High-resolution seismo-stratigraphy and sedimentological properties of late- and postglacial sediments in Lac Guillaume-Delisle Estuary and Nastapoka Sound, eastern Hudson Bay

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Abstract: *Lac Guillaume-Delisle* Estuary and Nastapoka Sound are two sedimentary basins that recorded the late Quaternary deglaciation on the eastern coast of Hudson Bay. Acoustic profiles reveal an average sediments thickness of 15 m in the estuary and 6 m in the sound. These sediments reach 70 m thick in deep glacial troughs. Within the studied basins, four seismo-stratigraphic units overlying the acoustic basement were recognized. Unit 1 (subaqueous ice-contact and draped glaciomarine deposits associated with the Quebec–Labrador Ice Sector (QLIS) of the Laurentide Ice Sheet (LIS) and the Tyrrell Sea) records the presence of a short ice-marginal stillstand during glacial retreat. Unit 2 (paraglacial and postglacial fluvial-deltaic deposits) and unit 3 (postglacial silty deposits) result from erosion of emerged sediments and redeposition in response to changes in relative sea level (RSL). Finally, unit 4 is composed of deformed deposits associated with a mass wasting event. The stratigraphic sequence and the spatial distribution patterns of deposits show that *Lac Guillaume-Delisle* is a good model to explain the dynamics of the QLIS margin during and after successive ice stillstands, continuous RSL fall, river discharge (ablation on land), and its final ablation inland. Additionally, seven cores were sampled in the southeast part of the estuary. Geochemical (organic carbon and total nitrogen) and carbon isotopic contents, used as alternative proxy, indicate that the sampled sediments correspond to the postglacial estuarine deposits of unit 3. Allochthonous sources of carbon dominate the supply to the sediments where the environment is regularly flushed by fresh and marine waters.

Résumé : L'estuaire *Lac Guillaume-Delisle* et le chenal Nastapoka sont deux bassins sédimentaires où l'on retrouve des évidences de la déglaciation, au Quaternaire tarif, sur la côte Est de la baie d'Hudson. Des profils acoustiques indiquent une épaisseur moyenne de sédiments de 15 m dans l'estuaire et de 6 m dans le chenal. Ces sédiments atteignent une épaisseur de 70 m dans des fosses glaciaires profondes. Dans les bassins à l'étude, on reconnaît quatre unités sismostratigraphiques au-dessus du socle acoustique. L'unité 1 (des dépôts de contact glaciaire sous l'eau et des dépôts glaciomarins drapés associés au secteur glaciaire Québec–Labrador de la calotte glaciaire laurentidienne et à la mer de Tyrrell) enregistre la présence d'une brève pause de stabilization de la bordure glaciaire durant le retrait de la glace. L'unité 2 (des dépôts para-glaciaires et post-glaciaires fluvio-deltaïques) et l'unité 3 (des dépôts postglaciaires silteux) proviennent de l'érosion et de la redéposition de sédiments émergés en réponse aux changements du niveau relatif de la mer. Finalement, l'unité 4 est composée de dépôts déformés associés à un événement de mouvement de masse. La séquence lithologique et les patrons de répartition spatiale des dépôts montrent que le *Lac Guillaume-Delisle* est un bon modèle pour expliquer la dynamique de la bordure du secteur Québec–Labrador de la calotte glaciaire laurentidienne, durant et après des phases de stabilization successives, la chute continuelle du niveau relatif de la mer, la décharge des rivières (l'ablation sur la côte) et l'ablation finale à l'intérieur des terres. De plus, sept carottes ont été échantillonnées dans la partie sud-est de l'estuaire. Les contenus géochimiques (carbone organique et azote total) et en isotopes du carbone, utilisés en tant que mesure alternative, indiquent que les sédiments échantillonnés correspondent aux dépôts post-glaciaires estuariens de l'unité 3. Les sédiments sont approvisionnés par des sources allochtones de carbone là où l'environnement est régulièrement délavé par des eaux douces et marines.

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Introduction

This paper presents the first available high-resolution acoustic stratigraphic surveys in *Lac Guillaume-Delisle* and in the southern part of Nastapoka Sound located on the east coast of Hudson Bay. These basins are key locations and are of particular interest for interpreting the late Quaternary eastward retreat of Quebec–Labrador Ice Sector (QLIS) of the Laurentide Ice Sheet (LIS) and the invasion of the Tyrrell Sea (precursor of the Hudson Bay) over glacio-isostatically depressed lowlands. *Lac Guillaume-Delisle* was probably the last proglacial marine basin to be deglaciated in Quebec with the particularity that the southern part was probably deglaciated earlier (ca. 200 years) than the rest of the coast (Lavoie 2006).

