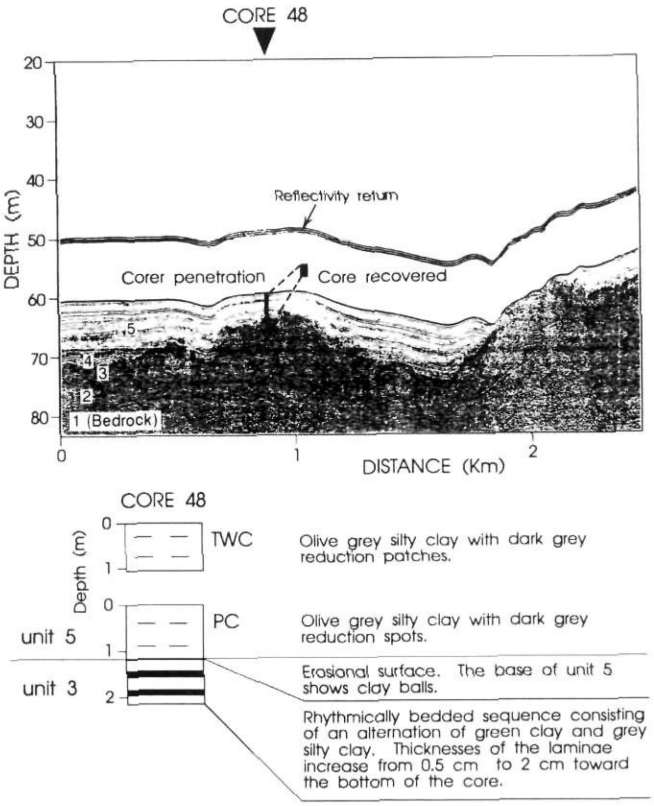

FIGURE 12. Lithostratigraphy of core 48 and its position and penetration on the seismic section. Core description is from Henderson (1989). See Figure 2 for core locality. TWC = trigger weight core. PC = piston core.

Lithostratigraphie de la carotte 48, avec son emplacement et la profondeur de pénétration. La description de la carotte est tirée de Henderson (1989). Voir la figure 2 pour la localisation de la carotte. TWC = carottier déclencheur PC = carottier à piston.

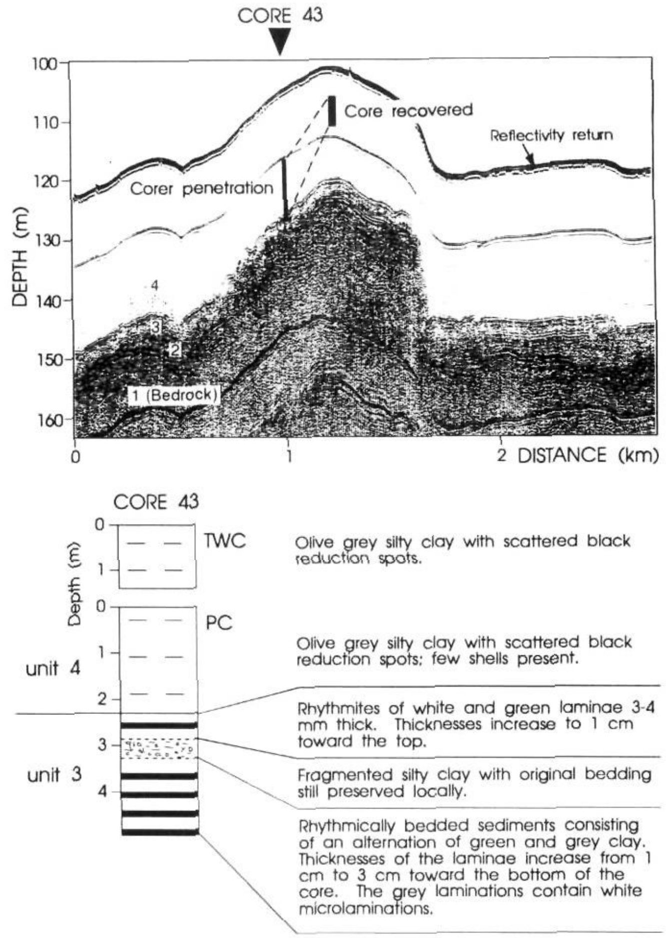

FIGURE 13. Lithostratigraphy of core 43 and its position and penetration on the seismic section. Core description is from Henderson (1989). See Figure 2 for core locality. TWC = trigger weight core. PC = piston core.

Lithostratigraphie de la carotte 43, avec son emplacement et la profondeur de pénétration. La description de la carotte est tirée de Henderson (1989). Voir figure 2 pour la localisation de la carotte. TWC = carottier déclencheur PC= carottier à piston.

Because of increasing faintness of the reflectors away from the river entrance and the decreasing volume of sediment, the exact offshore limit of the unit is difficult to determine. However, from the analysis of the seismic records, it seems that these sediments are not observed northwest of the bedrock ridge located approximately 11 km from the shoreline (Fig. 17). Figure 18 illustrates how that limit was established. On the left end of the figure, southeast of the ridge, the upper unit is interpreted as unit 5 on the basis of faint acoustic stratifications as well as a thin and weak basal reflector. On the other side of the ridge, to the northwest, the upper unit shows weak stratifications but no basal reflector and is comformable with the underlying units. These features are more characteristic of unit 4, and so this acoustic interval is interpreted to represent that unit. Hence unit 5 does not occur northwest of the ridge.

Unit 5 is an olive grey silty clay (Munsell colour code 5Y 4/1) with numerous dark grey reduction spots that were formed by the decomposition of buried organic matter or bioturbation. It shows more silt (37-55%) and less clay (38-58%) than unit 4, as well as little sand (1-12%) and gravel (0-6%) (Henderson, 1989). The unit has been sampled by cores 47 (3.47 m; Fig. 9), 48 (2.23 m; FiB. 12), 50 (0.89 m), 68 (7.45 m), 70 (2.42 m), and 71 (4.70 m).

The lower contact with unit 4, observed only in core 47 (Fig. 9), is sharp. In core 48 (Fig. 12), unit 5 lies abruptly on an erosional surface at the top of unit 3.

Geotechnical analyses show a bulk density of 1.56-1.87 g·cm^{-3}, a water content of approximately 39.9 to 87.3% of dry weight, and a shear strength of 3.3-15.4 kPa. However, a trend toward an increase in bulk density and a decrease in water content downward indicative of normal consolidation is not observed. This suggests underconsolidation, possibly due to high sedimentation rates (Marsters, 1988).

