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La géologie marine de la baie des Chaleurs
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Article abstract

Baie des Chaleurs is the fourth largest estuary in eastern Canada. The bay is a broad and shallow basin, filled with up to 50 m of unconsolidated Quaternary sediment. The distribution of this sedimentary mass is in part controlled by a Cenozoic (Tertiary or Quaternary) drainage system that follows the main structural elements of the underlying Paleozoic sedimentary bedrock. Ice-contact Pleistocene sediment, including till, is generally thin or absent. However, in the central and outer bay the Cenozoic channels contain linear morainal accumulations up to 30 m thick. These deposits may indicate the terminal position of the Gaspé ice dome. Six large but separate glacimarine fans mark the position of major discharge outlets that operated during the retreat phase of the regional ice sheets. These Pleistocene deposits were partly eroded by glacifluvial drainage channels during a low sea level stand (-90 m) circa 9000 years BP. Subsequently, during the early to middle Holocene marine transgression, the glacigenic sediments were subjected to wave erosion. These deposits thus thin towards shallower water and are marked by shore-parallel terraces and surface lags along the margins of the bay. By 7000 years BP, a sandur complex located in the shallower inner bay was also transgressed by the rising sea. Early Holocene sedimentation occurred initially in the deeper waters of the central and outer bay, and subsequently formed an extensive veneer across the inner bay sandur with rising sea levels. These paraglacial sediments show a progression in bedding styles and particle size related to sea level position and sediment source. Modern océanographie conditions became established circa 5000 years ago, and include increased tidal and wave activity, and decreased sediment discharge. Modern sediments are deposited principally beneath a mid-bay gyre set up by the influx of the Gaspé current along the north shore and the efflux of fresher water along the New Brunswick shore.

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MARINE GEOLOGY OF BAIE DES CHALEURS*

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ABSTRACT Baie des Chaleurs is the fourth largest estuary in eastern Canada. The bay is a broad and shallow basin, filled with up to 50 m of unconsolidated Quaternary sediment. The distribution of this sedimentary mass is in part controlled by a Cenozoic (Tertiary or Quaternary) drainage system that follows the main structural elements of the underlying Paleozoic sedimentary bedrock. Ice-contact Pleistocene sediment, including till, is generally thin or absent. However, in the central and outer bay the Cenozoic channels contain linear morainal accumulations up to 30 m thick. These deposits may indicate the terminal position of the Gaspé ice dome. Six large but separate glacimarine fans mark the position of major discharge outlets that operated during the retreat phase of the regional ice sheets. These Pleistocene deposits were partly eroded by glacifluvial drainage channels during a low sea level stand (−90 m) *circa* 9000 years BP. Subsequently, during the early to middle Holocene marine transgression, the glacigenic sediments were subjected to wave erosion. These deposits thus thin towards shallower water and are marked by shore-parallel terraces and surface lags along the margins of the bay. By 7000 years BP, a sandur complex located in the shallower inner bay was also transgressed by the rising sea. Early Holocene sedimentation occurred initially in the deeper waters of the central and outer bay, and subsequently formed an extensive veneer across the inner bay sandur with rising sea levels. These paraglacial sediments show a progression in bedding styles and particle size related to sea level position and sediment source. Modern oceanographic conditions became established *circa* 5000 years ago, and include increased tidal and wave activity, and decreased sediment discharge. Modern sediments are deposited principally beneath a mid-bay gyre set up by the influx of the Gaspé current along the north shore and the efflux of fresher water along the New Brunswick shore.

RÉSUMÉ *La géologie marine de la baie des Chaleurs*. La baie des Chaleurs, quatrième estuaire en importance de l'est du Canada, est un large bassin peu profond rempli de sédiments non consolidés d'une épaisseur allant jusqu'à 50 m. La répartition de cette masse sédimentaire est en partie imposée par le réseau de drainage datant du Cénozoïque (Tertiaire ou Quaternaire), qui suit les principaux éléments structuraux du socle sédimentaire sous-jacent. Les dépôts de contact glaciaire pléistocènes, y compris le till, sont généralement minces ou absents. Toutefois, au centre et vers l'extérieur de la baie, les chenaux cénozoïques renferment les accumulations morainiques linéaires, jusqu'à 30 m d'épaisseur, qui pourraient signaler l'emplacement final du dôme de la Gaspésie. Six grands cônes glaciomarins identifient les exutoires en fonction pendant la phase de retrait des calottes régionales. Ces dépôts pléistocènes ont en partie été érodés par des chenaux de drainage fluvioglaciaires pendant une phase de bas niveau marin (−90 m), vers 9000 BP. Par la suite, au cours de la transgression marine de l'Holocène inférieur à moyen, les sédiments glaciaires ont été soumis à l'érosion par les vagues. Les dépôts s'amincissent donc en eaux peu profondes et sont caractérisés par la présence de terrasses parallèles à la rive et des surfaces de sédiments grossiers le long des marges de la baie. À 7000 BP, le complexe de sandur qui occupait le fond peu profond de la baie a aussi été atteint par la transgression marine. La surface du delta était protégée par une barrière morainique. Les sédiments de l'Holocène inférieur ont d'abord été déposés dans les eaux plus profondes du centre et de l'entrée de la baie et ont subséquemment formé une pellicule sur le sandur du fond de la baie à mesure que le niveau marin montait. Ces sédiments montrent une progression dans la stratification et la granulométrie en relation avec les fluctuations du niveau marin et des sources sédimentaires. Les conditions océanographiques modernes se sont établies il y a environ 5000 ans.

ZUSAMMENFASSUNG *Marine Geologie der Baie des Chaleurs*. Die Baie des Chaleurs ist das viertgrößte Mündungsbecken in Ostkanada. Die Bucht ist ein breites und flaches Becken, das mit bis zu 50 m dicken, nicht konsolidierten Quaternär-Ablagerungen angefüllt ist. Die Verteilung dieser Sediment-Masse wird zum Teil durch ein Abflußsystem aus dem Cenozoikum (Tertiär oder Quaternär) kontrolliert, das den hauptsächlichen Strukturelementen der darunterliegenden Ablagerung anstehenden Gesteins aus dem Paläozoikum folgt. Eis-Kontakt-Sediment aus dem Pleistozän einschließlich Till ist im allgemeinen dünn oder nicht vorhanden. Indessen enthalten die Cenozoikum-Kanäle im Zentrum und in deräußeren Bucht bis zu 30 m dicke, lineare Moränen-Akkumulationen. Diese Ablagerungen könnten die Endposition des Gaspé-Eisdoms anzeigen. Sechs breite aber getrennte glaziomarine Fächer zeigen die Position der wichtigsten Wasserabflüsse an, die während der Rückzugsphase der regionalen Eisdecke aktiv waren. Diese Pleistozän-Ablagerungen wurden zum Teil durch glazifluviale Abflußkanäle während eines niedrigen Meeresniveaus (−90 m) um etwa 9000 Jahre v.u.Z. abgetragen. Danach, während der marinen Transgression im frühen bis mittleren Holozän, unterlagen die glazigenen Ablagerungen einer Abtragung durch Wellen. Diese Ablagerungen verdünnen sich auf diese Weise zum seichteren Wasser hin, und zeichnen sich durch parallel zur Küste liegende Terrassen und Flächen groben Sediments entlang den Rändern der Bucht aus. Um 7 000 Jahre v.u.Z. erreichte die Transgression des ansteigenden Meeres einen Sandur-Komplex, der sich in der seichteren inneren Bucht befand. Anfangs kam es zu früher Holozän-Sedimentierung in den tieferen Wassern des Zentrums und Eingangs der Bucht, und diese bildete anschließend einen extensiven Schleier durch die Sandur der inneren Bucht, während der Meeresspiegel anstieg. Diese paraglazialen Sedimente weisen eine Progression in der Stratifizierung und der Korngröße auf, abhängig von der Position des Meeresniveaus und der Sedimentquelle.

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INTRODUCTION

Since the early 1970's, the Geological Survey of Canada (GSC) has investigated estuaries along the east coast of Canada (for review see Syvitski, 1986). Research focussed on "type" estuaries, documenting the spectrum of oceanographic processes and geological products. Little information was available before these baseline environmental studies were undertaken. This "pure" side of research was often twinned with the release of environmental impact statements on a variety of federal concerns: tidal power development, ocean dumping, ocean mining, marine sewage and toxic chemical disposal, oil spill contingencies, and lately mariculture. In celebration of the 150th year of the Geological Survey of Canada. This manuscript provides an example of the GSC's work in Baie des Chaleurs, a region of general interest to Canadian Quaternary geologists. The manuscript is not intended as a literature review, as other references provided largely fulfil that role. Rather, a large geophysical and sedimentological data set are married to these prior syntheses to help interpret the depositional history of marine Quaternary deposits.

Baie des Chaleurs is the fourth largest estuary in eastern Canada (Fig. 1), after the St. Lawrence Estuary, Bay of Fundy and Hamilton Inlet. It extends 180 km in length and up to 38 km in width, covering a total area of 5 670 km^2. The estuary drains a hinterland basin of 25 800 km^2, and receives an annual freshwater discharge of 26 km^3. Baie des Chaleurs is a partially mixed estuary through the interplay of tidal currents, fresh water discharge, and wave-induced turbulence (Schafer, 1977; Schafer and Cole, 1978; Hildebrand, 1984). The estuarine hydraulics appear to be unique to the region: (1) the Bay of Fundy is well-mixed through tidal turbulence (Amos and Long, 1980); (2) the nearby Miramichi estuary is partially mixed but wave limited, protected from ocean swells by a well-developed barrier system (Vilks and Krauel, 1982); (3) the fjords of Nova Scotia, Newfoundland and Labrador are strongly influenced by wave turbulence; however, most have a very limited freshwater supply (Piper *et al.*, 1983); and (4) the fluvially-dominated fjords of the Saguenay (Sundby and Loring 1978), the St. Lawrence (Syvitski *et al.*, 1983) and Hamilton Inlet (Vilks and Mudie, 1983) are too deep to be strongly influenced by waves.

This paper aims to document the evolution of Baie des Chaleurs, from the bedrock controls of the tectonised Paleozoic sediments, through the development of a Cenozoic drainage system and hinterland ice sheets, to the rapid fluctuations of sea level through the Holocene. Together these geologic controls have determined the type and distribution of Quaternary sediment that presently fill and influence the circulation within the bay.

What makes Baie des Chaleurs such a fascinating case study is the long standing disagreements as to the regional growth and behaviour of Late Wisconsinan ice (Pronk *et al.*, 1989). Grant (1977) believed that the Gaspé region largely

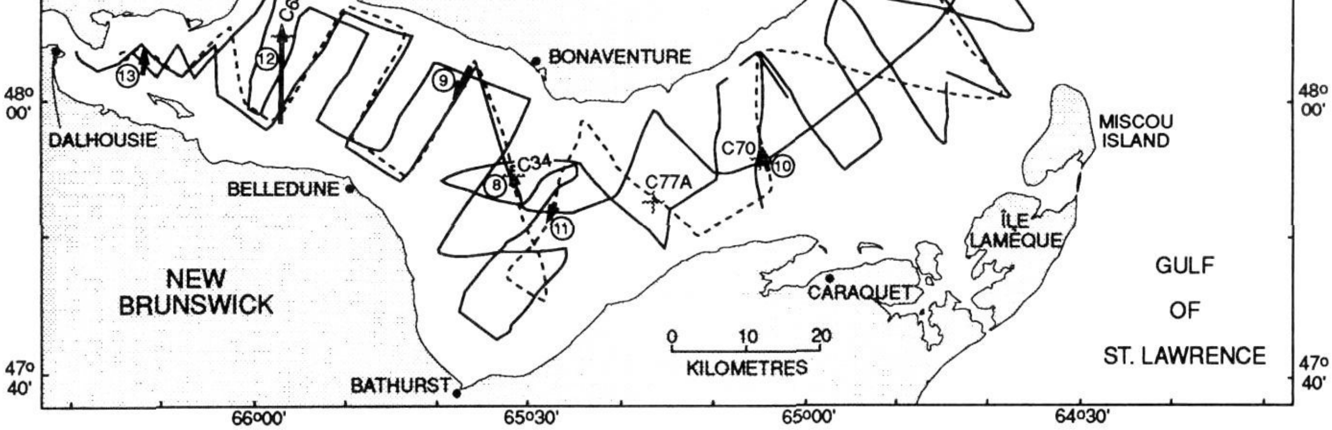

FIGURE 1. Baie des Chaleurs study area. Solid lines show the geophysical (airgun, sidescan) coverage collected in 1986; dashed lines show the 1987 geophysical (Huntec DTS, airgun, sidescan) coverage. Also located are cores cited in the text (crosses) and seismic profiles used in subsequent figures (arrow indicates ship direction). Not shown are the 9500 km of 14.5 kHz of hydrographic lines (except 12 and 13) and the remaining 235 grab and core samples that complete the data set.