Lac Guillaume-Delisle is a structural estuary contained in a Precambrian east–west-oriented graben. Close to the shore, Nastapoka Sound is a submerged basin located between two series of cuesta ridges that belong to the folded rocks of the Hudson Bay orogen. These basins are characterized by glacial valleys and troughs partly filled with late Quaternary sediments (Lavoie 2006). As glacio-isostatic rebound took place during and after deglaciation, both *Lac Guillaume-Delisle* Estuary and Nastapoka Sound acted as traps for sediments delivered from retreating glaciers and sediments derived from glacio-fluvial denudation. The area is still affected by falling relative sea level (RSL) at a rate in the order of 1.0 to 1.2 m/century (Webber et al. 1970; Hillaire-Marcel 1976; Allard and Tremblay 1983; Sella et al. 2007) as a result of ongoing glacio-isostatic rebound that still largely dominates over eustatic changes. Acoustic stratigraphy and core studies along the coast have been used previously to define stratigraphic sequences and sedimentary environments (e.g., Josenhans et al. 1988, 1991; Bilodeau et al. 1990; Josenhans and Zevenhuizen 1990; Gonthier et al. 1993; Zevenhuizen 1993; Roberge 1998; Hill et al. 1999; Lavoie et al. 2002; Fraser et al. 2005). These studies typically revealed the presence of a thin late Quaternary depositional succession defined in general by ice-contact, glaciolacustrine (?), glaciomarine, and postglacial to modern units. Despite these investigations, no comprehensive analysis of late- and post-glacial deposits has been completed in *Lac Guillaume-Delisle* Estuary. It remains a poorly known estuarine system with potential for a better understanding of deglaciation dynamics of the western margin of the QLIS in the eastern Hudson Bay coastal area and the subsequent environmental changes.

In this paper, the acoustic facies successions, thickness, and geographic distribution of sediments are presented. Units have been correlated with emerged deposits and their associated landforms surrounding to further improve the reconstruction of deglaciation history. Onshore, well-exposed ice-contact and glaciomarine deposits associated with the anchored west margin of the QLIS ice on the Nastapoka hills (Lajeunesse 2000; Lajeunesse and Allard 2003*a*, 2003*b*) and Low peninsula (Lavoie 2006) at ca. 8000 cal BP have provided a basis for detailed reconstructions of late-deglacial to postglacial events. In addition, seven percussion cores averaging 1.15 m in length were recovered in the estuary. The sediments were analyzed for their grainsize, as well as their carbon (C), total nitrogen (TN), and isotopic carbon ($\delta^{13}C$) contents. Because microfossils were rare in the sediments, a combination of C/N ratios and $\delta^{13}C$ values were used as an exploratory tool to provide information on the origin of the organic matter preserved in the sampled sediments and better characterize environmental conditions of sedimentation. The values are compared with analyses performed on similar, well-identified silty-clay deposits of glaciolacustrine, glaciomarine, and postglacial origin from the eastern coast of Hudson and James bays.

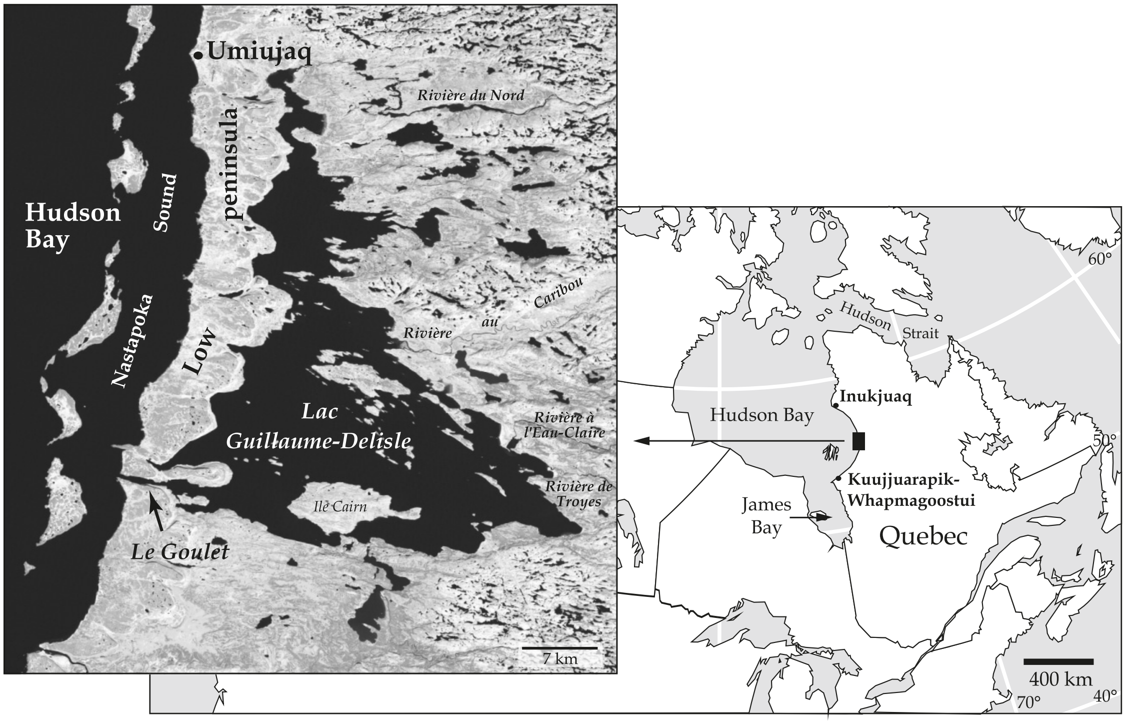
Setting

Lac Guillaume-Delisle Estuary is located southeast of the village of Umiujaq on the eastern shore of Hudson Bay (Fig. 1). According to Chandler (1982, 1988), the basin corresponds to a complexly faulted east–west-oriented Precambrian graben. The regional bedrock geology comprises two Late Proterozoic sedimentary–volcanic sequences over the regional bedrock of Precambrian granite-gneiss (Stevenson 1968; Avramtchev 1982; Ciesielski 1998). The Proterozoic rocks form a cuesta relief with east-facing cliffs, a gently inclined slope dipping toward Hudson Bay, and numerous transverse valleys. This relief has played a major role in controlling the stages of deglaciation and the sediment distribution in the area (Lavoie 2006).