DISCUSSION

DEPOSITIONAL SETTING AND PROVENANCE

The physical and acouscal characteristics of unit 2, as well

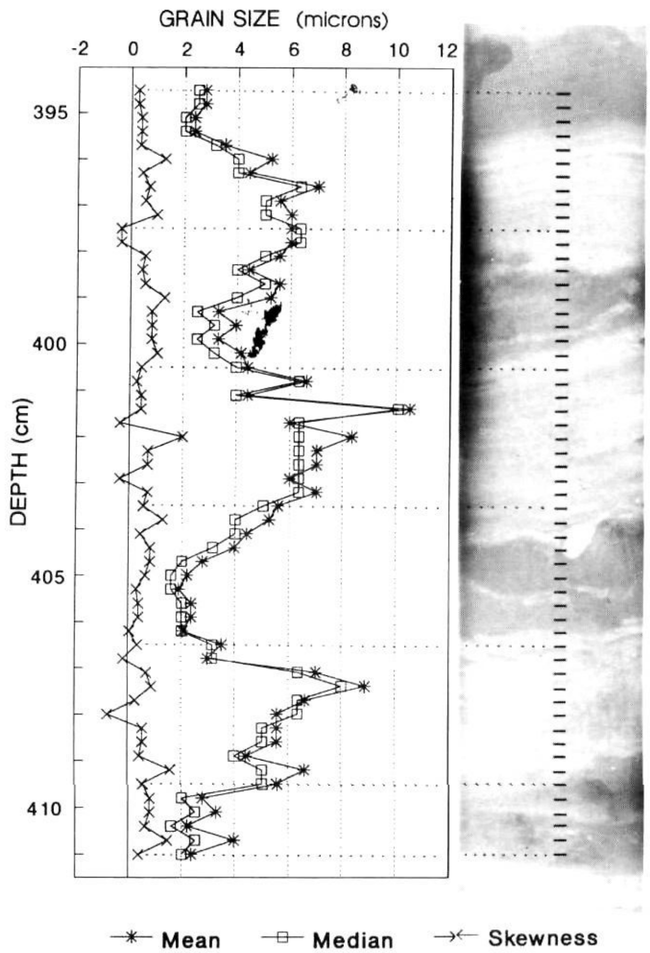

FIGURE 14. Graph showing variation of grain size in laminations of the ice proximal unit (unit 3) in core 43, aligned with X-radiographic negative print of the core slab.

Graphique illustrant la variation de la granulométrie des lamines de l'unité adjacente à la marge glaciaire (unité 3) dans la carotte 43. Graphique mis en parallèle avec le négatif de la radiographie de la carotte.

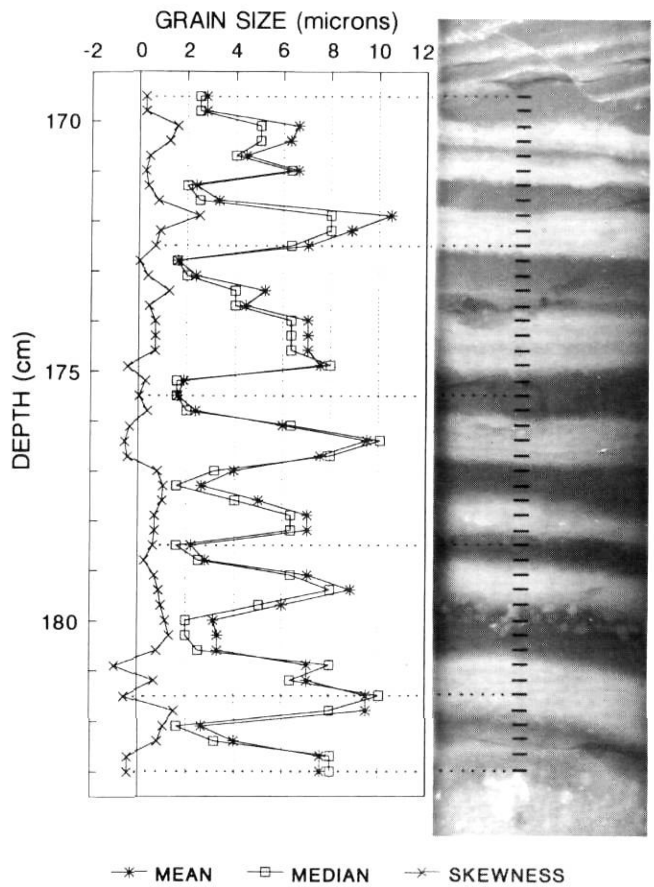

FIGURE 15. Graph showing variation of grain size in laminations of the ice proximal unit (unit 3) in core 48, aligned with X-radiographic negative print of the core slab.

Graphique illustrant la variation de la granulométrie des lamines de l'unité adjacente à la marge glaciaire (unité 3) dans la carotte 48. Graphique mis en parallèle avec le négatif de la radiographie de la carotte.

TABLE I

X-ray fluorescence analysis of individual laminae of unit 3 in core 43

Sample no. color texture	43-00 dark coarse	43-01 light fine	43-02 dark coarse	43-03 light fine	43-04 dark coarse
SiO_2 (%)	69.60	61.25	68.78	61.05	70.11
TiO_2 (%)	0.48	0.60	0.47	0.58	0.44
Al_2O_3 (%)	13.56	16.75	13.38	16.43	13.26
Fe_2O_3 (%)	4.25	6.47	4.75	7.78	4.08
MnO (%)	0.05	0.09	0.06	0.08	0.05
MgO (%)	1.73	3.52	1.92	3.21	1.72
CaO (%)	3.03	2.71	3.40	2.63	3.17
Na_2O (%)	3.83	4.48	3.74	4.16	3.74
K_2O (%)	3.25	3.89	3.26	3.82	3.22
P_2O_5 (%)	0.20	0.22	0.22	0.24	0.20
Co (ppm)	<10	11	<10	27	<10
Cr_2O_3 (ppm)	70	135	100	61	<15
Cu (ppm)	76	44	87	53	91
Ni (ppm)	16	42	*10	27	<10
Zn (ppm)	21	60	25	58	23

TABLE II

X-ray fluorescence analysis of individual laminae of unit 3 in core 48

Sample no. color texture	48-06 light fine	48-07 dark coarse	48-08 light fine	48-09 dark coarse
SiO_2 (%)	63.09	68.51	62.59	69.88
TiO_2 (%)	0.56	0.49	0.58	0.46
Al_2O_3 (%)	16.23	14.24	16.30	13.85
Fe_2O_3 (%)	6.01	4.60	5.83	4.39
MnO (%)	0.07	0.04	0.07	0.04
MgO (%)	2.79	1.60	2.95	1.18
CaO (%)	2.57	2.70	2.57	2.77
Na_2O (%)	4.72	4.35	4.97	4.10
K_2O (%)	3.70	3.21	3.89	3.07
P_2O_5 (%)	0.23	0.24	0.23	0.24
Co (ppm)	16	<10	10	<10
Cr_2O_3 (ppm)	119	111	118	50
Cu (ppm)	55	65	52	50
Ni (ppm)	30	30	35	20
Zn (ppm)	40	25	36	18

as its irregular thickness over the area, suggest a basal till. The presence of gravel composed of crystalline and of Proterozoic carbonate rock fragments derived from the coastal uplands (Henderson, 1989) to the east indicates that the material was transported westward by the ice sheet. The well compacted diamicton, not easily penetrated by the corer, suggests deposition under grounded ice.