La baie des Chaleurs. Les lignes pleines montrent les levés géophysiques de 1986 (canon à air, sonar latéral); les tiretés rassemblent les levés de 1987 (sondages Huntec, canon à air, sonar latéral). Localisation des carottes dont on parle dans le texte (croix) et des profils sismiques illustrés dans les figures suivantes (directions du navire données par les flèches). Ne figurent pas les 9500 km de lignes hydrographiques à 14,5 kHz (sauf les n^{os} 12 et 13) et les 135 échantillons de fond marin et carottes qui complètent les données.

escaped glaciation during the Late Wisconsinan. Later, Rampton *et al.* (1984) suggested that the Gaspé region, including northern New Brunswick, was home to regionally-limited Appalachian ice sheets. In a third model, these thin (100 m) and regionally-limited Appalachian ice sheets were eventually overridden by a 3000 m thick Laurentide Ice Sheet (David and Lebuis, 1985). More recently, Rappol (1989) suggested two major phases of Late Wisconsinan ice-flow patterns for the region: an early phase determined from the interaction of invading Laurentide ice and local accumulation centres (such as the Gaspé highlands), and a younger phase when an ice-flow pattern developed in response to drawdown following the rise in sea level. Can marine data help resolve this dilemma?

CONCLUSIONS FROM PREVIOUS STUDIES

Several papers have contributed substantively to the geological context of this investigation. Schafer (1977) interpreted the sediment texture and foraminifera content of 250 sediment samples collected in Baie des Chaleurs. It was suggested that Atlantic Waters flooded Baie des Chaleurs as early as 14 000 years ago. A depositional pattern similar to that of today, but with more marine (saline) conditions than present, probably occurred between 12 000 and 13 000 years BP. Marine regression occurred about 8000 to 10 000 years ago as a result of the rapid glacial rebound despite the eustatic sea-level rise. Deposition associated with the Holocene rise in sea level resulted in increased accumulation of relatively fine sediments in the deeper and/or protected parts of the bay. The interplay of water depth, tidal currents and wave environment have largely remained constant over the last 5000 years.

Rampton *et al.* (1984) provided an overview of Quaternary geology in New Brunswick, including aspects of the Gaspé region. Marine incursion into Baie des Chaleurs was found contemporaneous with ice retreat as evidenced by raised glacimarine deposits. A low salinity lake was postulated to have occupied Baie des Chaleurs around 12.7 ka in response to eustatic depression in sea level and a 73 m deep outer sill protecting the bay. (This 73 m outer sill was, however, based on old navigation charts, and the new Canadian Hydrographic Chart 15184-A shows the actual sill depth to ≈90 m.) Relative sea level fell below its present level by 10 ka as related to the isostatic adjustment of the landmass. The Gaspésien ice centre(s) to the north of Baie des Chaleurs were topographically influenced whereas the ice centres to the south were nourished by storms tracking directly overhead. Deglaciation was considered rapid because of the effects of rising sea level (rapid calving and a drawdown of the ice caps) and a cooler ocean (reduced winter precipitation). David and Lebuis (1985) suggested the opposite: the ice front retreated slowly in Baie des Chaleurs because the water is shallow and does not favour calving. Between 12.6 and 11 ka the climate substantially warmed, followed by a cooler interval between 11 and 9.5 ka (Rampton *et al.*, 1984).

Pronk *et al.* (1989) used striation analysis, clast provenance and fabric data to discuss the influence of Laurentide ice on local centres in the Baie des Chaleurs region. They suggested Appalachian-based ice flow into Baie des Chaleurs had occurred in four phases. The bay was considered a sufficient drawdown to these regional ice sheets that the basal ice regime may have permitted sediment remobilization and till deposition. The drawdown may have been contemporaneous with the local marine incursion that occurred between 12 700 and 12 000 years BP.

Syvitski and Praeg (1989) described the regional Late Wisconsinan marine geology including a brief description of Baie des Chaleurs. Their five regional seismo-stratigraphic units include: (1) a lowermost ice-contact unit (subglacially deposited and/or subglacially-loaded diamicton), (2) ice-proximal sands and muds, (3) ice-distal glacimarine muds and diamicton, (4) paraglacial coastal deposits, and (5) post-glacial sediments. Deposition (or ice loading) of unit (1) occurred initially during the period of globally (eustatic) lowered sea level (oxygen isotopic stage 2), and later in association with units (2) and (3) during a period of high sea levels related to local isostatic loading. Deposition of unit (4) occurred during the initial fall in sea level (isostatic recovery: oxygen isotopic stage 1) when ice had retreated onto land and was rapidly ablating. Deposition of unit (5) occurred during more complex and local sea level fluctuations. In Baie des Chaleurs, shore-parallel linear bedrock troughs were found to contain linear morainal accumulations up to 30 m thick, reflecting the terminal position of the Gaspé ice dome. Sea level was considered by Syvitski and Praeg (1989) to have fallen 70 m below present levels during the deglacial phase.

METHODS AND DATA

Echograms were collected by the Canadian Hydrographic Service in 1964-66 from the C.S.S. Kapuskasing and its launches using Kelvin-Hughes 14.25 kHz MS26B depth sounders. Approximately 9500 km of hydrographic lines, at average spacings of 450 m in the outer and central bay and 300 m in the inner bay, were examined (see Syvitski *et al.*, 1987a, for track coverage). Lines were positioned using radar triangulation from shore stations. The echograms provide information on seafloor morphology and the thickness of acoustically penetrable sediment (mud).

In 1981, the M/V Pandora II was employed with the manned submersible Pisces IV to investigate the sediment transport in the inner basin of Baie des Chaleurs. Oceanographic data were collected from both the mother ship and the submersible and included salinity, temperature, suspended sediment concentration, water turbidity, and current velocity (Syvitski *et al.*, 1983). The size frequency distribution of the suspended sediment samples was obtained using a modified IIA Coulter Counter.

In 1986, 655 cm^3 air gun, single channel, seismic reflection profiles (0.1-1.0 kHz) were collected from C.S.S. Dawson, along with 12 kHz echograms and Klein 100 kHz side-scan sonograms (Praeg *et al.*, 1987b). In 1987, coverage was extended to include profiling with the deeptowed Huntec high-resolution seismic system (0.8-10 kHz) (Praeg *et al.*, 1987a). A total of 1500 km of geophysical lines were run (Fig. 1), positioned by radar ranges and bearings from the adjacent shores, and Loran C. The air gun records provide the thickness and distribution of the main Quaternary sedimentary units, and features of the underlying Paleozoic sedimentary strata. The Huntec records provide details of the character and internal layering within each of the Quaternary sedimentary units. Interpretive methods were the same as described in detail by Syvitski and Praeg (1989). Fifteen 3.0 to 6.0 m long cores were collected in 1986 (Praeg *et al.*, 1987b) and subjected to carbon (±5 % of value reported) and particle size (±6 % of value reported) analysis.

PALEOZOIC CONTROL OF THE BAIE DES CHALEURS

Baie des Chaleurs is surrounded by sedimentary and volcanic rocks of Paleozoic age (Fig. 2). The marine (acoustic) bedrock consists of gently deformed sedimentary strata having dips less than 3° along fold axes that are oriented subparallel to the bay axis (Fig. 2). The structural styles and orientations suggest that these strata correlate with the Carboniferous conglomerates, sandstones and shales found locally around the margins of the bay. Major faults are located along the large synclines. The marine bedrock strata have been divided into two principle rock types based on acoustic properties (Fig. 2: Syvitski *et al.*, 1987a). Pennsylvanian sediments probably occupy the south-eastern part of the bay where the bedrock shows good acoustic penetration and strong coherent reflectors. Mississippian sediments probably occupy the northwestern parts of the bay where the bedrock has reduced acoustic penetration and strata offer only moderate coherent reflectors. This proposed distribution matches the location of Carboniferous strata found along the shores of the bay.

CENOZOIC DRAINAGE SYSTEM

Schafer (1977), following Loring and Nota (1973), suggested a pre-Quaternary drainage system for Baie des Chaleurs, based largely on contoured subsurface data from echo sounder profiles and modern bathymetry. Unfortunately, the sounder profiles did not penetrate the Quaternary glacigenic sequence (glacimarine and ice-contact deposits) and the channels that were observed on these records reflect a post-glacial period of lowered sea level (see below and Fig. 11).

A different and considerably deeper drainage pattern emerges if the depth to acoustic bedrock data is contoured (Fig. 3). Two large subparallel channels are recognised, originating from the present-day position of the Restigouche River and the Cascapedia River (located on Fig. 4). Compared to today's drainage pattern, the channels are wider and deeper. They follow the major structural elements of the Carboniferous bedrock (*cf.* Fig. 2). The channels exit Baie des Chaleurs at present water depths of 160 m. The average width and thalweg for each channel are nearly identical at 1.5 km and 0.3°, respectively. There are no interven-

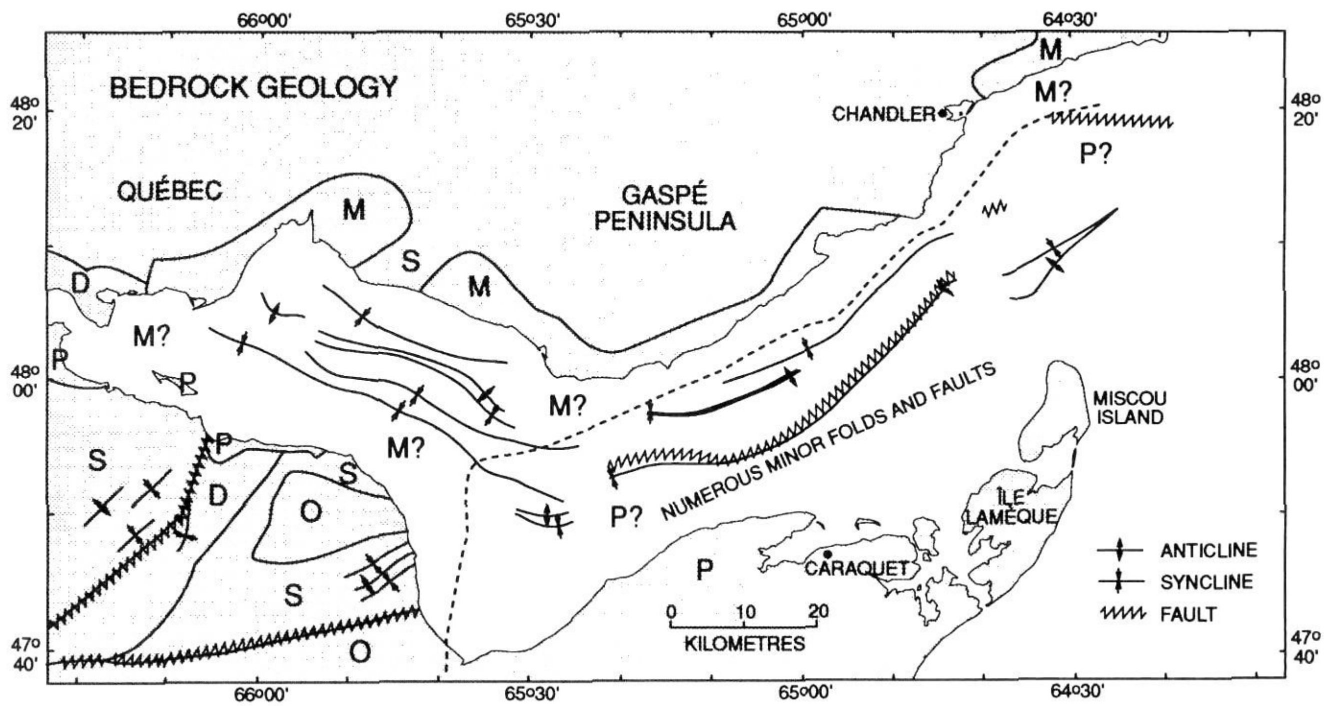

FIGURE 2. Elements of Paleozoic bedrock geology in Baie des Chaleurs. Shown are rock type (O=Ordovician, S=Silurian, D=Devonian, M=Mississipian, P=Pennsylvanian) and trends of major folds and faults. Surrounding terrestrial bedrock simplified after Geological Survey of Canada maps 1250A and 1251A (1970) and Potter *et al.* (1979). The dashed line is the inferred M/P boundary based on acoustical attributes.