The estuary is a 780 km^2 semi-enclosed basin connected to Hudson Bay through a 5 km long, narrow and shallow (average depth of 35 m) channel, *Le Goulet* (Fig. 1). It receives freshwater from a large eastern watershed. Four main rivers supply the majority of freshwater and have provided most of the sediment influx during the deglaciation period. The relief of the estuary floor shows glacial carving of submarine valleys that align with terrestrial ones, basins up to 150 m deep in the southern part of the estuary (Fig. 2) and numerous submerged east-facing asymmetric ridges with similar orientation to emerged islands and reefs (Lavoie 2006). Nastapoka Sound is located between the coast and Nastapoka Islands (Fig. 1) and extends northward to *rivière Boniface*. It averages 6 km wide in its southern part, just off *Le Goulet*. Between the study area and Kuujjuarapik-Whapmagoostui, the seafloor is characterized by numerous submarine valleys oriented east–west and aligned with the emerged glacial valleys and glacial troughs along the coast (Lavoie 2006).

Mean tidal range in Kuujjuarapik-Whapmagoostui, to the south, and Inukjuak, to the north, is 1 m and 0.4 m, respectively (Fisheries and Oceans Canada 2005). No wave measurements are available in the study area, but qualitative observations were made during three field seasons of the summer. Wave heights generated by westerly and northwesterly winds are fetch-limited in Nastapoka Sound by the offshore Nastapoka Islands and by Low peninsula in the *Lac Guillaume-Delisle* Estuary. Easterly winds from hinterland generated the largest storm waves in the estuary. Although these waves are the most important, they are lower than the 3 m high storm waves observed in the Kuujjuarapik-Whapmagoostui region (Hill et al. 2003). In the estuary and the sound, ice-free water occurs during summer and continuous ice cover is present in winter, except for an area around *Le Goulet*, where a polynia exists in winter due to

Fig. 1. Location of the study area; *Lac Guillaume-Delisle* and Nastapoka Sound (Landsat 7 ortho-image 2002, courtesy Geomatics Canada, Centre for Topographic Information).



strong tidal currents. In the estuary, ice thickness in April 2004 varied between 0.73 and 1.27 m (average 0.90 m) in the east sector of the Southern basin.

The Holocene sediments exposed in the coastal areas around the estuary include ice-contact and glaciomarine sediments that record sedimentation in proximal and distal tidewater glacier environments (Lavoie 2006). These sediments are associated with the retreat of the QLIS and they occur in various landforms and sedimentary facies, such as (1) 25–35 m thick subaqueous frontal moraines pitted by kettles, (2) subaqueous outwash fans and trains composed of stratified sand and silt $\sim$20 m thick and characterized by shell-rich layers with interbedded diamictons, and (3) fossiliferous fine-grained deposits that sporadically contain ice-rafted debris (IRD). As the shoreline advanced seawards in response to continued glacio-isostatic rebound, paraglacial and postglacial sediments accumulated in diverse deposits, such as successive perched deltas and terraces, flights of raised beach ridges, and eolian deposits. The marine limit from Kuujjuarapik-Whapmagoostui to *rivière Nastapoka* is located at the present-day altitude of ca. 250 m above sea level (a.s.l.) except for the area surrounding *Le Goulet*, where it is at 270 m a.s.l (Stanley 1939; Lee 1960; Hillaire-Marcel 1976; Lavoie 2006).