In contrast, the fine-grained texture of unit 3, which is draped over and comformable to the upper surface of unit 2 or rests directly over the bedrock, suggests deposition in a quiescent deep environment. Low pollen concentration at the base of unit 4 suggests an environment typical of deglaciation time (Bilodeau *et al.*, 1990). Thus, unit 3 would have been deposited earlier, *i.e.* prior to the Tyrrell Sea invasion, which began around 8000 BP, and during the time when Lake Ojibway is reported to have extended over the lower Grande Rivière de la Baleine estuary (Hillaire-Marcel, 1979).

A paleontological analysis made only on core 69 indicates that micro-organisms in unit 3 are very sparse, consisting only of badly preserved ostracods interpreted to possibly indicate a lacustrine environment by Bilodeau *et al.* (1990). However, the percentages of sulphur recorded in the individual laminae (up to 4.61% in core 48 and to 5.25% in core 43 as SO_3; Gonthier, 1992) reach values that are not characteristic of a lacustrine environment. Berner and Raiswell (1984) indicated that dissolved sulfate concentrations in fresh water are much lower, averaging less than 1% of that found in the oceans. Table II shows that sulfur concentrations (as SO_3) are over 1% in all the coarse laminae of core 43, and in half of all the laminae of core 48. This can be explained by one of the two following processes: 1) the lake water was contaminated by sea water from northeastern Hudson Bay seeping under the Hudson Ice Sheet barrier, and became brackish; or 2) the lake water was fresh during deposition of the sediment but the interstitial pore waters were contaminated by downward diffusion of sea water sometime between the time of the Tyrrell Sea invasion and the present, hence increasing the sulphur content within the sediments.

The second hypothesis is more plausible for three reasons. First, the pore waters have salinity values of 30.1 to 34‰ (Marsters, 1988), which are consistent with values for Tyrrell Sea and modern Hudson Bay waters, suggesting the

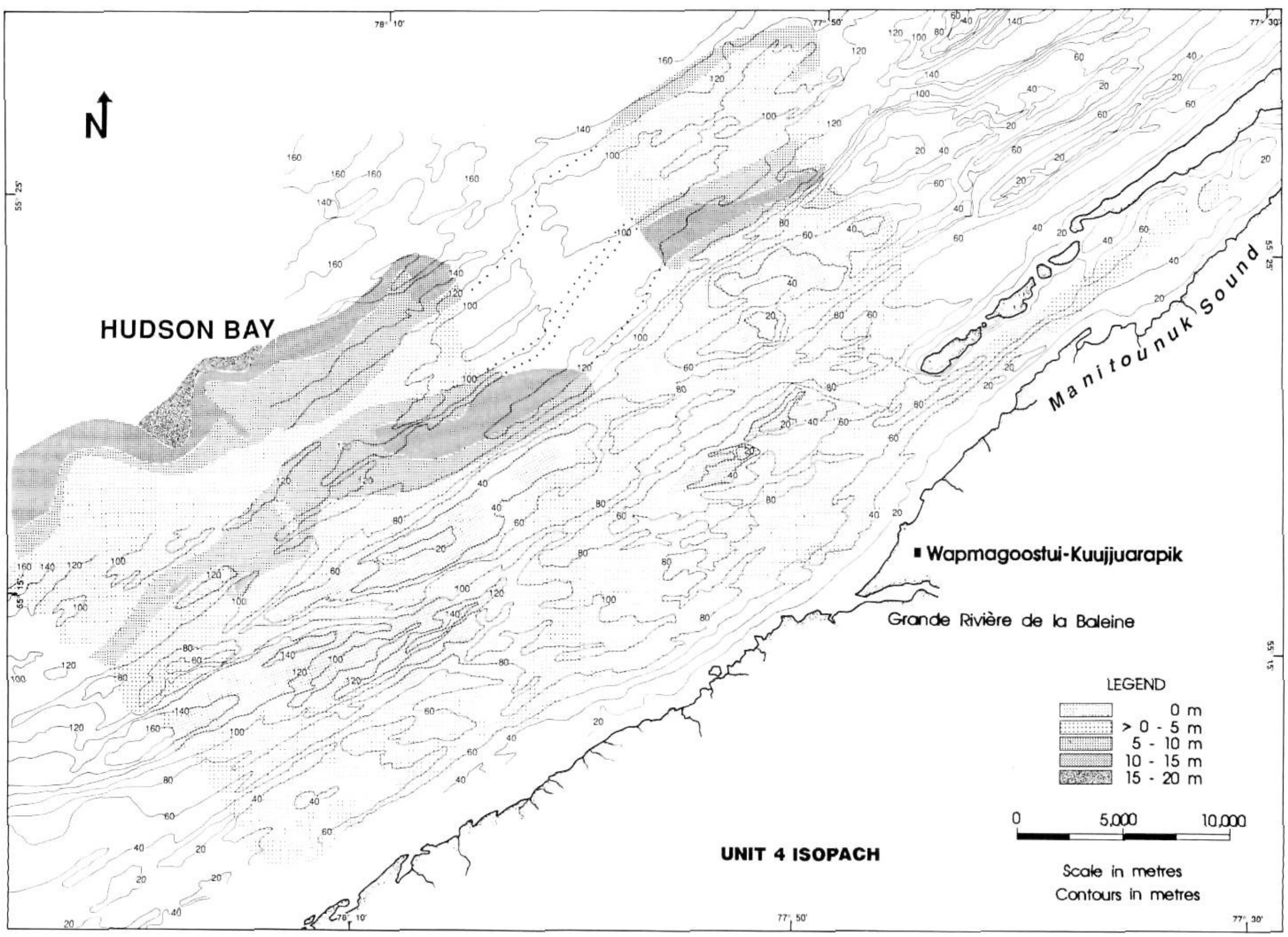

FIGURE 16. Isopach map of unit 4 (postglacial marine muds). *Carte isopaque de l'unité 4 (boues marines postglaciaires).*