Éléments de la géologie du socle paléozoïque de la baie des Chaleurs. On illustre les catégories de roches (O=Ordovicien, S=Silurien, D=Dévonien, M=Mississipien, P=Pennsylvanien) et les directions des principaux plis et failles. Géologie du socle terrestre environnant simplifiée à partir des cartes 1250A et 1251A de la Commission géologique du Canada (1970) et de Potter et al. *(1979). Le tireté donne la limite proposée entre le M et le P, en se fondant sur les propriétés acoustiques.*

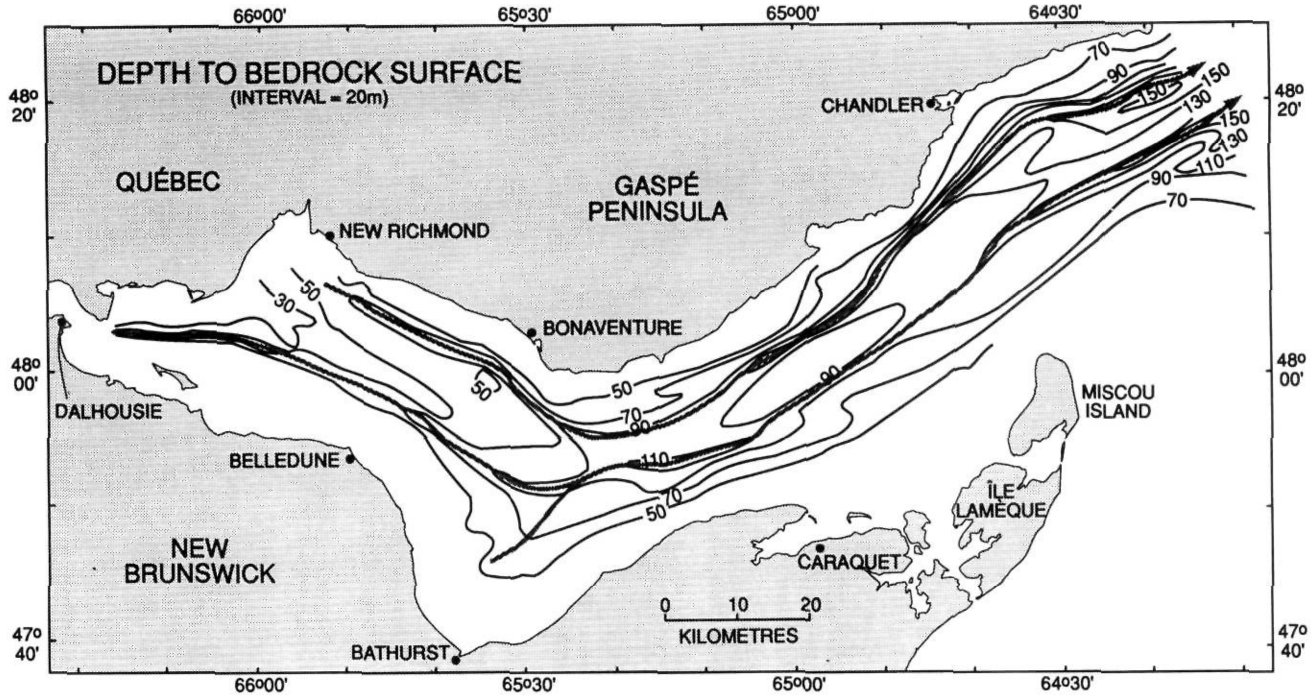

FIGURE 3. Depth to bedrock below the present sea level defines an older, possibly Tertiary, drainage pattern eroded into the Paleozoic rock surface.

La profondeur, jusqu'au substratum sous le niveau actuel de la mer, révèle un réseau de drainage plus ancien, peut-être tertiaire, érodé sur la surface rocheuse paléozoïque.

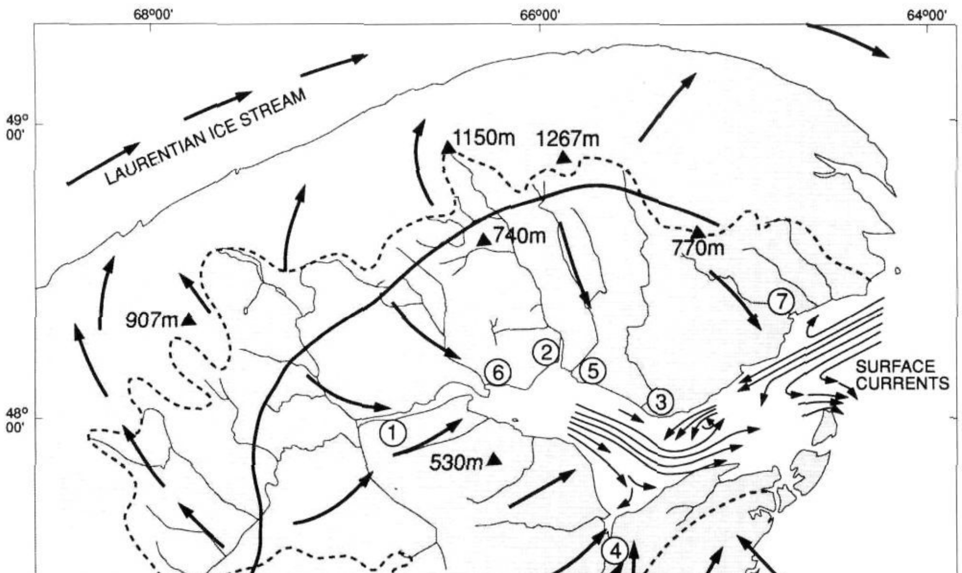

FIGURE 4. The hinterland drainage basin of Baie des Chaleurs identifying seven of the largest rivers (1) Restigouche River with a discharge of 7.2 km^3 a^{-1}; (2) Cascapedia at 1.9 km^3 a^{-1}; (3) Bonaventure at 1.6 km^3 a^{-1}; (4) Nepisquit at 1.4 km^3 a^{-1}; (5) Petite Cascapedia at 1.0 km^3 a^{-1}; (6) Nouvelle at 0.9 km^3 a^{-1}; (7) Grande Rivière at 0.4 km^3 a^{-1}. Hinterland elevations are given in metres. Surface currents in the Bay are after Legendre and Watt (1970). Superimposed is the regional ice divide during the Late Wisconsinan and ice flow directions (after Pronk *et al.*, 1989).

Bassin de drainage de l'arrière-pays de la baie des Chaleurs illustrant sept des plus grandes rivières. (1) Restigouche avec un débit de 7,2 km^3 a^{-1}; (2) Cascapédia, 1,9 km^3 a^{-1}; (3) Bonaventure, 1,6 km^3 a^{-1}; (4) Nepisquit, 1,4 km^3 a^{-1}; (5) Petite Cascapédia, 1,0 km^3 a^{-1}; (6) Nouvelle, 0,9 km^3 a^{-1}; (7) Grande Rivière, 0,4 km^3 a^{-1}. Les courants de surface sont tirés de Legendre et Watt (1970). La ligne de partage des glaces au Wisconsinien supérieur et la direction de l'écoulement des glaces (d'après Pronk et al., *1989) sont données en superposition.*

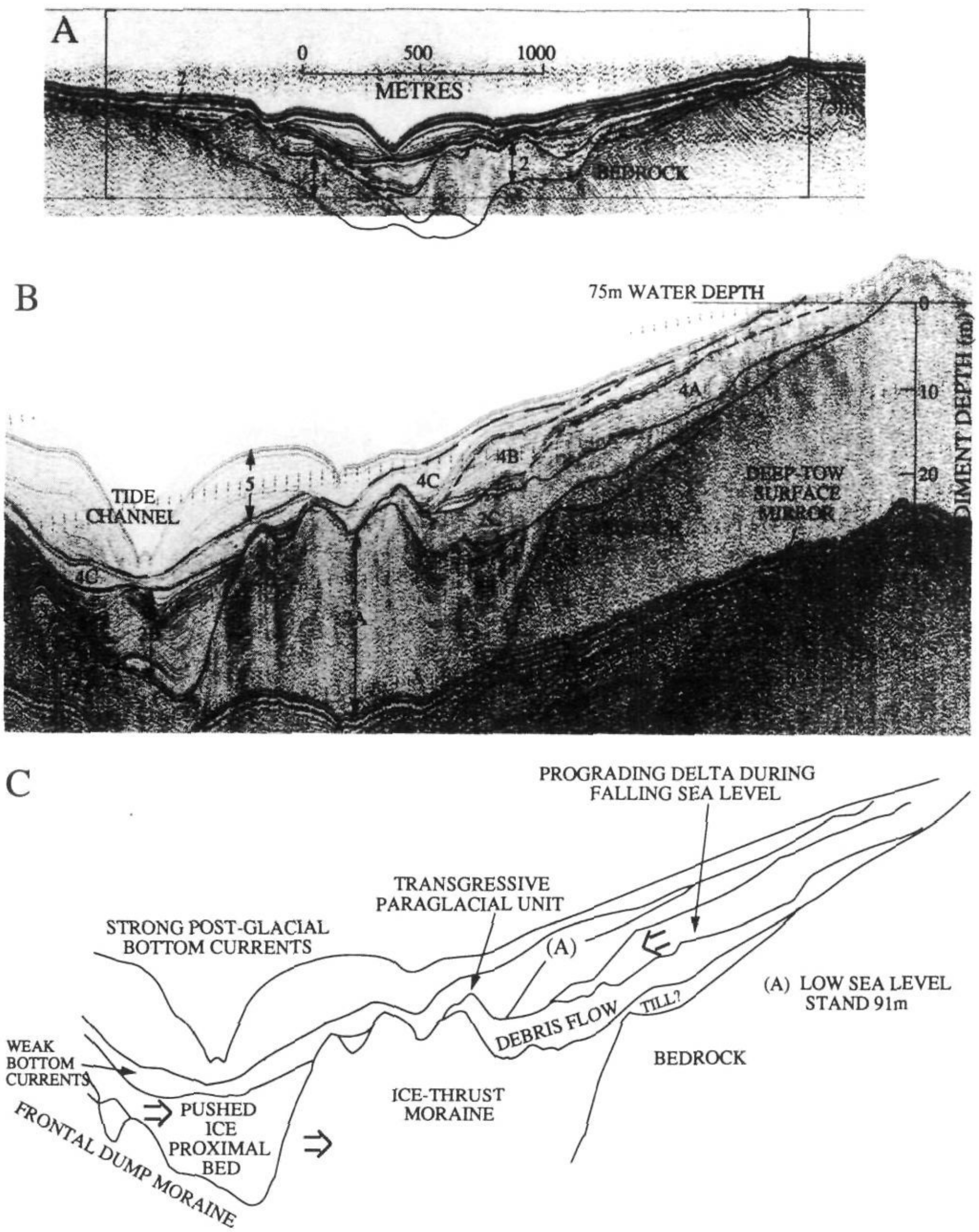

FIGURE 5. An example (profile 1, Fig. 1) of the complex nature of sediment deposition throughout the Late Wisconsinan in outer Baie des Chaleurs. A) Airgun profile identifies the major unit boundaries and differentiates between bedrock and unit 1 (ice-contact deposits). B) Huntec DTS profile highlights the internal layering relationships within each depositional unit. C) Interpretive scenario of sediment accumulation (see text for details).

Exemple (profil 1, fig. 1) de la complexité de la mise en place des sédiments au cours du Wisconsinien supérieur à l'entrée de la baie des Chaleurs. A) Le profil par canon à air identifie les limites des principales unités et différencie le substratum de l'unité 1 (dépôts de contact glaciaire). B) Le profil Huntec fait ressortir les liens entre les couches internes de chacune des unités. C) Processus interprétatif de l'accumulation sédimentaire.

ing Mesozoic strata in Baie des Chaleurs. The surface morphology of the Paleozoic rocks is both erosional and fluvial in nature. Due to the water depths that presently overlie this drainage system (> 150 m), the drainage system may have formed during the Tertiary period of regionally lowered sea level. An alternate hypothesis is that the drainage system formed during one of the Quaternary glaciations, as a conduit for subglacial discharge. There is no acoustic evidence of fluvial sedimentary deposits within these river channels; at the very least such sediment was removed during the Quaternary glaciations.

ICE CENTRE DEVELOPMENT AND FLOW

Field data suggests that Late Wisconsinan ice flowed into Baie des Chaleurs via a number of regional ice centres that surround the bay (Rampton *et al.*, 1984; Pronk *et al.*, 1989). Flow was both easterly through the head of the bay, and laterally from the Gaspé mountains to the north and the Miramichi Highlands to the south (Fig. 4). The ice sheets were probably thin (≈400 to 800 m) based on: (1) the isostatically-controlled rebound along the margins of the bay [maximum marine limit of 100 m in the outer parts of Baie des Chaleurs (Rampton *et al.*, 1984) plus a maximum sea level fall to −90 m in the early Holocene (this study)] and (2) the reconstructed ice flow history (Thomas *et al.*, 1973; Rampton *et al.*, 1984; Gray 1987). Small portions of the Gaspé highlands may have been ice free during the Late Wisconsinan (Grant, 1977). There is also a notable lack of Laurentide transported Shield erratics (Pronk *et al.*, 1989), except on the hinterland considerably west of the bay (Rappol, 1989).