Methods

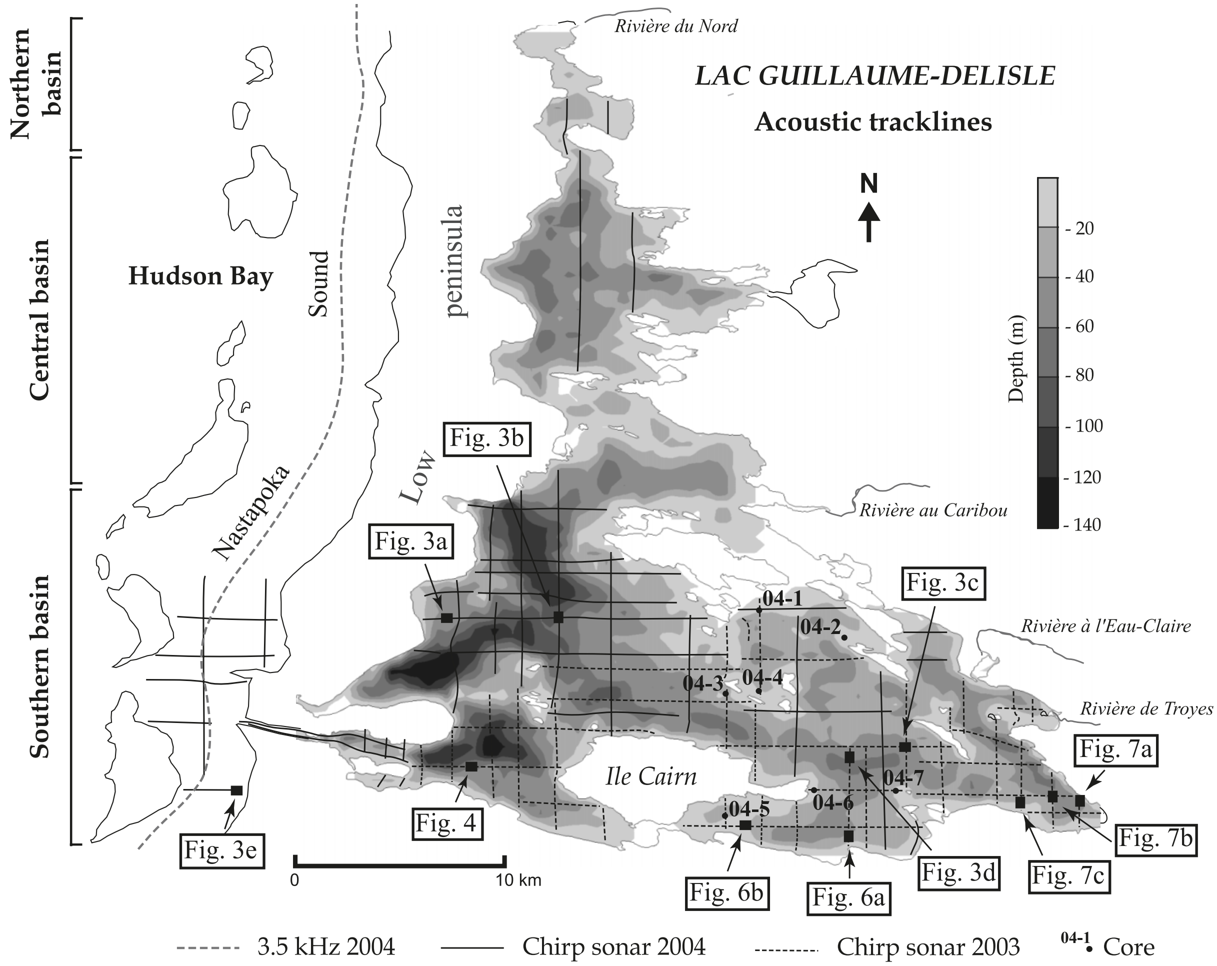
Marine geophysical surveys

High-resolution sub-bottom profiles were collected in *Lac Guillaume-Delisle* Estuary and in Nastapoka Sound with an X-Star EG&G/Edgetech chirp sonar acoustic system from an 8 m boat during the summers of 2003 and 2004 (Fig. 2). From Kuujjuarapik-Whapmagoostui to Inukjuak, including Nastapoka Sound, one trackline was gathered with a hull-mounted Knudsen 3.5 kHz system from the research ice-breaker Canadian Coast Guard ship (CCGS) Amundsen during the September cruise of 2004 (ArcticNet leg 1). Data in digital SEG-Y format were processed using SonarWeb (Chesapeake Technology Inc.) software. Approximate water depths and sediment thicknesses ($\sim$0.5 m vertical resolution) were derived from the acoustic return times using an assumed sound speed of 1500 m/s. The registered depths were validated by cross-checking results between acoustic track lines and with profiles from a 320 M Knudsen digital sounder. No tidal correction was applied to the data considering their small variations (<1m). Positional data on the boat were acquired using a WAAS-capable (wide area augmentation system) GPS (global positioning system) receiver, providing a horizontal accuracy of approximately <4.5 m.

Physical, geochemical, and isotopic analyses

Seven percussion cores (corer modified from Nesje 1992), 10 cm in diameter and averaging 1.15 m in length, were collected from the ice cover in April 2004 (Fig. 2) in an attempt to sample outcropping glaciomarine sediments on the estuarine floor. The coring sites were selected from the acoustic stratigraphy profiles. The cores were split, photographed, visually described with respect to texture and sedimentary structures, and sampled at intervals of 20 cm. Water content was calculated by weighing of wet and dry subsampled sediments. For comparison purposes, samples of emerged glaciolacustrine sediments from glacial Lake Ojibway in the James Bay region, emerged glaciomarine

Fig. 2. Bathymetric chart of the study area showing (1) the location of chirp sonar and 3.5 kHz track lines in *Lac Guillaume-Delisle* Estuary and Nastapoka Sound, and (2) cores recovered in this study. Acoustic profiles in Figs. 3, 4, 6, and 7 are highlighted.



sediments from *rivière Nastapoka* (eastern Hudson Bay) and James Bay, as well as postglacial sediments from James Bay and a marine core collected near the mouth of *Grande rivière de la Baleine* (Kuujjuarapik-Whapmagoostui) in Hudson Bay, were also obtained for analyses through field visits and from other researchers. Because there was no material suitable for radiocarbon dating, there is no direct chronologic control on our cores.

Samples, conserved at 4°–5°, were submitted for grain-size analysis and TN, organic carbon (OC), carbonates ($CaCO_3$), C_{org}/N_{tot} atomic and molar ratio, and $\delta^{13}C$ determinations. Approximately 3 g of wet sediment were weighted, dried at 40 °C, weighted again, ground to a fine powder, and divided into two subsamples. The first subsample was used to determine total carbon (TC) and TN content by combusting a weighted aliquot in a Carlo-Erba elemental analyzer. The second aliquot was acidified twice with dilute HCl (10%) to remove carbonates and then washed three times with distilled water, dried, and ground. This other subample was analyzed for (1) residual nitrogen and carbon, which is considered to represent OC and (2) $\delta^{13}C$ ratios using the Vienna Pee Dee Belemnite (V-PDB) as a standard. Uncertainties of OC and TN ($\pm 1\sigma$) average ± 5% (St-Onge and Hillaire-Marcel 2001) and of stable isotope measurements are lower than ± 0.1‰, as determined from routine replicate measurements of standards. We calculated inorganic carbon (IC) data from the difference between TC and OC. IC content for all cores is expressed as $CaCO_3$ equivalent in dry weight percent of total sediment. Grain-size analyses were carried out on the half of the second subsample before it was dried and ground using a Beckman Coulter laser particle analyzer LS-13320. Prior to analysis, the samples were mixed with 10% calgon and shaken for 3 h. Grain-size parameters were calculated geometrically using Folk and Ward's (1957) graphical method in GRADISTAT version 4 (Blott and Pye 2001). Results are presented in Tables 1 and 2, where grain size, TN, and carbon (OC and $CaCO_3$) contents are expressed in dry weight percent of total sediment. Also, distinctive source combinations of atomic/molar ratio of OC to TN (C/N by multiplying by 14/12) or C_{org}/N_{tot} and $\delta^{13}C$-values (‰) are shown.