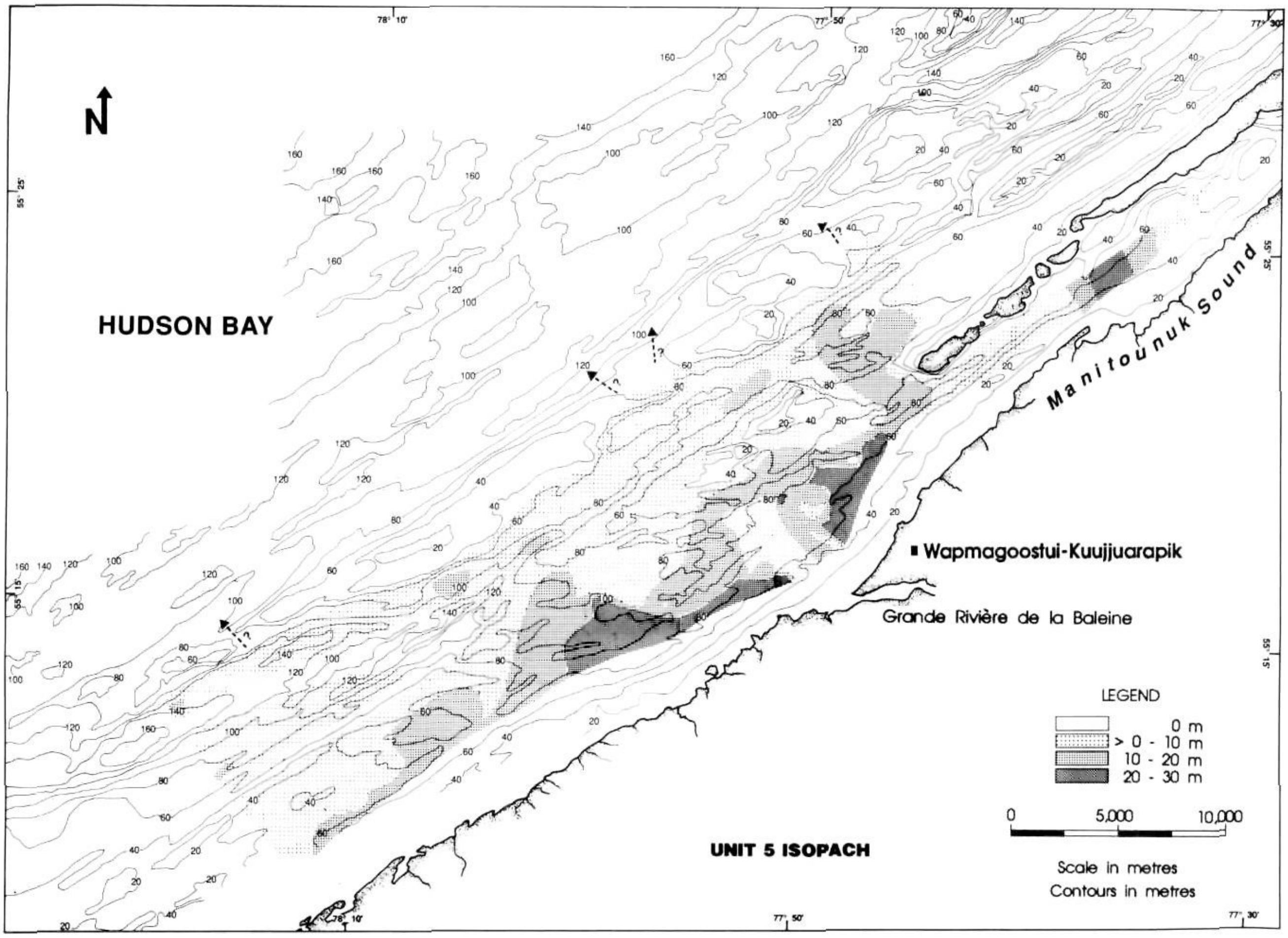

FIGURE 17. Isopach map of unit 5 (distal fluvio-deltaic sediments) *Carte isopaque de l'unité 5 (sédiments fluvio-deltaïques distaux).*

possibility of marine contamination of pore waters. Secondly, the fracturing and fragmentation of sediments observed in segments of unit 3 within cores 43, 47, 48 and 69 are interpreted as being due to post-depositional freezing of the interstitial freshwater in lake sediments suddenly exposed to temperatures below 0°C during invasion of the area by marine waters during and after the Tyrrell Sea invasion (Bilodeau *et al.*, 1990). Such a process was discussed by Chamberlain and Gow (1979). The freezing would have acted only on subsurface lake sediments not yet invaded by salt diffusion from above. Finally, the isotopic ratios of Li^6/Li^7 in sediments of unit 3 have concentrations that are similar to those observed in modern lakes (A. Mucci, pers. comm., 1991), suggesting a fresh water environment during deposition. The continuity of the unit as observed on seismic profiles suggests a similar depositional environment throughout the area.

As lacustrine deposits, the rhythmites of unit 3 are probably varves. Varved sediments consist of annually-produced couplets with usually a light-colored silt layer deposited during the active melting period of ablation (summer), and a dark-colored clay layer deposited during the closed lake ice cover period (winter) (Eyles and Miall, 1984), with a sharp contact between the two laminae (Smith and Ashley, 1985). The fine layers commonly show normal grading, whereas the coarser layers rarely show grading. The coarse layer thicknesses vary, but the finer layers maintain a consistent thickness throughout the basin. In addition, multilaminations are commonly present in proximal coarse layers, reflecting short-term fluctuations in source intensity. Except for the color/grain-size relationship, the rhythmites of unit 3 have all these characteristics. Fining upward in the fine-grained laminae, is disclosed by the grain size analysis of core 48 (Fig. 15), multilaminations is observed in the coarse-grained laminae of core 43 (Fig. 14), and sharp interfaces between the light (fine) and dark (coarse) laminae are observed in both core sections (Figs. 14 and 15). The fine-grained layers display more constant thicknesses (generally from 3 mm to 1 cm with a maximum of 4 cm) than the coarser-grained ones (generally from 3 mm to 2 cm with a maximum of 14 cm). The overall trend in all cores toward thinner couplets upward may be related to retreat of the ice front and of the sediment sources.