This simple glaciologic model nicely fits all the field data. Yet it has often been abandoned in the literature in favour of

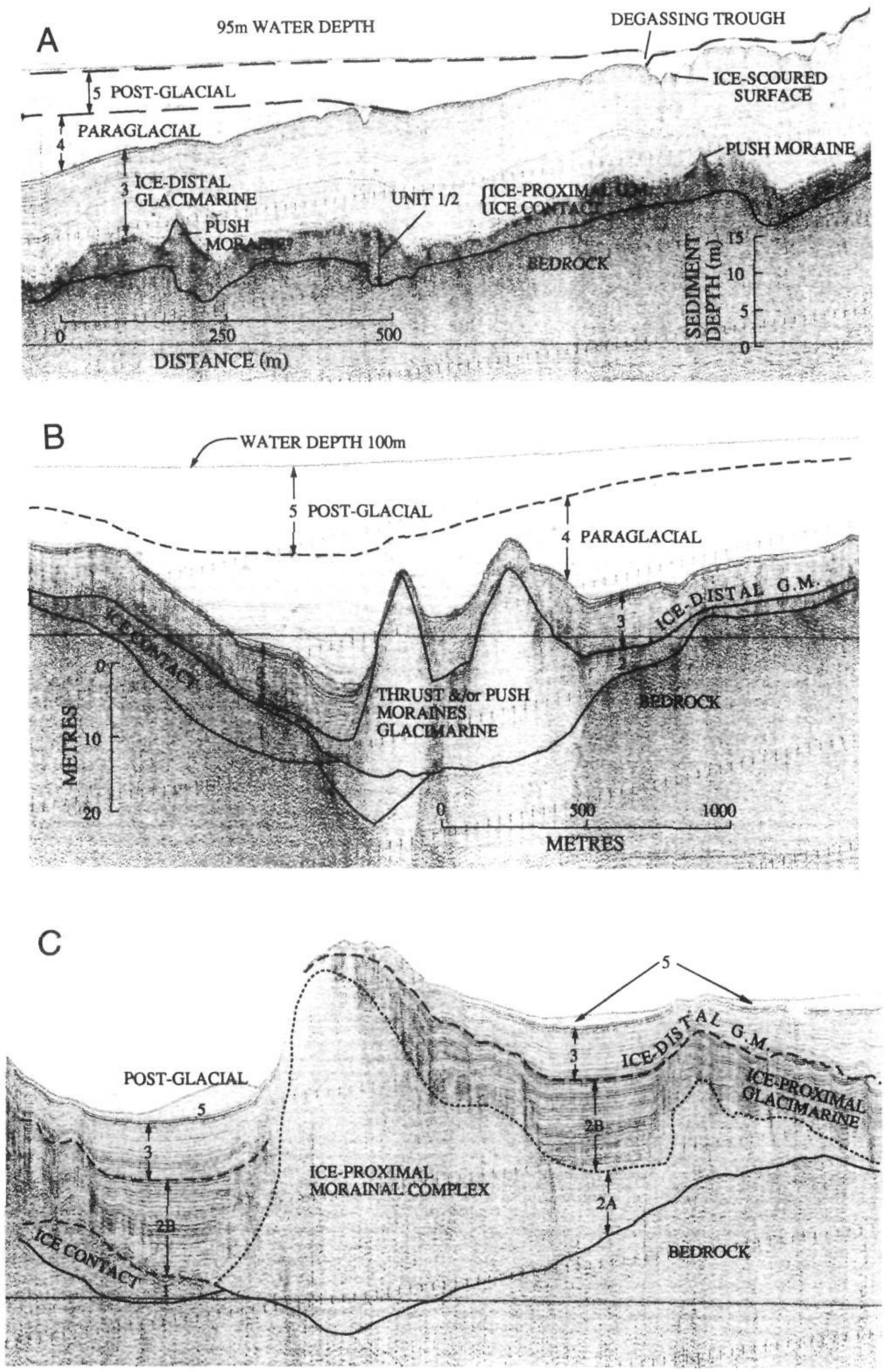

FIGURE 6. Huntec DTS profiles of the thick deposits in the distal portion of Baie des Chaleurs. A) Conformable nature of the ice-distal glacimarine unit 3, as it drapes over a variable thickness deposit of ice-proximal and/or ice-contact deposit (profile 2, Fig. 2). B) The thrust or push morainal complex that occupies an older Tertiary? river channel (cf. Fig. 5) (profile 3). C) Possible frontal dump moraine overlain by ice-proximal and ice-distal glacimarine units (profile 4).

Profils Huntec des épais dépôts de la partie distale de la baie des Chaleurs. A) Conformité de l'unité 3 composée de sédiments glacio-marins distaux recouvrant un dépôt d'épaisseur variable de sédiments proximaux ou de contact glaciaire (profil 2, fig. 2). B) Le complexe de moraines de poussée qui occupe un ancien chenal (tertiaire ?) (voir fig. 5) (profil 3). C) Moraine terminale probable recouverte par des unités proximales et distales (profil 4).

complex schemes of extensive and thick Laurentide Ice. These alternate schemes show 3 km thick Laurentide Ice Sheet crossing the Laurentian Channel and overriding both the Gaspé mountains and the regional ice caps that covered them (David and Lebuis, 1985). Furthermore, the flow direction of the Laurentide Ice Sheet is hypothesised to have divided vertically; the dirty basal portion of the Laurentide Ice Sheet was funnelled eastward along the Laurentian Channel while the upper cleaner portion of the ice sheet flowed southward fusing, pushing or overriding the regional ice sheets (Pronk *et al.*, 1989). There is no known modern analogue of this type of complex ice sheet behaviour (that I am aware of), and the scenario runs contrary to modern physics describing ice sheet behaviour (Paterson, 1981).

Such complex ice sheet models should be abandoned. If we were to remove the Late Wisconsinan sedimentary fill

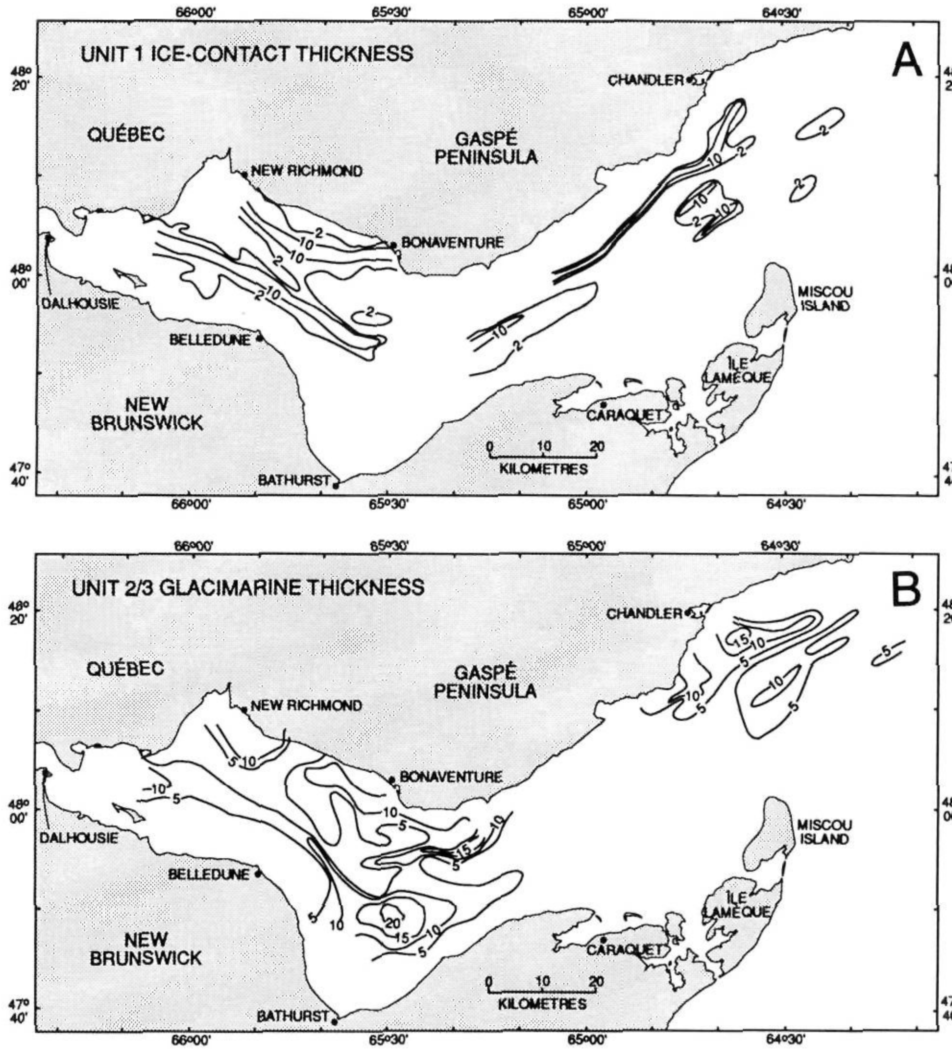

FIGURE 7. A) The distribution of the acoustically unstratified unit 1 (and unit 2A as shown in Fig. 6C), interpreted to represent any of a wide variety of ice-contact deposits (*e.g.* till, frontal dump moraine, eskers). The deposits are largely found occupying older drainage channels. B) The distribution of the acoustically stratified units 2 and 3, interpreted to represent ice-proximal and ice-distal glacimarine sediment. Note that most of the glacimarine deposits appear to have come from well-defined discharge outlets located around the margin of the bay. (Isopach in metres).

A) La répartition de l'unité 1 non stratifiée selon les ondes acoustiques (ainsi que l'unité 2A montrée en fig. 6C), qui pourrait représenter une grande variété de dépôts de contact glaciaire (till, moraine terminale, eskers). Les dépôts occupent surtout d'anciens chenaux de drainage. B) La répartition des unités 2 et 3 stratifiées selon les ondes acoustiques, qui pourraient représenter des sédiments glacio-marins proximaux et distaux. Noter que la plus grande partie des dépôts glaciomarins semble parvenir d'exutoires bien définis situés en bordure de la baie (isopaques en mètres).

within the Laurentian Channel, so as to restore the pre-Late Wisconsinan bathymetry, the water depth would exceed 700 m northeast of the Québec-New Brunswick border while the surrounding land mass would exceed 600 m above sea level (Syvitski and Praeg, 1989). This 1300 m relief would control and direct the ice flow of the Laurentide Ice Sheet down the length of the Laurentian Channel. The glaciological result would be the much discussed Laurentian Ice Stream (see Syvitski, in press). Measured marine limits throughout the northern Gulf of St. Lawrence also support the notion of much thicker Late Wisconsinan ice north of the Gaspé mountains compared to the south (Baie des Chaleurs). Furthermore, striation data supports this notion of multiple ice centres and flow directions (Dyke and Prest, 1987).

The ice sheet retreat phase is better understood for Baie des Chaleurs. Late Wisconsinan ice retreated *circa* 14 000 years BP (Schafer, 1977) and was completed by 12 300 years BP (Rampton *et al.*, 1984). The retreat occurred as a number of distinct phases through the independent action of the various local ice sheets (Rampton *et al.*, 1984; Pronk *et al.*, 1989). The lack of a consistent regional behaviour to the mass balance of these ice sheets during the deglacial phase suggests a strong interplay between winter storm-tracking and hinterland topography. As the storm-track shifted in a north-south direction over New Brunswick, different ice sheets become favoured in terms of ablation or accumulation. A severe Maritime snow storm in February of 1992 provides an anecdotal reminder that elevation does not necessarily ensure increased precipitation levels: the city of Moncton, near sea level, received the largest snowfall for the region (1.6 m of snow in 24 hours).

GLACIGENIC SEDIMENTATION

The Quaternary fill within Baie des Chaleurs consists of five seismo-stratigraphic units that can also be found throughout the N.W. Gulf of St. Lawrence (Syvitski and Praeg, 1989) and indeed reflect regionally-extensive sedimentation patterns operating during with the Late Wisconsinan (Syvitski, 1991). These deposits within Baie des Chaleurs are relatively thin, and aerially limited. The deposits therefore reflect local sediment sources and transport pathways on a scale smaller than the bay itself. Although this heterogeneity complicates discussion of the deposits on a regional scale, it provides clues to the sediment transport efficiency of the local ice sheets.

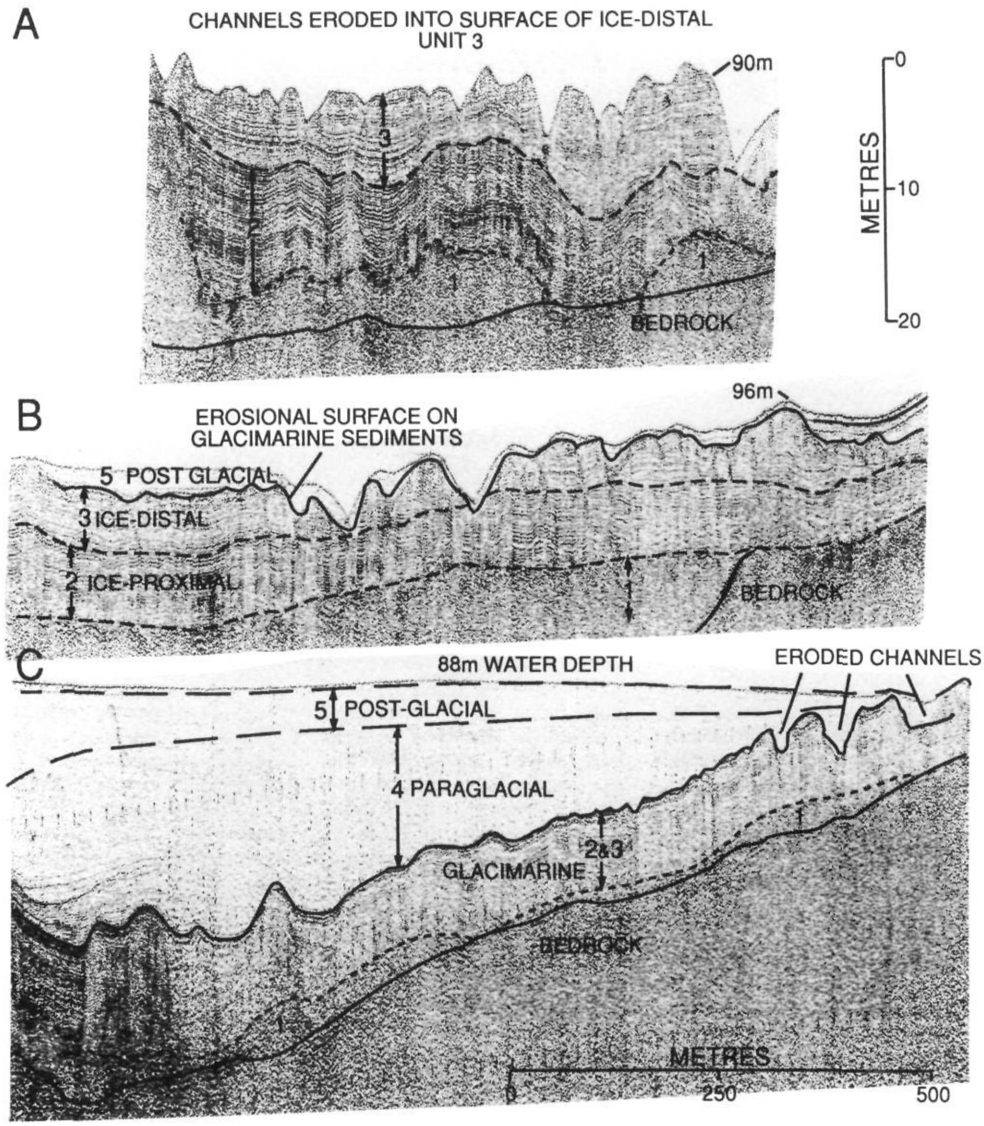

FIGURE 8. Huntec DTS profiles showing erosion channels cut through the surface of the glacimarine deposits (units 2 and 3) during a period of lowered sea level. Subsequently the seafloor may have experienced (A) no sediment deposition (profile 5, Fig. 1, or (B) minor post-glacial deposition (profile 6) or (C) significant paraglacial and post-glacial deposition (profile 7). Units 2 and 3 are not differentiated in (C).