High-resolution seismo-stratigraphy units

Late Quaternary sediments reach averages thickness of 15 m in the *Lac Guillaume-Delisle* Estuary, except in glacial

Table 1. Grain-size distribution and geochemical and isotopic properties of *Lac Guillaume-Delisle* Estuary sediments (location of cores is shown on Fig. 2).

	Grain size (%)				Carbon (%)				
Depth (cm)	Sand	Silt	Clay	TN (%)	OC	$CaCO_3$	C/N	$\delta^{13}C$ (‰)	Depositional environment
Core 04-1 (North of Southern basin)									
0	45.0	49.5	5.5	0.07	0.39	0.55	6.68	–25.46	Postglacial
20	19.3	61.8	18.9	0.07	0.44	0.23	7.51	–23.06	Postglacial
40	10.8	66.0	23.3	0.06	0.36	0.45	6.77	–23.99	Postglacial
60	3.6	75.1	21.2	0.06	0.33	0.72	6.19	–24.39	Postglacial
80	5.2	68.1	26.7	0.06	0.30	0.32	6.08	–24.48	Postglacial
100	6.1	70.4	23.5	0.05	0.28	0.21	6.04	–24.68	Postglacial
110	22.6	69.2	8.3	0.05	0.26	0.05	6.08	–24.75	Postglacial
Core 04-2 (Northeast of Southern basin)									
0	7.6	71.4	21.0	0.06	0.35	0.21	6.87	–24.04	Postglacial
20	2.1	71.8	26.1	0.06	0.32	0.24	6.58	–24.61	Postglacial
40	5.4	74.5	20.1	0.05	0.24	0.25	5.56	–24.29	Postglacial
60	0.0	72.6	27.4	0.05	0.26	0.15	5.82	–24.77	Postglacial
80	5.8	75.1	19.1	0.04	0.19	0.00	4.98	–26.26	Postglacial
100	0.0	72.2	27.8	0.04	0.31	0.00	8.07	–30.06	Postglacial
120	3.7	73.3	22.9	0.04	0.34	0.61	9.05	–31.12	Postglacial
130	0.0	70.8	29.2	0.04	0.30	0.20	8.87	–30.35	Postglacial
Core 04-3 (Central sector of Southern basin)									
0	14.2	64.4	21.4	0.06	0.52	0.00	9.29	–23.92	Postglacial
20	8.5	65.3	26.2	0.06	0.37	0.11	7.32	–24.24	Postglacial
40	19.6	65.6	14.8	0.05	0.26	0.08	5.91	–24.82	Postglacial
60	12.4	67.1	20.5	0.05	0.23	0.00	5.79	–25.25	Postglacial
80	10.9	73.0	16.1	0.05	0.27	0.00	6.46	–28.89	Postglacial
100	16.9	73.6	9.6	0.05	0.23	0.34	5.37	–25.03	Postglacial
125	21.1	68.8	10.1	0.05	0.21	0.21	5.19	–24.63	Postglacial
Core 04-4 (Central sector of Southern basin)									
0	13.2	64.2	22.6	0.05	0.25	0.09	5.87	–24.51	Postglacial
20	4.9	77.0	18.1	0.06	0.28	0.68	5.93	–23.97	Postglacial
40	7.4	68.1	24.5	0.07	0.35	0.43	6.22	–24.00	Postglacial
60	11.6	71.7	16.8	0.06	0.37	0.35	6.80	–23.46	Postglacial
85	5.3	70.9	23.9	0.07	0.45	1.34	7.42	–22.81	Postglacial
Core 04-5 (South of Southern basin)									
0	2.6	72.2	25.2	0.06	0.36	0.53	6.63	–23.75	Postglacial
20	1.1	76.5	22.5	0.06	0.38	0.51	7.08	–24.12	Postglacial
40	16.7	68.8	14.5	0.07	0.40	0.64	7.15	–23.76	Postglacial
60	15.9	72.2	11.9	0.06	0.37	0.73	7.14	–24.16	Postglacial
80	0.8	78.6	20.6	0.06	0.38	0.93	7.32	–24.00	Postglacial
100	5.2	72.5	22.3	0.06	0.39	0.87	7.16	–23.95	Postglacial
110	3.8	73.6	22.6	0.06	0.46	0.58	8.35	–23.84	Postglacial
Core 04-6 (Southeast of Southern basin)									
0	15.4	64.1	20.5	0.08	0.39	0.12	6.10	–23.77	Postglacial
20	9.0	66.3	24.7	0.06	0.34	0.16	6.13	–23.79	Postglacial
40	13.1	70.9	16.0	0.06	0.34	0.27	6.77	–23.80	Postglacial
60	8.0	76.1	15.9	0.06	0.30	0.65	5.46	–24.16	Postglacial
80	2.1	73.8	24.0	0.06	0.30	0.76	5.80	–23.82	Postglacial
100	11.2	78.2	10.6	0.06	0.33	0.71	6.77	–24.15	Postglacial
125	6.5	67.9	25.6	0.06	0.34	0.31	6.98	–24.69	Postglacial
Core 04-7 (Southeast of Southern basin)									
0	17.3	64.0	18.7	0.07	0.36	0.71	6.19	–24.06	Postglacial
20	18.8	68.8	12.4	0.05	0.25	0.44	5.43	–24.53	Postglacial
40	8.8	73.2	18.0	0.04	0.21	0.00	5.37	–25.46	Postglacial
60	4.1	65.8	30.1	0.05	0.27	0.00	6.67	–30.11	Postglacial
80	3.7	73.2	23.1	0.05	0.23	0.17	6.06	–26.79	Postglacial

Table 1 (*concluded*).