The regularity as well as the systematic difference in grain-size between dark and light laminae noted in the rhythmites provides additional evidence that these are varves. A plot of the arithmetic quartile deviation (QDa) (Fig. 19), which is indicative of sorting, versus mean grain size of both light and dark laminae of core 48 illustrates the well defined bimodality of the varved sediments, as samples of the light laminae are

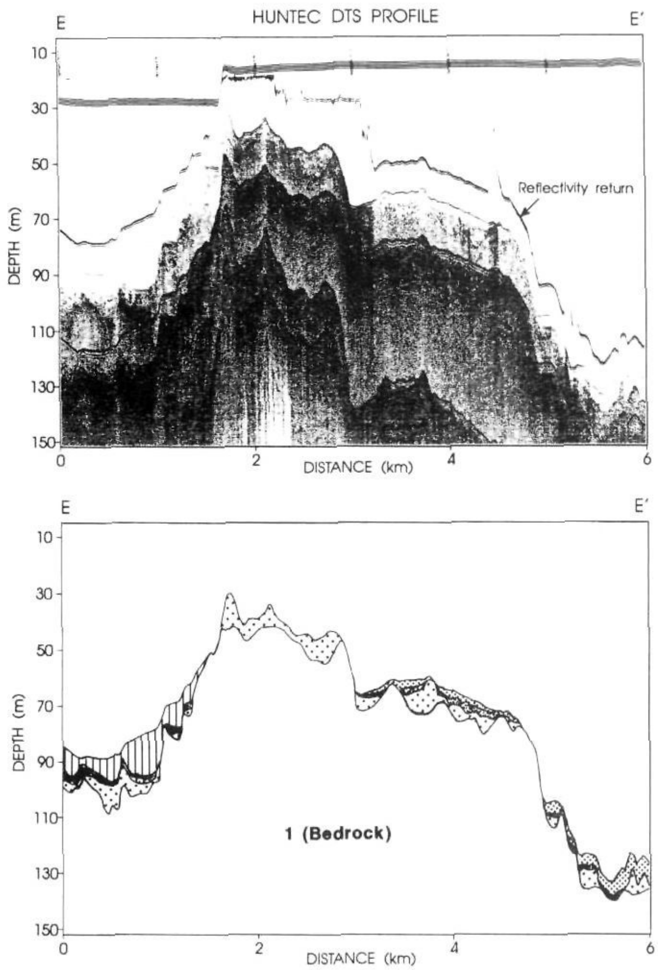

FIGURE 18. Seismic profile E-E' (Fig. 1), showing an example of the disappearance of the distal fluvio-deltaic unit (unit 5) to the northwest (Fig. 4 for legend). Note that this figure is at half the scale of Figures 4-7.

Profil sismique E-E' (fig. 1) illustrant un exemple de la disparition vers le nord-ouest de l'unité fluvio-deltaïque distale (légende à la fig. 4). L'échelle est la moitié de celle des figures 4-7.

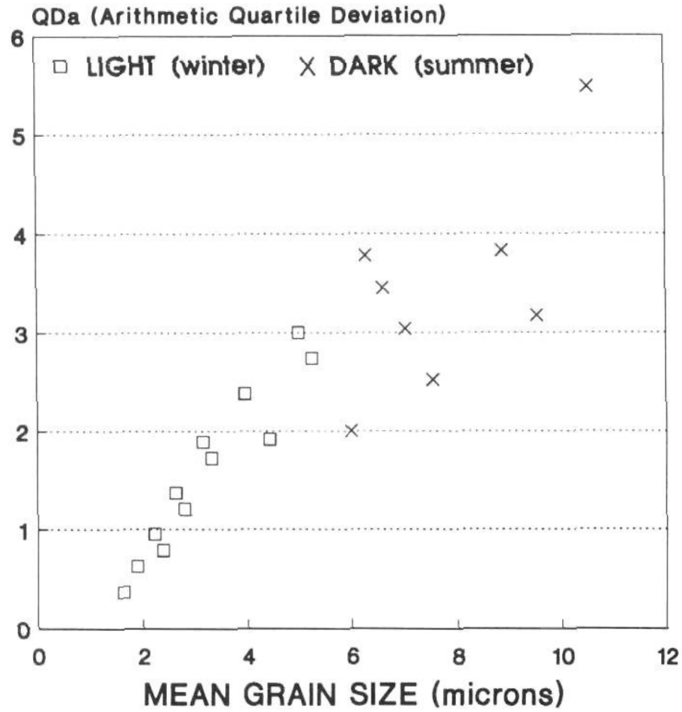

FIGURE 19. Plot of mean grain size versus arithmetic quartile deviation (QDa) in samples from core 48 as shown in Figure 15. The number of values plotted is less than the number of samples indicated on Figure 15 as plots of samples with equal values overlie each other. A lower value of QDa indicates better sorting.

Graphique de la moyenne granulométrique en fonction de la déviation quartile arithmétique (QDa) des échantillons provenant de la carotte 48 (fig. 15). Le nombre des valeurs présentes sur le graphique est inférieur au nombre d'échantillons indiqués à la figure 15 en raison de la superposition des points de valeur égale. Une valeur de QDa moins élevée indique un meilleur tri.

both finer and better sorted than those of the dark ones. This is also observed in the varves of core 43 (Fig. 20), although the bimodality is not as sharply defined due to the multilaminated nature of the dark coarse layers that incorporate microlaminations of clay within the silt layer. This bimodality of the laminae indicates that each couplet is not a uniformly graded bed, but consists of two distinct populations of particles deposited by two alternating processes. Considering the quantity of sediments involved in the deposition of each couplet over the entire study area, the consistent repetition of two processes responsible for the rhythmicity of unit 3 is better explained by an annual cycle rather than by haphazard processes of sediment supply.

These observations add further support to the conclusion of Hillaire-Marcel (1979), based on river bank sections along the Grande Rivière de la Baleine, that glacial Lake Ojibway in its late phase extended to the latitude of this river. The lake probably extended even farther north into Manitounuk Sound as core 48, collected 5 km into the sound, contains 0.98 m of varve-type deposits belonging to unit 3, which is interpreted as lacustrine. Also, unit 3 as identified on the seismic profile extends 15 km into the sound (Fig. 2).

The alternation of dark "summer" laminae and lighter "winter" laminae, which is inverse to the color banding commonly observed within varved sediments (Eyles and Miall, 1984), is explained, on the basis of geochemical data, by the conditions of deposition in glacial Lake Ojibway. Coarse laminae may represent more active suspension transport and greater terrigenous inputs by seasonal meltwaters. This is supported by the higher Si/Al ratios and the more abundant quartz and feldspars observed in the dark laminae. Mildly reducing conditions could have developed in the sediments as a result of the accumulation of detrital organic debris. With sufficient rates of burial, black disseminated sulfides would have formed, explaining the dark coloration. The lower amounts of oxidized Fe in the dark layers as compared to the light ones (Tables I and II) may mean that some Fe was removed in solution in the suboxic pore water environment. It is assumed that enough sulfate was available in the lake waters to form authigenic iron monosulfides which have been found to occur in fresh or brackish water sediments (Berner