Profils Huntec montrant les chenaux d'érosion entaillés à la surface des dépôts glaciomarins (unités 2 et 3) alors que le niveau de la mer était bas. Par la suite, soit (A) qu'il n'y ait eu aucune accumulation (profil 5, fig. 1), soit (B) qu'il y eut faible accumulation postglaciaire (profil 6), soit (C) qu'il y eut forte accumulation paraglaciaire et postglaciaire sur les fonds marins (profil 7). Les unités 2 et 3 ne sont pas différenciées en (C).

A lowermost unit 1 is found largely within the troughs cut into the Paleozoic sediment (Figs. 5, 6, 7A, 8 and 9). The unit has not been sampled yet and interpretations must remain speculative, although the acoustic properties and stratigraphic position suggest that the unit is similar ice-contact deposits sampled and mapped throughout the Gulf of St. Lawrence (Syvitski and Praeg, 1989). In places the geomorphic shape — long, curvilinear, and positioned along the landward edge of a steep slope — has the appearance and distribution of a frontal dump moraine (Figs. 5A and 9). These ridges may exceed 30 m in thickness (Fig. 6C). In other locales of more gentle bathymetry, the unit merges with deposits (interpreted as ice-proximal glacimarine) that show signs of deformation — possibly as a result of a push or thrust of an ice margin (Fig. 6). Outside of these morainal deposits, unit 1 is thin (Fig. 6A) to absent in Baie des Chaleurs (Fig. 7A).

The overlying or adjacent units 2 and 3 are typically associated with unit 1 and are interpreted as being glacimarine. Units 2 and 3 sediment can often be divided on the basis of their acoustic attributes (see Syvitski and Praeg, 1989; Syvitski 1991): unit 2 is a well-stratified, partly conformable and partly wedge-shaped unit, and is interpreted to be ice-proximal in genesis; and unit 3 is an overlying and more acoustically-transparent unit, interpreted to reflect ice-distal deposition (Fig. 6C). Unit 3 is mostly conformable in nature, as it drapes over the topographically irregular surface of units 1 and 2 (Fig. 6A). Cores of units 2 and 3 (as shown on Fig. 8A; Praeg *et al.*, 1987b) have an extremely low organic carbon content (0.1 to 0.2 % by weight), that probably reflect the lack of terrestrial organic sources and high rates of inorganic sedimentation (*cf.* Syvitski *et al.*, 1990). These glacimarine sediment are very fine-grained; for example in core C76 (Fig. 1) the sediments had clay contents greater than 70 %. They contain rare pebbles, possibly dropstones from ice rafting. The lack of sand suggests a possible sampling bias — we were unable to penetrate the thicker wedge-shaped deposits of unit 2 (Figs. 7B, 8A).

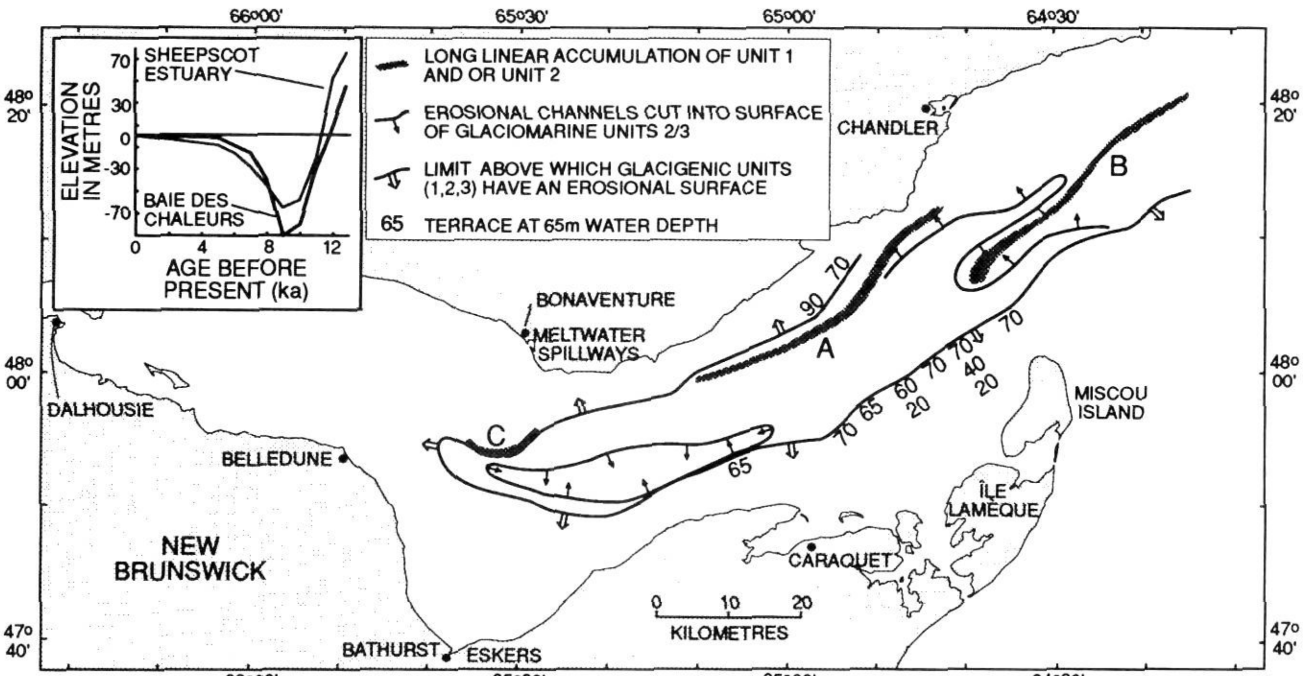

FIGURE 9. Main Quaternary geologic features of Baie des Chaleurs showing (i) three major moraines (A=frontal dump, B=thrust or push, C=wave reworked); (ii) zones of intense channelising of the surface of glacimarine sediment, possibly through surface runoff erosion during a period of lowered sea level; (iii) zone of current/wave reworking of the surface of glacimarine sediments, including terrace development in both Quaternary and Carboniferous sediment. Inset shows the sea level curve proposed for Baie des Chaleurs and is compared to a similar shaped sea level curve of Belknap *et al.* (1986) for the Sheepscot Estuary, Maine.

Principaux éléments du modelé quaternaire de la baie des Chaleurs: (i) les trois principales moraines (A=terminales, B=de poussée, C=remaniées par les vagues); (ii) zones de fort ravinement à la surface des sédiments glaciomarins, peut-être par ruissellement lorsque le niveau de la mer était bas; (iii) une zone de remaniement par les vagues et les courants à la surface des sédiments glaciomarins, et d'édification de terrasses dans les sédiments quaternaires et carbonifères. En carton, courbe proposée de l'évolution du niveau de la mer de la baie des Chaleurs comparée à celle de l'estuaire du Sheepscot, au Maine, de Belknap et al. *(1986).*

Isopach maps of the interpreted glacimarine sediment thickness show a number of fan shaped deposits. These may relate to possible discharge outlets along the ice front that surrounded the bay some 14 000 to 12 400 years ago (Fig. 7; timing after Rampton *et al.*, 1984; and through dated cores: C. Rodrigues, pers. comm., 1992). Schafer (1977) notes a local concentration of terrestrially-exposed eskers near Bathurst and meltwater spillways near Bonaventure that support this notion of marginal discharge outlets. Offshore of these locations are thick (15 to 20 m) deposits of units 2 and 3 (Fig. 7B). Depocentres of glacimarine sediment are also located offshore of Chandler and New Richmond (Fig. 7B).

Acoustic units 1, 2 and 3 all have their terrestrial equivalents (*c.f.* Rampton *et al.*, 1984), often exposed as outcrops of Late Wisconsinan sediment located between the marine limit (+ 50 m) and the modern shoreline (Gray, 1987). For example, the Restigouche-Elmtree moraine system south and southeast of Dalhousie is considered to represent a series of nested and pitted deltas, intimately associated with offshore sediments and mark an episodic period of high meltwater expulsion during deglaciation (Pronk *et al.*, 1989). Exposed sections within this system indicate large scale deltaic foresets (≈ unit 4 described below), fossiliferous glacimarine (units 2 and 3) and ice contact deposits equivalent to unit 1 (Pronk *et al.*, 1989).

In the outer part of Baie des Chaleurs, units 1, 2 and 3 (the glacigenic sequence) were deformed during two separate episodes (Figs. 5B and 6B) of what is believed to represent ice front readvances. One these advances apparently generated a debris flow (Figs. 5B and C): interpretation being based on acoustical attributes relative to known modern debris flows (Syvitski and Farrow, 1989). The direction of the ice push (perpendicular to the axis of the bay) locally suggests ice flow out of the Gaspé mountains.

SEA LEVEL FLUCTUATIONS AND HOLOCENE SEDIMENTATION

The following is offered as a working hypothesis on Late Quaternary sea level fluctuations and their affect on sediment deposition. When the regional ice sheets coalesced in Baie des Chaleurs, their isostatic load depressed the crust causing a local and relative rise in sea level. This would have occurred during a period of eustatically lowered sea level. When the ice sheets retreated on land, sea level was at its highest level as affected by the depressed crust from the regional ice load. The limit of the glacially-influenced sea level (known as the Goldthwait Sea stand) was highest (100 m) in the outer bay at 13.2 ka. Due to its diachronous nature, the marine limit is found at lower elevations toward the head of the bay as a result of continued crustal rebound — 67 m at the head of the bay at 12.4 ka (Rampton *et al.*, 1984), and 46 m near the middle of the bay near Bonaventure at 12.2 ka (Gray, 1987).

With continued ablation of the terrestrial ice sheets and reduction in the isostatic load, sea level rapidly fell as the land rebounded. The depth to the minimum low sea level stand was in part determined by the lowered eustatic sea level. The sea level effects related to the collapse of the forebulge as suggested by Quinlan and Beaumont (1981) remain undetermined. Glacimarine sedimentation was thus followed by a period during which sea level fell rapidly from a marine limit of some 50 m to 100 m above present sea level to a depth 90 m below sea level. The best evidence for this lowered sea level is from numerous 10 to 30 m wide and 2 to 6 m deep channels that have been cut into the surface of the glacimarine sediment (Figs. 8 and 9). The channels are oriented perpendicular to the shoreline and coalesce in a down-slope trend. They are v-shaped with walls of exposed and truncated sedimentary layers. The channels do not resemble iceberg scours in their geometry, shape, acoustic character and lack of cross-cutting relationships. They resemble drainage channels cut into muddy sediments. No channels are observed below 100 m water depth. If the channels relate to subaerial meltwater drainage, then as is normal with river channels entering the sea, the channels would extend below sea level for a small distance seaward of the low tide line. Thus the maximum shoreline position could be some 5 to 10 m above the maximum channel depth of 100 m.

Other indications of low sea level stand are slope nick points and terraces eroded into the surface of unit 3. In a few locations a −90 m terrace has been observed (Fig. 9). A paleo shoreline (−91 m) associated with deltaic or shoreface deposits prograded offshore during this period of lowered sea level (see point A on Fig. 5C). Together these data suggest that sea level reached or approached 90 m below present sea level in the very early Holocene. Based on the interpolation of the terrestrially-determined rebound rates of Gray (1987) to a water depth of −90 m (Fig. 9 inset), the timing of the low sea level stand would occur *circa* 9000 years BP [in agreement with chronostratigraphy of dated marine cores of C. Schafer (pers. comm., 1992) and C. Rodriques (pers. comm., 1992)]. Such a sea level curve would suggest a rapid rebound or uplift rate of 40 mm per year during this phase. The modern uplift rate in Glacier Bay, Alaska, as a consequence of recent deglaciation, is of similar magnitude (Table 1.2 in Syvitski *et al.*, 1987b).