	Grain size (%)				Carbon (%)				
Depth (cm)	Sand	Silt	Clay	TN (%)	OC	$CaCO_3$	C/N	$\delta^{13}C$ (‰)	Depositional environment
100	2.4	67.4	30.2	0.04	0.20	0.28	5.09	–25.13	Postglacial
125	1.3	74.0	24.7	0.04	0.16	0.00	4.71	–27.08	Postglacial

Note: OC, organic carbon; TN, total nitrogen.

Table 2. Gain-size and geochemical and isotopic proprieties of sediments in the Hudson Bay core and from emerged sediments in eastern James and Hudson Bay territory.

	Grain size (%)				Carbon (%)				
Sample location	Sand	Silt	Clay	TN (%)	OC	$CaCO_3$	C/N	$\delta^{13}C$ (‰)	Depositional environment
Hudson Bay (Offshore)									
56.3804°N, 76.5800°W	10.9	68.3	20.8	0.07	0.39	3.93	6.04	–23.90	Postglacial
56.3804°N, 76.5800°W	5.6	62.7	31.7	0.09	0.45	4.20	5.91	–23.65	Postglacial
James Bay									
53.8135°N, 78.9230°W	22.4	72.1	5.5	0.07	0.28	2.54	4.98	–26.70	Postglacial
53.7448°N, 78.6056°W	0.8	77.8	21.4	0.09	0.59	9.54	8.02	–24.99	Postglacial
53.7623°N, 78.8480°W	4.8	64.5	30.7	0.07	0.22	10.19	3.75	–24.96	Glaciomarine
53.7256°N, 78.0904°W	10.3	76.0	13.7	0.06	0.17	3.03	3.32	–23.70	Glaciomarine
53.6223°N, 77.5651°W	6.1	74.2	19.7	0.04	0.08	7.83	2.02	–24.68	Glaciomarine
53.3444°N, 77.5659°W	39.6	46.0	14.4	0.00	0.00	0.00	—	–25.06	Glaciolacustrine
N.A.	0.0	62.3	37.7	0.00	0.02	0.03	—	–25.35	Glaciolacustrine
52.3699°N, 77.1138°W	1.7	71.8	26.5	0.00	0.01	0.00	—	–25.39	Glaciolacustrine
51.1432°N, 77.5100°W	28.2	55.3	16.4	0.00	0.00	0.03	—	–27.13	Glaciolacustrine
50.5265°N, 77.5372°W	0.0	73.4	26.6	0.00	0.01	0.10	—	–27.42	Glaciolacustrine
Rivière Nastapoka, eastern Hudson Bay									
N.A.	2.5	73.3	24.2	0.04	0.09	0.10	2.64	–27.83	Glaciomarine
N.A.	71.6	23.3	5.1	0.05	0.03	0.05	0.83	–24.46	Glaciomarine
N.A.	34.0	50.8	15.2	0.04	0.05	0.07	1.40	–24.79	Glaciomarine
N.A.	78.8	18.6	2.6	0.03	0.03	0.02	1.25	–25.03	Glaciomarine
N.A.	81.4	16.4	2.2	0.04	0.10	0.00	3.09	–25.49	Glaciomarine

Note: — indicates that C/N ratio not defined because TN (% total nitrogen) value is nil. OC, organic carbon; N.A., not available.

troughs and valleys, where it is not known but exceeds 35 m. Inner Nastapoka Sound contains a typical sediment thickness of 6 m although as much as 70 m of sediments are found in some depressions. Acoustic units are recognized and interpreted on the basis of three prominent disconformities, acoustic attributes, bedding and stratigraphic position. We distinguish and interpret an acoustic basement and four units in the sediments of the study area.

Acoustic basement

Description

A strong basal seismic reflector (Fig. 3) can be traced over most of the area, except in glacial troughs and valleys. This reflector extends to at least 190 m below the present sea level, forming a highly irregular surface with steep relief, characterized by enclosed depressions, valleys, and ridges. In Nastapoka Sound, the reflector depth reaches 240 m in basins. In *Le Goulet* area, the acoustic basement outcrops as seafloor; there are two different types of limited acoustic penetration defined by a smoothed surface and an irregular one. A striking landform in the estuary, located east of *Le Goulet,* is an isolated mound of 335 m length and almost 15 m height, with a chaotic internal reflection configuration (Fig. 4). The mound lies across the seafloor perpendicular to the direction of ice flow and is characterized by an eastern slope steeper than the western one.

Interpretation

This high-amplitude seismic reflector, characterized by a lack of acoustic penetration, is interpreted as the upper surface of the buried acoustic basement, generally corresponding to bedrock. The mound east of *Le Goulet* has a similar acoustic appearance to ridges described by Josenhans et al. (1988) in Hudson Bay, which are interpreted as being moraine ridges.