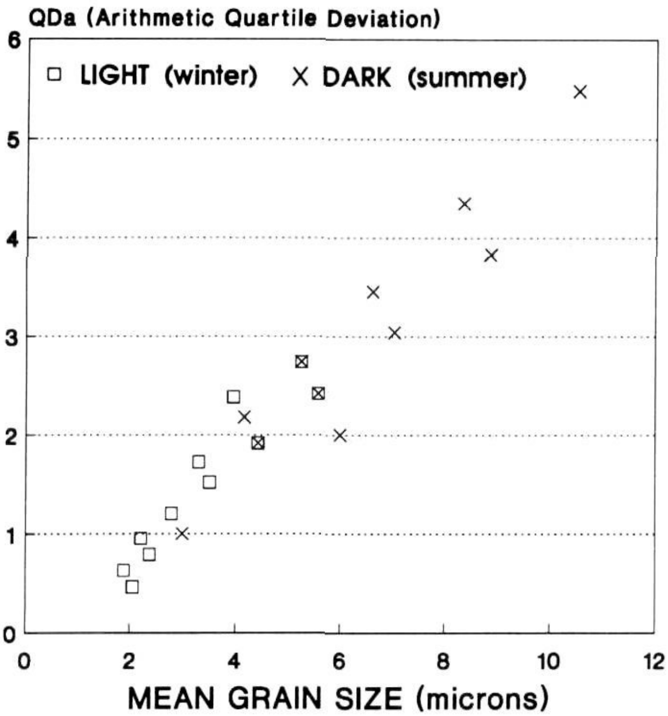

FIGURE 20. Plot of mean grain size versus arithmetic quartile deviation (QDa) in samples from core 43 as shown in Figure 14. The number of values plotted is less than the number of samples indicated in Figure 14 as plots of samples with equal values overlie each other. A lower value of QDa indicates better sorting.

Graphique de la moyenne granulométrique en fonction de la déviation quartile arithmétique (QDa) des échantillons provenant de la carotte 43. (fig. 14). Le nombre des valeurs présentes sur le graphique est inférieur au nombre d'échantillons indiqués à la figure 15 en raison de la superposition des points de valeur égale. Une valeur de QDa moins élevée indique un meilleur tri.

et al., 1979). In this interpretation the dark laminae could be "summer" layers, which are different from the coarse light summer layers of classical varves (Eyles and Miall, 1984).

In contrast, the better sorted fine-grained layers may indicate quiet winter settling, perhaps under an ice cover, of finer inorganic particles held in suspension in the water column, with little or no addition of new material from the rivers. Higher concentrations of Fe and Mn in the light laminae as compared to the dark coarse layers (Table I and II) suggest lower rates of burial, allowing oxic conditions to develop in the surface sediments. Lower Si/Al ratios indicate a quiet environment favorable to fine clay particle settling. The light laminae would then be the "winter" layers.

Contrasts in textural and chemical compositions between layers can be used to interpret the depositional processes of the varves. The composition of the fine light-colored laminae, which contain more clay minerals and finer detrital particles than in the dark layers, suggests that their deposition resulted from the overflow-interflow dispersal process described by Smith and Ashley (1985). This mode of sediment delivery leads to deposition of the coarse grains nearer to the ice margin, whereas the finer silt- and clay-size particles are transported throughout the lake by inertia and subsequently settle to the bottom during the winter.

The coarse layer was formed in a more dynamic environment, as the larger detrital grains, mainly quartz and feldspars, demand more energy to be distributed across the lake. The process responsible for these accumulations must then have been dominated by single pulsating or intermittent density underflows with possibly a minor contribution of pelagic material from overflow-interflows. As described by Smith and Ashley (1985) the underflows occur during the glacial melt season when the water released from the ice sheet, which contains large concentrations of sediments, spread along the bottom of the lake due to its high density. The dominance of the underflow currents as the main depositional process of the coarse layer is supported by its multilaminated nature and the fact that it is usually thicker than the fine layers, hence indicating a larger sediment contribution. As the ice front regressed eastward, the couplets became much thinner, and the laminae attained similar thicknesses. The underflow dominance therefore diminished in favor of the overflow interflow processes.

The combination of underflows with overflow-interflows tends to form thicker accumulations in the bathymetric lows than in the highs because underflows are constrained by the bottom relief. In contrast, sediments deposited only by overflow-interflows form a uniform deposit over the entire area (Smith and Ashley, 1985). As a result of the seasonal alternation of these two sediment transport processes, thin deposits would have formed on the ridge crests and thick ones in the troughs. Therefore, the absence of sediments on the ridge tops as observed on Figure 11 probably results from preferential deposition of the sediments in the troughs and nondeposition on the ridge crests.

Because of its fine texture and its draping over the substratum, unit 4 also appears to have been deposited in a deep quiescent environment at some distance from the ice margin. The microfaunal and palynological assemblages indicate a marine origin of Tyrrell Sea age (post 8000 BP; Bilodeau *et al.*, 1990). Unit 4 therefore consists of hemipelagic postglacial marine muds of that period overlain by recent muds deposited in the Hudson Bay environment. The recent muds cannot be differentiated acoustically nor physically from the remainder of unit 4 sediments because the environment of deposition has not changed substantially; the present Hudson Bay is merely a remnant of the Tyrrell Sea.

Unit 5 sediments consist of thick postglacial accumulations of silts and clays that are interpreted to be detrital sediments transported out of the watershed as the strandline prograded westward. They are most probably the distal equivalents of the onshore alluvial deltaic sands, described by Hillaire-Marcel and de Boutray (1975) which form raised terraces that reach an altitude of 40 m on the south side of the channel upstream of the river exit. These sands deposited on top of the Tyrrell Sea clays during marine regression vary in grain-size from fine to coarse, and contain lenses of gravel or pebbles (Bilodeau, 1990). They represent deposition of material derived from remobilization of glacial sediments farther upstream during the late phase of emergence (Hillaire-

Marcel and de Boutray, 1975). The finer particles, which originated from winnowing of glacial drift and from eroded marine sediments in the watershed of the river were transported offshore and formed unit 5. Because nearshore areas shallower than 40 m could not be surveyed by the CSS Hudson, information is missing from within 3 km of the river mouth, a region where the transition between the topset deltaic sands to sandy silts onshore and the bottom set clayey silts offshore is expected to occur.

In recent times, the seaward progradation and southward expansion of the sand barrier by longshore processes has favored the southward migration of the river channel, undercutting the raised deltaic sand terraces along the south bank of Grande Rivière de la Baleine and causing cliff recession. Most of the sediments from these terraces have settled near the river mouth as suggested by the presence of a shallow (depth of 1 to 1.5 m) sandbar (Ingram, 1981).

The time interval covering the deposition of unit 5 can be indirectly estimated by reference to the known regional emergence rates, assuming that these rates are the main control on the river solid discharge. A high emergence rate would result in rapid river channel downcutting and thus in high solid discharge. The solid discharge would diminish as the emergence rate diminishes.