Core 76, collected in 77 m of water depth in outer Baie des Chaleurs (Fig. 1), has sampled units 3, 4 and 5. Unit 4 consists of poorly sorted gravelly sandy mud (14 % gravel, 24 % sand, 24 % silt and 37 % clay) with the appearance of a winnowed lag at the surface of the much finergrained unit 3 (27 % silt and 73 % clay). Unit 3 is a poor source of sand and gravel. Unit 4 is thus interpreted to result from the wave reworking of coarser proglacial sediment deposited initially during a period of lowered sea level. Unit 5 conformably overlies unit 4, does not contain gravel and is finer-grained (9 % sand, 35 % silt and 56 % clay).

Belknap and Shipp (1991) present a similar scenario and evidence for the west-central Maine shelf and coast Quaternary depositional sequence. For example Belknap *et al.* (1986), describing Sheepscot Estuary in Maine, note distinct breaks in slope of their seismic profiles collected across the 60 to 70 m isobath. These breaks were invariably accompanied by a change from thick marine-mud filled basins below this level to thin sediment cover above this level. Additional evidence included: (1) clear indications of channeling to at least 80 m below present, (2) slope nick points and eroded sedimentary units suggesting a stillstand shoreline, and (3) a change in character of the Pleistocene-Holocene contact

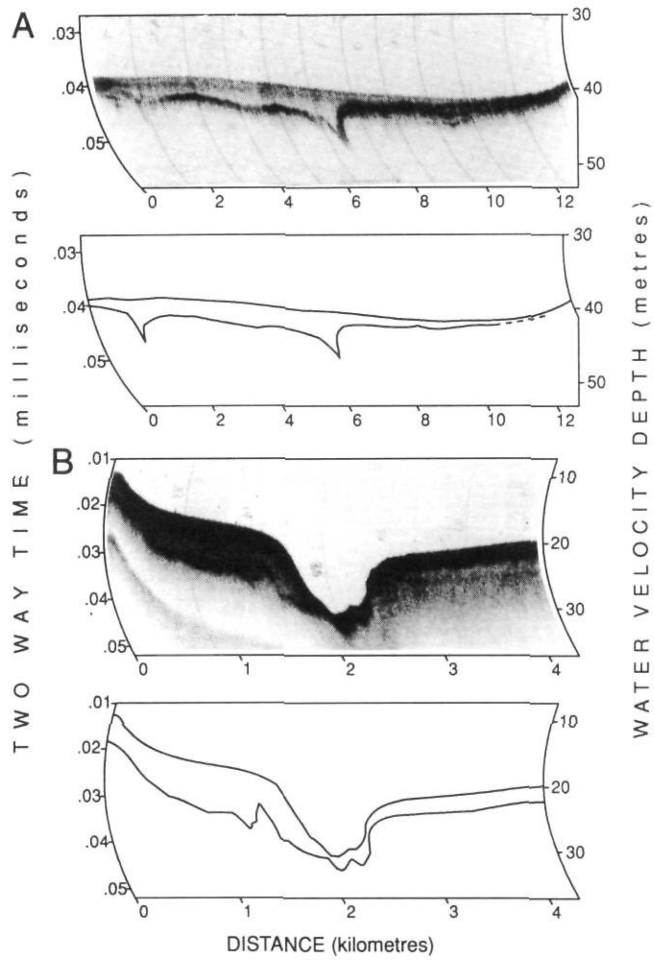

FIGURE 10. Examples of two Kelvin-Hughes 14.25 kHz MS26B hydrographic profiles collected from inner Baie des Chaleurs. Profiles penetrate the Holocene mud deposits (units 4 and 5). A) Profile 12 (Fig. 1) shows two buried channels cut into the surface of the glacimarine unit (2/3). Base of Holocene mud (units 4/5) was 7500 ± 200 years BP (UQ-1623). B) Profile 13 shows one of these channels crossed further up inlet and with little fill of Holocene sediment due to strong tidal action (*cf.* Fig. 16).

Exemples de deux profils Kelvin-Hughes (MS26B à 14,25 kHz) provenant du fond de la baie des Chaleurs. Les profils traversent les dépôts de boue holocène (unités 4 et 5). A) Le profil 12 (fig. 1) montre deux chenaux enfouis entaillés à la surface de l'unité glaciomarine (2/3). Le niveau inférieur de boue holocène a été daté à 7500 ± 200 BP (UQ-1623). B) Le profil 13 montre un de ces chenaux plus en amont et peu remblayé par des sédiments holocènes entraînés en raison de la forte activité des marées (fig. 16).

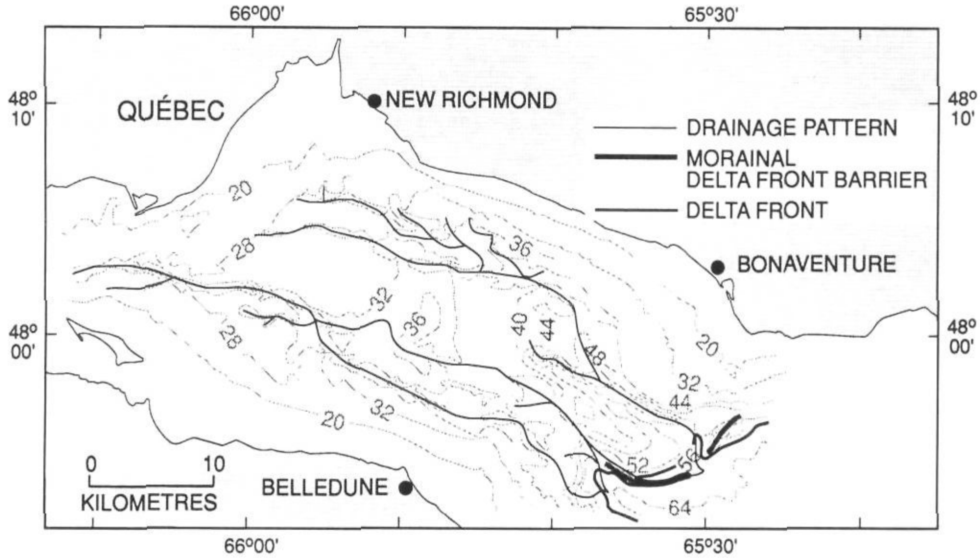

FIGURE 11. Depth to the pre-Holocene sediment surface (unit 3) from present sea level in the inner Baie des Chaleurs (see Syvitski *et al.*, 1987, for a more detailed and larger map). Note the pattern of channels indicate a subaerial delta protected by a morainal delta front barrier (*cf.* Fig. 12A), with limited deposition at the delta front.

Profondeur jusqu'à la surface des sédiments pré-holocènes (unité 3) à partir du niveau actuel de la mer au fond de la baie (carte plus détaillée dans Syvitsky et al., *1987). Noter que le réseau des chenaux dévoile un delta subaérien protégé par une barrière morainique (fig. 12A), avec accumulation limitée au front du delta.*

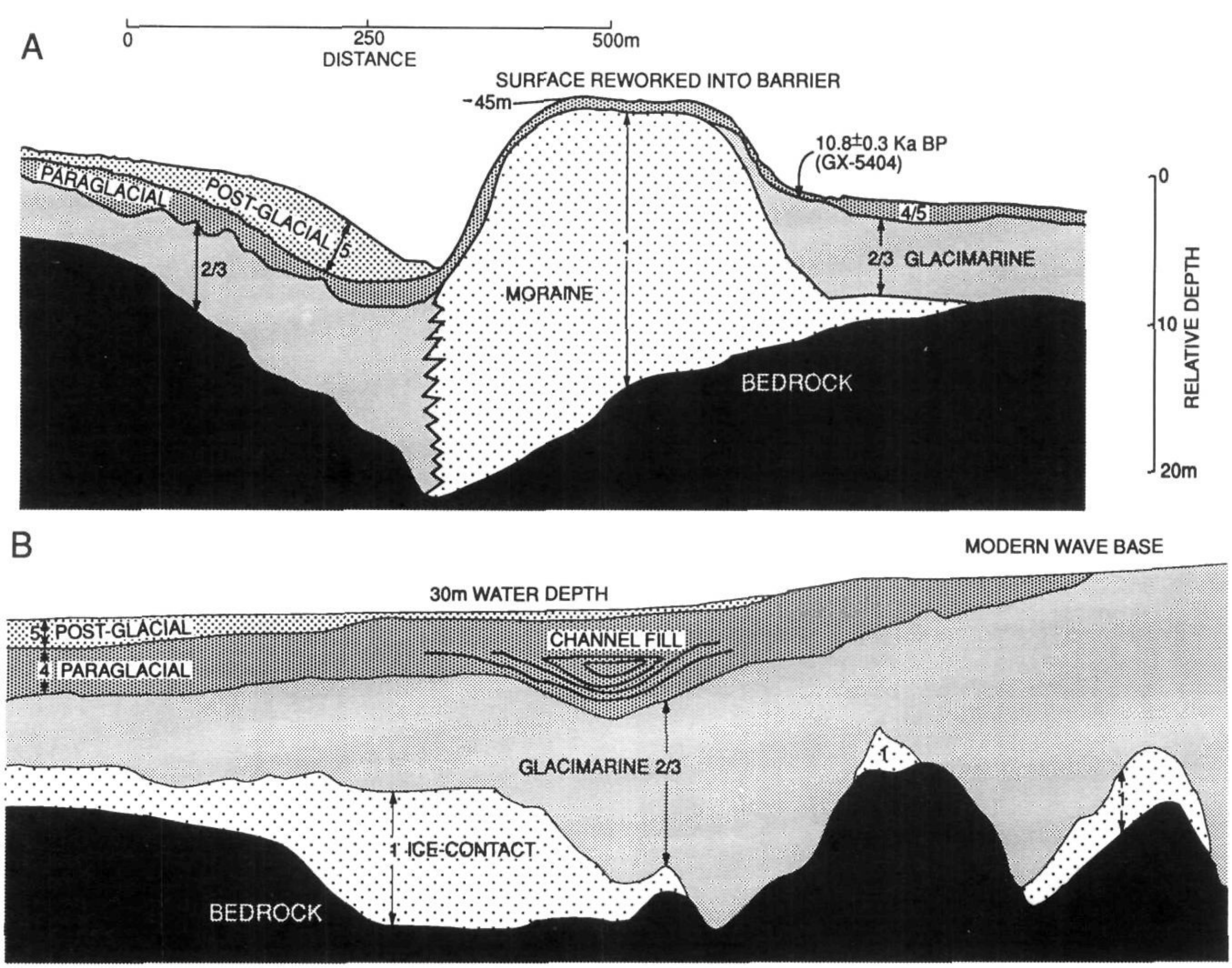

FIGURE 12. Interpretation of Huntec DTS profiles from the inner portion of Baie des Chaleurs. A) Surface of moraine reworked by waves into a delta front barrier (profile 8, Fig. 1). B) Thick ice-contact (till?) sediments deposited on the lee side of bedrock ridges (profile 9). Both Paraglacial (unit 4) and Glacimarine (unit 2/3) deposits have been truncated by wave action at a water depth of 28 m.

Interprétation des profils Huntec du fond de la baie des Chaleurs. A) Surface des moraines remaniée par les vagues en une barrière d'avant-delta (profil 8, fig. 1). B) Épais dépôt de contact glaciaire (till?) sur le côté abrité des crêtes (profil 9). Les dépôts paraglaciaires et glaciomarins (unité 2/3) ont été tronqués par l'action des vagues à une profondeur de 28 m.

from a hard seismic return, erosional unconformity (probably oxidized and lag-covered) to a less distinct paraconformity below 60 to 70 m level. Figure 9 shows a comparison between the proposed sea level curve by Belknap *et al.* (1986) for Sheepscot Estuary, and the sea level curve proposed for Baie des Chaleurs.

Two phases of sediment influx occurred during the period of falling sea level (units 4A and 4B on Fig. 5). The sediment may have been supplied from the reworking of the seafloor by wave or fluvial action, and by the melt of the terrestrial ice sheets. This period of increased marine sediment supply has become known as the Paraglacial phase (Syvitski and Praeg, 1989; Syvitski, in press). Eventually with isostatic recovery nearly complete, local sea level follows the rising global sea level trend as the rapidly ablating Laurentide Ice Sheet pours water into the oceans. Modern sea level is reached *circa* 5000 years BP. As the sea level rose, the deltaic and shoreline deposits were subsequently buried by a transgressive deposit (unit 4C on Fig. 5), and relatively fine sediments were deposited in the deeper and or protected parts of the bay (such as the inner bay). Reworking of the margins of the bay by waves during this sea level rise has thinned and winnowed the glacigenic sediment cover, supplying fines to the deeper parts of the bay (*cf.* Fig. 6B). The erosional surface along the margins of the bay (Fig. 9) is typically smooth at the macro scale, *i.e.* as seen on Huntec seismic records.