Unit 1

Description

Unit 1 can be divided into three subunits based on acoustic facies: unit 1a consists of one or two uniform and strong (dark) reflectors showing drape geometry over the underlying acoustic basement. Unit 1b is discontinuous and acoustically transparent. Unit 1c is stratified and shows diverging internal reflectors with drape geometry and a stronger reflector in the upper part (Fig. 3). The complete unit is observed in northern and southwestern sectors of the estuary and in

Fig. 3. Profiles showing character of buried acoustic basement and units 1, 2, and 3. Location of profiles is shown on Fig. 2.

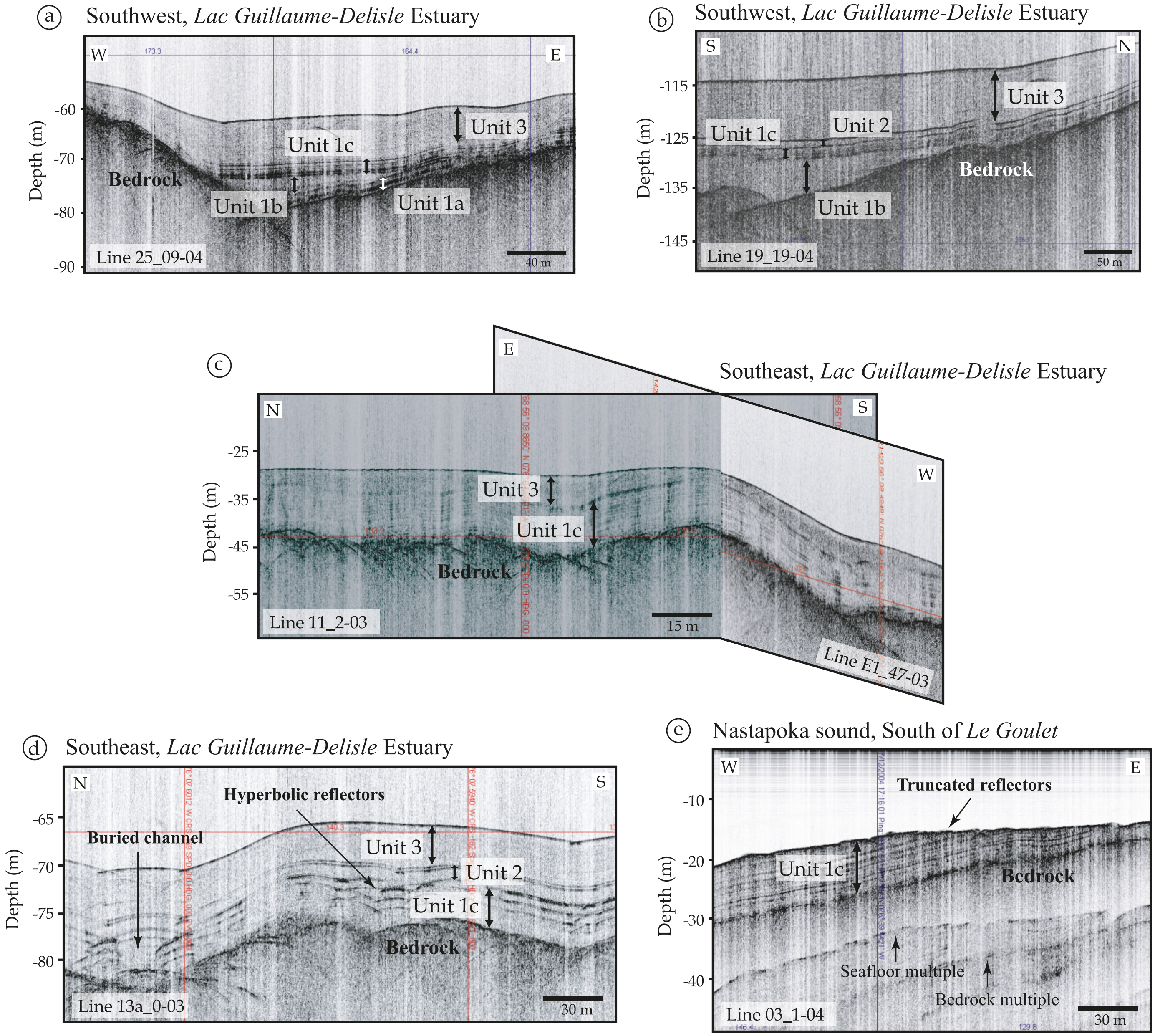
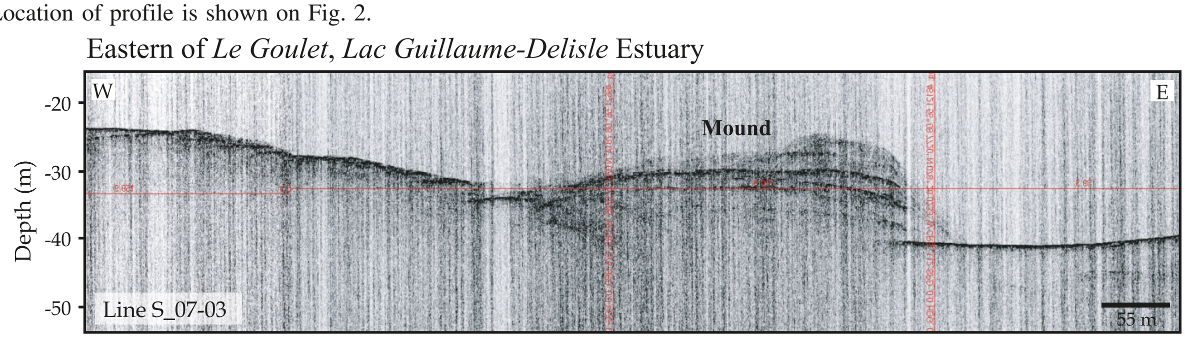


Fig. 4. Profile showing chaotic acoustic character of the acoustic basement surface and the morainic mound on the seafloor close to *Le Goulet*. Location of profile is shown on Fig. 2.