Based on the regional topography, ^{14}C dating, and Andrews' (1968) emergence curve, Hamelin and Cailleux (1972) postulated the migration of the coastline through time. If the paleo-shores are interpreted in the light of the emergence curve of Hillaire-Marcel and Vincent (1980), the present river channel came into existence at around 4000 BP, which suggests an upper limit to the age of unit 5. As a ^{14}C age of 3810 + 50 BP (TO-1099), measured on marine shells, was obtained in a river bank section by Bilodeau (1990) at 1 m below the boundary between the deltaic sands and the Tyrrell Sea sediments. the deltaic deposition must have started around 3500 BP. Near that time the fluctuating regional emergence rates temporarily reached values as high as 4.5 cm yr^{-1} with a mean value of 2.9 cm yr^{-1} (Hillaire-Marcel and Fairbridge, 1978). At these rates, peak periods of channel downcutting, river sediment transport, and unit 5 buildup could be expected. The current emergence rate of 1.1 cm yr^{-1} was reached around 2800 BP (Allard and Tremblay, 1983; Vincent *et al.*, 1987), an age which likely marked a substantial reduction in the rate of deposition of unit 5. At the present emergence rate, the sediment discharge is in the order of only 0.5×10^6 t yr^{-1}, with offshore sedimentation rates of only 2 to 3 mm yr^{-1} (d'Anglejan and Biksham, 1988). Because emergence rates have not varied much over the past 2800 years, we can assume that sedimentation rates have also remained comparable. Therefore, assuming an average sedimentation rate of 2.5 mm yr^{-1} for the last 2800 years, the thickness of sediments accumulated during that time would be approximately 7 m. The average thickness of unit 5 was estimated at 15 m. Thus the remaining 8 m constitutes a reasonable estimate of the thickness of sediments deposited from 3500 BP to 2800 BP, which gives an average sedimentation rate of approximately 1.1 cm yr^{-1} during that time interval. The slightly coarser nature of the top sediments of unit 5 compare to the modern mud overlying unit 4 support the interpretation that unit 5 is still being deposited.

Distribution of the deltaic sediments, as observed on Figure 17, was mainly controlled by bottom currents and seabed morphology. The sediments accumulated preferentially in basins and troughs with thinner deposits over bedrock ridges. Two lobes of thick sediments present north and south of the present river channel axis (Fig.17) indicate the presence of two topographic depressions in the bedrock.

Where it underlies unit 5, unit 4 occurs only as a thin (>5 m) layer (Figs. 17 and 18). Based on sedimentation rates estimated at 75 to 100 cm 10^{-3} yrs in the Tyrrell Sea (Bilodeau *et al.*, 1990), and assuming 4500 years of deposition following the marine invasion at 8000 years BP prior to the onset of unit 5 deposition, the Tyrrell Sea sediments thickness nearshore should be approximately 3.4 to 4.5 m. These values are consistent with observed thicknesses nearshore of about 1 to 5 m for unit 4 where it underlies unit 5. Unit 5 sediments nearshore are in lateral continuity with the upper marine muds of unit 4 offshore and are contemporaneous with them.

It is likely that during the period of high discharge which produced over half of unit 5, the river's finest suspension load was dispersed seaward to the deeper parts of the basin along general directions imposed by bottom currents and seabed morphology, shown by arrows on Figure 17. Deposition of these suspended sediments may have contributed to unit 4 offshore, increasing its thickness, as observed in the deeper troughs there (Fig. 16).

A final observation concerning the depositional setting in the area is the absence of units 3, 4 and 5 in some parts of the SW Trough (Fig. 1 for location) that are deeper than 120 m. This may result from two processes. First, slumping of the entire sedimentary sequence toward the southwest and out of the surveyed area of the trough, in spite of the moderate slope gradient (3 m km^{-1}), may have resulted from the weight of unit 5, thick and underconsolidated, lying on the quick clays of units 3 and 4. The presence of large slumps on the delta front off Petite Rivière de la Baleine, which has produced sediment flows that extend up to 7.5 km seaward of the delta (Josenhans *et al.*, 1991), shows that this mechanism is possible. Secondly, sedimentary furrows have been observed by sidescan sonar at the bottom of the SW Trough (Josenhans *et al.*, 1991). Furrows are indicative of recurring, directionally stable, strong (± 50 cm/sec) bottom currents (Flood, 1983). The southwest orientation of the furrows parallel to the trough axis (Josenhans *et al.*, 1991) suggests nondeposition or erosion due to present bottom currents. Thus, the absence of sediments in some parts of the SW Trough may have resulted from slumping of the sedimentary sequence and/or nondeposition of sediments due to strong bottom currents.

RELATIONSHIP TO ONSHORE STRATIGRAPHY

A biostratigraphic correlation based on micropaleontology and palynology was made by Bilodeau (1990) between an onshore section along Grande Rivière de la Baleine and core 69 (Fig. 2). Core 47, taken closer to shore, provides additional