The inner part of Baie des Chaleurs appears to have been partly protected from the onslaught of Early Holocene marine transgression, by a mid-bay moraine (Figs. 11 and 12A). The top of the barrier, at 45 m, would have protected the inner bay until *circa* 8000 years BP based on the proposed sea level curve of Figure 9. A wood sample taken from the base (330 cm) of core 64 collected in a water depth of 23 m (*cf.* Fig. 1 and Fig. 10A) and at the erosional boundary at the base of unit 4 and above unit 3, gave an age of 7500 ± 200 BP (UQ-1623). As a result of the protection offered by the barrier, the paleo-sandur surface is preserved under units 4 and 5 (Fig. 11).[A 1:36 000 map of the sandur surface, contoured at a 2 m interval, is available to readers through the offices of the Geological Survey of Canada (Syvitski *et al.*, 1987a).] The sandur channels are 50 to 400 m wide and 4 to 10 m deep (*cf.* Fig. 10B). After the barrier was breached and the sandur was transgressed by the rising sea level, most of the channels were filled with unit 4 sediments (Figs. 12B and 13). Modern spits and bars remain the only indicator of a continued but more gradual sea level rise (Rampton *et al.*, 1984).

Unit 4 represents sediment delivery related initially to melting of terrestrially positioned ice caps and later to the rapid fluctuations in sea levels where subaerially exposed marine sediments were subjected to erosion by surface runoff and later to breaking shoreline waves. The organic carbon content of this early to middle Holocene sediment is high (1 % or greater), and the sand content is variable (20 to 80 %). The sand content is highest where unit 4 has been subjected to wave erosion, particularly in the development of sheet sands along the shallow shelves surrounding the bay (Fig. 14A),

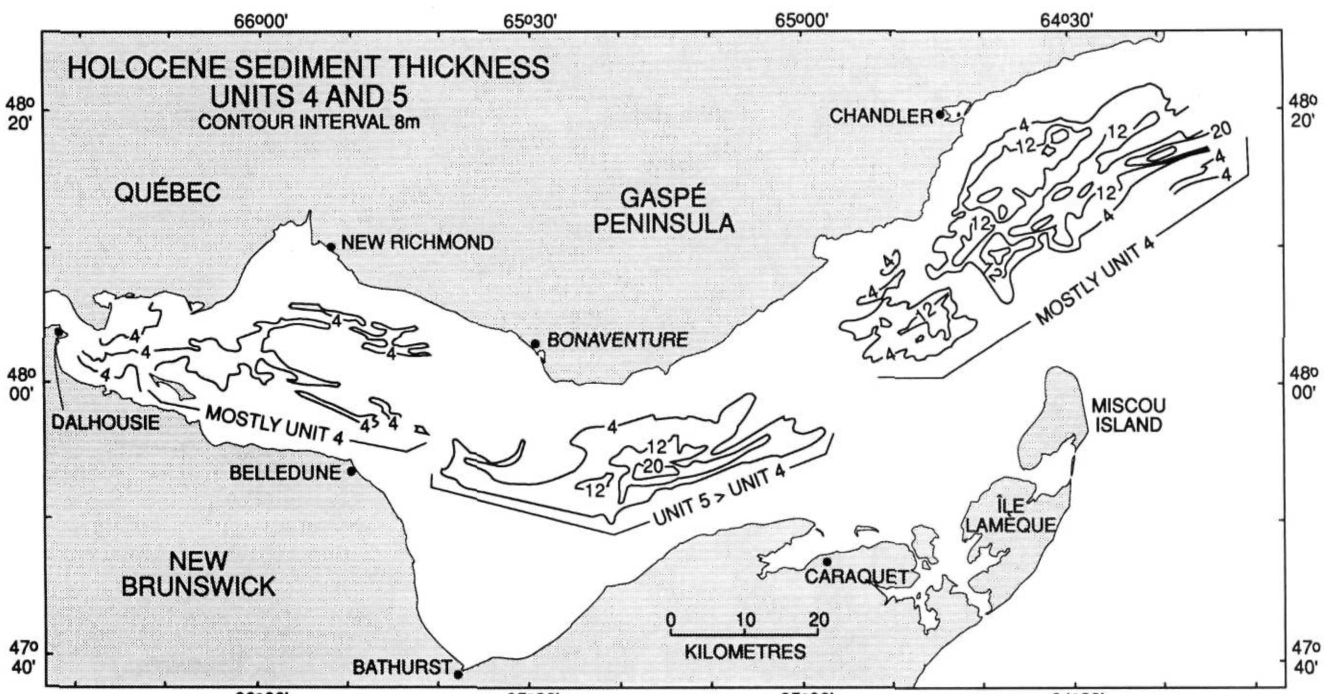

FIGURE 13. Holocene sediment thickness (units 4 and 5 combined) in Baie des Chaleurs. Three depocentres are noted: inner Bay infill of paleo-sandur channels (*cf.* Figs 11 and 12B); middle Bay under the cyclonic gyre of surface currents (*cf.* Fig. 4); and outer Bay related to the early Holocene sea level fluctuations.

Épaisseurs des sédiments holocènes (unités 4 et 5 combinées) dans la baie des Chaleurs. On observe trois zones de grande accumulation: le fond de la baie, avec le remblaiement des chenaux du paléo-sandur (fig. 11 et 12B); le centre de la baie, sous les courants gyratoires cycloniques de surface (fig. 4); et l'entrée de la baie, en raison des fluctuations du niveau marin à l'Holocène.

such as near Bathurst and New Richmond. Unit 4 sediments also contain copious broken and transport-damaged mollusc shells. The two main depocentres of unit 4 are in the outer bay near Chandler where it can reach thicknesses of 12 m, and in the inner bay as channel fills where thicknesses are typically less than 5 m.

Tidal current strength apparently increased during the middle Holocene as modern sea levels were established. In the outer bay, a large tidal channel developed concomitant with the deposition of post-glacial sediments (unit 5: Fig. 5). In the inner bay, one of the sandur channels (Figs. 10B and 15) continues to be swept free of potential unit 5 sediment deposition through the action of tides (Fig. 16). Unit 5 has accumulated mostly in the middle of the bay (Fig. 13) between the interplay between the inflowing water of the Gaspé current and the outflowing Restigouche current (Fig. 4). A cyclonic gyre has been recognized between these opposing surface currents (Legendre and Watt, 1970), although the permanency of the gyre is being re-investigated (M. El Sabh, pers. comm., 1992). Seventeen metres of unit 5 sediments have accumulated in this middle bay area (Fig. 13).

Unit 5 is typical of post-glacial sediments throughout the Gulf of St Lawrence and has two facies: (A) an acoustically transparent mud unit that is well-bioturbated and that accumulates in the sheltered and deeper basins; and (B) poorly sorted shallow water lags of muddy sand and gravel. The carbon content of unit 5 is particularly high in deposits situated under the mid-bay surface gyre: in core 70 (Fig. 1) organic carbon values exceed 2 %. Decomposition of this organic matter produces an acoustic masking related to the formation of methane gas bubbles within these sediments (Fig. 14B).

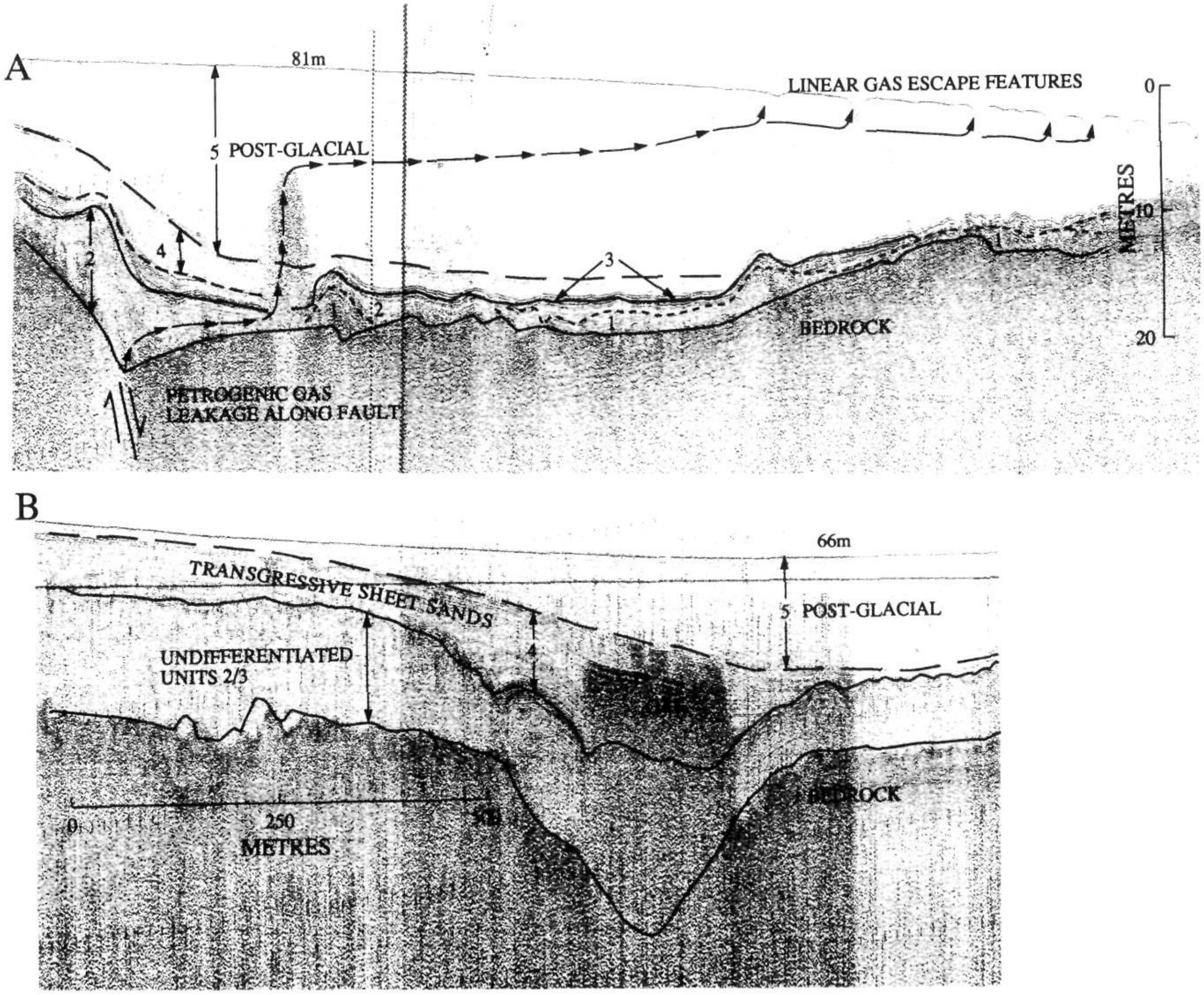

FIGURE 14. Examples of gas appearing in Quaternary deposits. A) Gas can be traced to petrogenic leakage along faults cutting through Pennsylvanian and Mississipian source rocks (profile 10). Gas leakage through the sedimentary cover is often associated with linear gas escape troughs. B) Commonly, gas appears to relate to methane produced from decomposing post-glacial organic matter (profile 11, Fig. 1).

Exemples de la présence de gaz dans les dépôts quaternaires. A) Présence de gaz due à des fuites le long de failles dans les roches du Pennsylvanien et du Mississipien (profil 10). Les fuites de gaz à travers la couverture sédimentaire sont souvent associées à des dépressions linéaires d'échappement de gaz. B) Généralement, le gaz est associé au méthane produit par la décomposition de matière organique postglaciaire (profil 11, fig. 1).

Gas may also leak from the Carboniferous sediments underlying Baie des Chaleurs along the major faults (Figs. 2 and 14A). Long (kilometres) linear troughs in the surface of unit 5 (and marking the seafloor) have been mapped by sidescan sonar (Syvitski *et al.*, 1987a). They range from 0.3 to 2 m deep and 3 to 15 m wide. They are consistently situated along or just adjacent to the major bedrock faults. Some of these pock features were observed on video, using an unmanned submersible, to have bubbles leak from the seafloor (Praeg *et al.*, 1987b).

BAIE DES CHALEURS TODAY

The present day bathymetry of Baie des Chaleurs reflects elements of the pre-Quaternary bathymetry (*cf.* Fig. 3), the pre-Holocene bathymetry (*cf.* Fig. 11), and distribution of Quaternary sediment (*cf.* Fig. 7, 13). The result is a modern estuary that is large, with both an outer sill (90 m) and an inner sill (22 m). The inner basin is 33 m deep and is known as the Restigouche Channel (Fig. 16); the water depth in the outer basin reaches 135 m.

Baie des Chaleurs is affected by the interplay between waves, tides and river discharge. Schafer (1977) reported that swells within the bay are commonly 2.1 m high with periods up to 9 s; storm waves reach 4.9 m high with periods of 7 to 8 s. Waves may also exceed 4.9 m (swells from the Gulf) with periods reaching 9 s, impacting the seafloor above 68 m. Such conditions explain the present distribution of sand waves observed along the margins of the bay (Syvitski *et al.*, 1987a). Recent sediments comprise a relatively thin veneer in many parts of the bay. The presence of gravel on the seafloor relates to both the erosion of older glacigenic diamicton and contributions from present day ice-rafting. The bay is variably covered by sea ice from January through March.

Superimposed on this effective wave action is a surface circulation dominated by a 2-3 m tidal variation. On rising tide, currents tend to be stronger along the northern shore of the bay, and on falling tide, stronger along the south shore. The net movement is outward and stronger along the southern shore (F. Jordan, pers. comm., 1983). This surface circulation is further augmented by a continuous (baroclinic) influx of water entering the bay along the Gaspé side and semi-continuous (barotropic) efflux of water from river discharge flowing along the New Brunswick shore. These two opposing currents may occasionally result in a surface mid-bay cyclonic (anti-clockwise) gyre (Fig. 4). This cyclonic eddy corresponds to a zone of comparatively high primary production rates of phytoplankton (summer average near 1 gC m^{-2} day^{-1}: Legendre and Watt, 1970).

The Restigouche River is the major (50 %) freshwater and sediment input to the bay (Fig. 4; Schafer, 1977). Sediment discharged from the Restigouche River is initially deposited at depths from which it can be resuspended (Schafer, 1977). Hildebrand (1984) suggests that suspended particulate matter (SPM) becomes trapped within the central gyre (Fig. 4) and settles out in the central bay. This hypothesis agrees well with our isopach map of the deposition of middle to late Holocene sediment (unit 5: Fig. 13). Most of the rivers along the Québec shore discharge into enclosed basins that act as

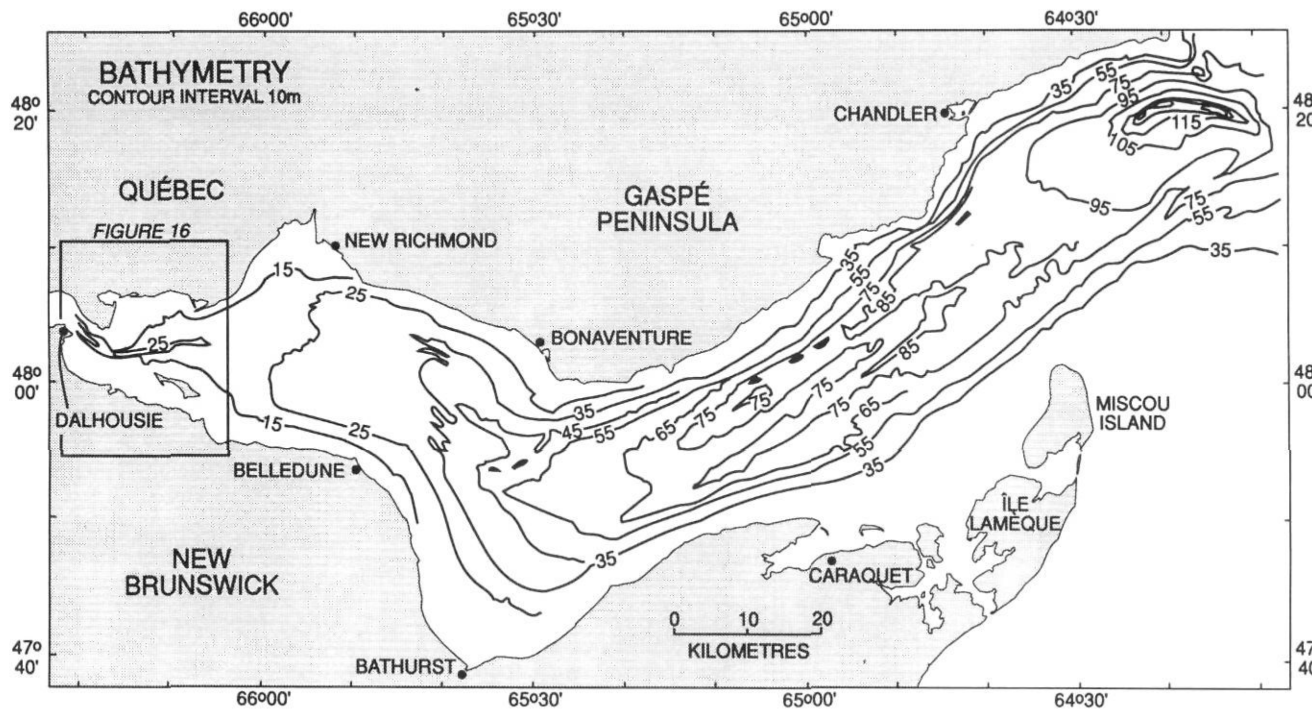

FIGURE 15. Present seafloor bathymetry of Baie des Chaleurs reflects elements of the pre-Quaternary bathymetry (*cf.* Fig. 3) and the pre-Holocene bathymetry (*cf.* Fig. 11), and Quaternary sediment deposition (*cf.* Figs. 7 and 13). The result is a large estuary with both an outer sill (90 m) and an inner sill (22 m).

Bathymétrie du fond marin actuel de la baie des Chaleurs qui révèle des éléments des bathymétries pré-quaternaire (fig. 13) et pré-holocène (fig. 11) et l'accumulation de sédiments quaternaires (fig. 7 et 13). Il en résulte un grand estuaire comprenant un seuil externe (90 m) et un seuil interne (22 m).

catchments for fluvial sediment. The Cascapedia, being more similar to the Restigouche in flow characteristics and sediment discharge, is an exception.

The bottom currents in Baie des Chaleurs were studied by Bezanson (1982) who released 477 seabed drifters at the Heron Island dump site (Fig. 16) in 1980. The drifter study revealed two directions of net sediment transport from this site: a dominant seaward directed flow along the southern side of the bay (≈0.7 cm/s), and a less dominant flow up inlet into the Restigouche Harbour.

A dump site was established offshore of Heron Island in 1973 for the disposal of dredge spoil from the Port of Dalhousie, N.B. (Fig. 16). Concerns over the seafloor stability at the dump site were raised due to the contamination by cadmium in the dredge spoils (Packman *et al.*, 1984). Data from a GSC seafloor stability study provide an oceanographic snapshot of flow dynamics within Baie des Chaleurs. The water at the dump site in the summer of 1981 was well stratified, with a very thin (2 m) surface layer of brackish water over a thicker outflowing layer of warm water (Fig. 16A). At the seafloor was a much colder and well-mixed saline layer that was more turbid, with SPM values 3 to 5 times greater than the surface layer (Fig. 16A), and comprised of coarser-grained sediment (Fig. 16C). At low slack water, most of the flow was directed out of the estuary in the surface layer (Fig. 16B). During rising tide water in the bottom layer flowed up the bay. At high slack tide, currents were weak but still dominated by the outward flowing surface layer (Fig. 16B). During falling tide, the outward flow of water was largely through the bottom layer. Longer-term currents are closely related to the spring and neap tidal cycles (Packman *et al.* (1984). Maximum current speed measured 1.3 m above the seafloor is 0.4 m s^{-1}.

SUMMARY

Gently deformed Carboniferous sedimentary strata form the lithified acoustic basement underlying the Quaternary sedimentary deposits within Baie des Chaleurs. The structural elements within these Paleozoic strata determined the position of a major Cenozoic (Tertiary fluvial or Quaternary sub-glacial) drainage system. Faults running along the length of the bay through the Paleozoic strata contribute petrogenic gas to the Quaternary sediment and eventually to the waters of the bay through a series of linear gas escape troughs.

Baie des Chaleurs appears to have been affected by regionally-limited Appalachian ice sheets during the Late Wisconsinan, in support of the conclusions reached by Rampton *et al.* (1984). The Cenozoic drainage system

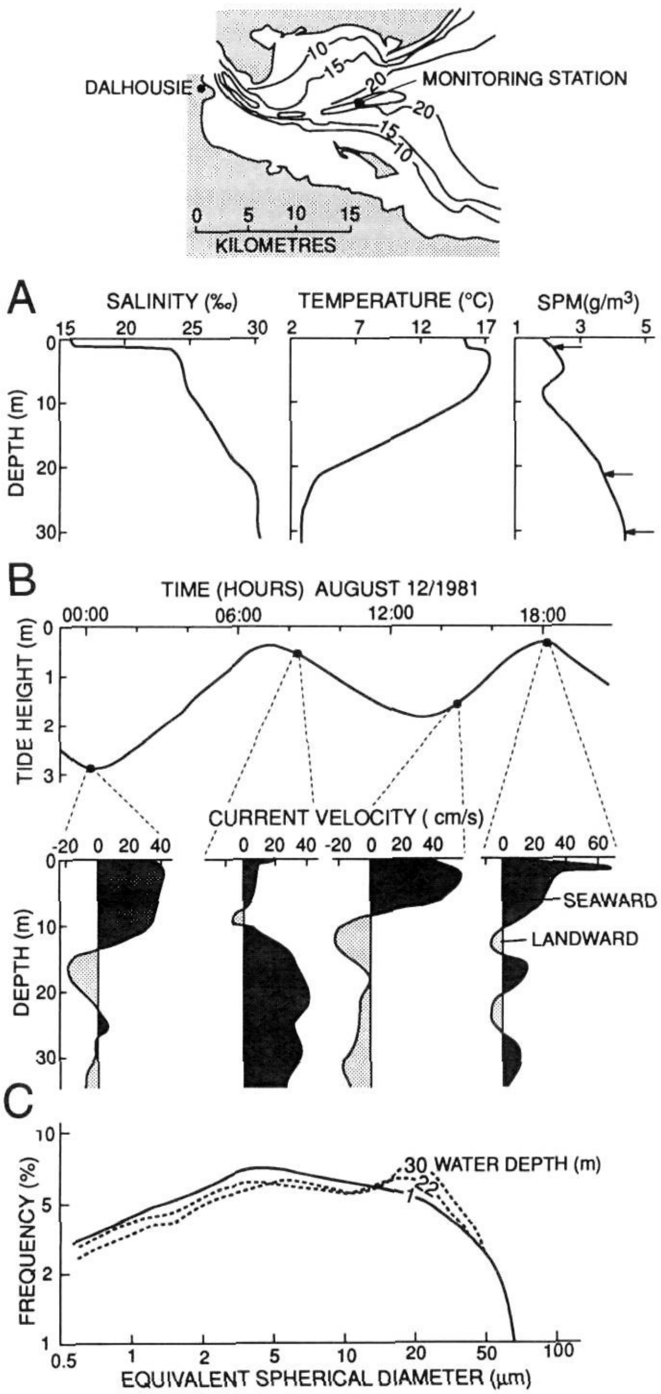

FIGURE 16. Oceanographic environment in the inner portion of Baie des Chaleurs (*cf.* Fig. 15 for location). Data collected on August 17, 18, 1981. A) Averaged (25 hours) profiles of salinity, temperature and SPM (suspended particulate matter) for monitoring station shown above. B) The semidiurnal tidal cycle for the 25 hour monitoring period. Representative velocity profiles for low and high tide, and ebbing and flooding conditions. C) Size frequency distribution of deflocculated suspended sediment samples. The distributions represent averages from samples collected throughout the 25 hour monitoring period for three depths (see SPM profile in A, for sample location).

Environnement océanographique du fond de la baie des Chaleurs (localisation à la fig. 15). Données recueillies les 17 et 18 août 1981. A) Profils moyens (25 h) de la salinité, de la température et des particules en suspension à la station de contrôle. B) Le cycle des marées semi-diurnes au cours de la période de contrôle (25 h). Profils représentatif de la vitesse des marées hautes et basses, ainsi que les conditions au flot et au jusant. C) Répartition en fréquence des échantillons de particules en suspension défloculées selon leur dimension. La répartition représente une moyenne à partir des échantillons prélevés tout au long de la période de contrôle de 25 heures à trois profondeurs données (voir profils en A).

provided an ideal bathymetric element for the location of a stillstand position of the Gaspé Ice Sheet. As a consequence of this equilibrium ice marginal position, three irregular ridges of glacigenic sediment accumulated. A number of significant depocentres of glacimarine sediment were associated with these ridges and other ice terminal positions. Much of the ice-contact and glacimarine sediments (seismic units 1, 2 and 3) were deposited during the high sea level stand, *i.e.* the expanded Goldthwait Sea.

During the period of subaerial ice sheet ablation, sea level fell rapidly from a marine limit of 100 m above present sea level to an early Holocene low of possibly 90 m below modern sea level. Our best circumstantial timing of this low sea level stand is *circa* 9 000 years BP. As a consequence of this low stand, proglacial drainage channels were cut into the exposed glacimarine sediments while coastal and other deltaic deposits (unit 4) were developed further offshore. This rapid fall in sea level was followed with a slower rise in sea level and concomitant formation of terraces (now located between 20 and 90 m water depth). A mid-bay moraine acted as a barrier to wave erosion and preserved a paleo-sandur surface beneath seismic units 4 and 5 in the inner bay region.

Modern oceanographic conditions began to develop some 5000 years ago. Tidal influence increased substantively during this period and tidal erosion is strong throughout the bay today. Presently, most fluvial-sediment input to the bay is transported to the centre of the bay where currents are weak; a local gyre may aid in the accumulation of thick organic rich post-glacial sediment (unit 5). The concentration of organic matter within these thick accumulations of sediments has generated local pockets of methane bubbles.

Baie des Chaleurs is a large and dynamic estuary. The above overview can be refined on many fronts and research on the following topics should be encouraged: i) the determination of a more tightly controlled sea level curve, ii) the placer potential of the inner bay sandur, and iii) the macro and microbenthic faunal succession in an environment of rapidly fluctuating sea levels, tidal and wave conditions, primary productivity, water temperature and sedimentation rates.

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