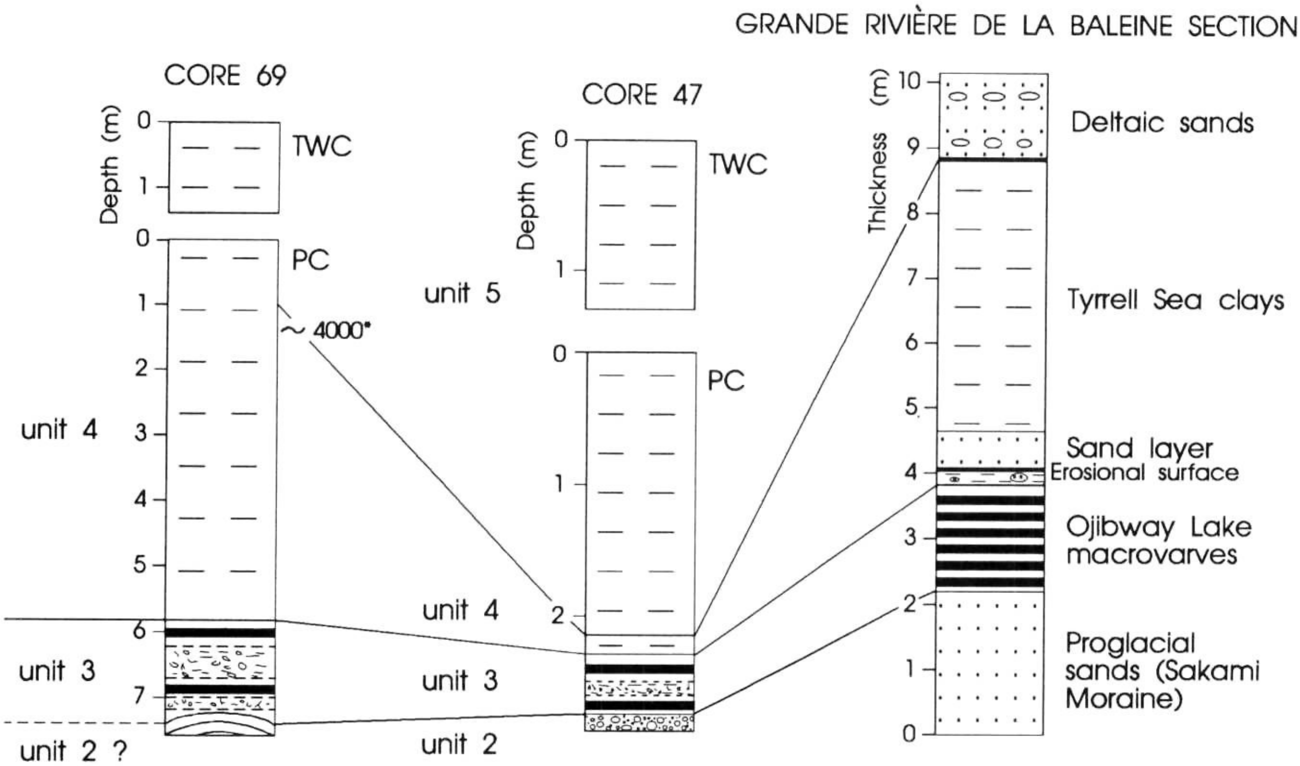

FIGURE 21. Correlation between onshore and offshore stratigraphic sequences (see Figures 9 and 10 for lithologic descriptions; see Figure 2 for core localities). The Grande Rivière de la Baleine section is located 4 km east of Wapmagoostui-Kuujjuarapik and is taken from Bilodeau (1990). * The age of 4000 BP based on palynostratigraphic data is from Bilodeau (1990). TWC = trigger weight core. PC = piston core.

*Corrélation entre les séquences stratigraphiques des zones cotières et de haute-mer (descriptions lithologiques aux fig. 9 et 10; localisation des carottes à la fig. 2). La coupe de la Grande rivière de la Baleine est située à 4 km à l'est de Wapmagoostui-Kuujjuarapik et est tirée de Bilodeau (1990). * L'âge de 4000 BP proposé sur des bases palynostratigraphiques est tiré de Bilodeau (1990). TWC= carottier déclencheur PC = carottier à piston.*

lithostratigraphic details as it includes unit 5.

As shown in Figure 21, the proglacial sands observed onshore are thought to represent a lateral time equivalent of the basal till offshore. As explained earlier, this unit is observed in both cores 47 and 69, and therefore the bases of those two cores are correlated (Fig. 21).

The overlying unit (unit 3) consists of rhythmites thought to have been deposited in glacial Lake Ojibway. It is traced continuously from onshore to offshore, suggesting that the lake occupied much or all of the Grande Rivière de la Baleine region. Offshore, the postglacial marine clays (unit 4) directly overlie unit 3, whereas onshore a 60 cm sand layer separates them. This layer was first interpreted by Hillaire-Marcel and Vincent (1980) as a by-product of the rapid drainage of glacial Lake Ojibway into the Tyrrell Sea (around 8000 BP). However, Bilodeau (1990) established that it is more recent (5190 ± 60 BP determined by ^{14}C dating, TO-1098) of shell fragments at the base of the overlying marine clays), and suggested that it might record strong subaquatic currents associated with a major landslide upstream. This is in better agreement with the lack of a sand layer noted offshore.

The upper unit of deltaic sand onshore correlates stratigraphically with the nearshore silty clays of unit 5. As mentioned earlier, unit 5 is absent farther offshore and is the time equivalent of the upper Tyrrell Sea and recent muds (unit 4). The slightly coarser nature of the sediments at the top of unit 5 compared to the recent muds at the top of unit 4 support the hypothesis that unit 5 is still being deposited.

SUMMARY AND CONCLUSIONS

Medium- and high-resolution seismic profiles and piston cores were used to interpret four acoustic stratigraphic units and to map their lateral distributions in front of Grande Rivière de la Baleine. These interpretations are supported by the lithostratigraphy provided by seven piston cores, as well as textural, geotechnical, paleontological, and palynological information available on four of these from previously published studies. This study agrees largely with the interpretations of Hillaire-Marcel and Vincent (1980) and of Bilodeau *et al.* (1990) concerning the Holocene stratigraphy and deglaciation processes, but it encompasses a larger data base and covers a much greater area, and thus significantly expands and refines our understanding of the sedimentation and deglaciation processes that have occurred in the area since retreat of the Laurentide Ice Sheet. The additional details and refinements include the following:

1) Unit 2, interpreted as basal till, is present as a generally thin, irregular deposit over most of the surveyed area dis-

cussed in this paper. It was transported by a westward-flowing ice sheet and deposited under grounded ice.

2) Sedimentological and geochemical studies of the rhythmites of unit 3 support the view that these sediments are true varves. Paleontological analysis results, which suggest that the unit was deposited in a lacustrine environment, are available only from core 69 (Bilodeau *et al.*, 1990), but the continuity of the unit as observed on seismic profiles suggests a similar depositional environment throughout the area. Such an environment would have been provided by glacial Lake Ojibway, which extended farther north than the present site of Grande Rivière de la Baleine. The reverse coloration of the laminae from that commonly observed within varved sediments is explained on the basis of geochemical data. Grain size variations as well as mineral and chemical compositions suggest that the "summer" coarse-grained laminae were transported by a combination of underflows and overflows-interflows, whereas the "winter" fine-grained laminae were transported by overflows-interflows only. The importance of underflows in the lake basin diminished as the ice sheet retreated eastward, which explains the thinning of the couplets upward.

3) Unit 4 consists of hemipelagic postglacial marine muds deposited in the Tyrrell Sea and of recent muds being deposited in Hudson Bay. It occurs as a comformable layer throughout the area.

4) A distal deltaic unit (unit 5) formed in front of the mouth of Grande Rivière de la Baleine. Over half of it probably accumulated between approximately 3500 BP and 2800 BP, but sedimentation has continued until today at a slower rate. The sediments forming this unit originated from uplift-induced excavation of the river channel through the glacial deposits and the glaciolacustrine and marine muds exposed presently along the banks of Grande Rivière de la Baleine. The approximate volume of this unit is 6×10^9 m^3, and the expected rate of sedimentation was in the order of 1.1 cm yr^{-1} between 3500 BP and 2800 BP, and 2.5 mm yr^{-1} for the last 2800 years. Evidence suggests that unit 5 sediments are contemporaneous with and distal to the deltaic sands exposed along the banks of Grande Rivière de la Baleine, implying that the deltaic sequence grades from sands onshore to clayey silts offshore. Unit 5 correlates with the upper part of the Tyrrell Sea sediment and modern muds (unit 4) farther offshore.

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