Nastapoka Sound (Fig. 5*a*). Unit 1a lies immediately over the bedrock surface at total depths (water column + above sediments) generally between 70 and 160 m and reaches a maximum thickness of 4 m. Unit 1b varies in thickness, from more than 15 m in Nastapoka Sound to between 2 and 10 m in the estuary. Unit 1c extends throughout the investi-

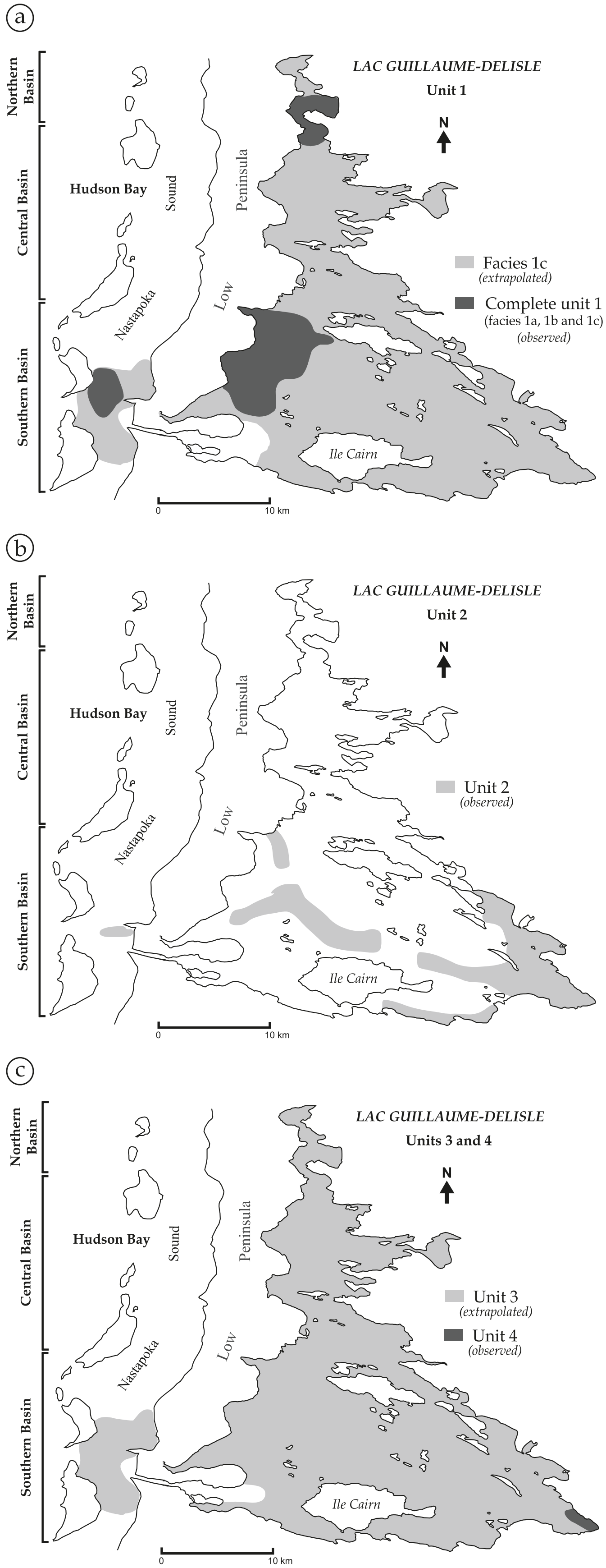


Fig. 5. Mapped extent of the accoustic units in the study area. (*a*) Unit 1, (*b*) unit 2, (*c*) units 3 and 4. See text for description of the units.

gated area and measures about 10–12 m in thickness. It overlies unit 1b, drapes unit 1a when unit 1b is not present, or forms a uniform drape over the bedrock surface where both units 1a and 1b are absent (Fig. 3*c*). Unit 1c has specific characteristics in some parts of the estuary. In the southeast, reflectors are defined by high acoustic contrast with strong hyperbolic reflectors (Fig. 3*d*). East of *Ile Cairn*, in the southern part of the estuary, the upper part of this facies is disrupted (Fig. 6*a*). In some shallow sectors of the Nastapoka Sound and in the estuary, unit 1c shows evidence of truncated reflectors (Fig. 3*e*).

Interpretation

Based on the pronounced stratification, alternately draped and filling character, sediments of unit 1 would have been deposited in an area largely controlled by the topography and by subaquatic glacial depositional processes. The associated acoustic pattern is characteristic of a proximal to ice-distal glaciomarine environment governed by a tidewater glacier (Syvitski 1991). Facies 1c has the acoustic aspect of an ice-distal deposit that was deposited within kilometres of an ice front (Powell 1981; Syvitski 1991). The hummocky acoustic character found in this facies in the estuary is enigmatic. The hyperbolic reflectors are evidence of significant surface roughness and could be interpreted by the presence of small bedforms, deformed sediments caused by slides or debris flows, or development of a lag surface of coarser sediments. As these strong hyperbolic reflectors are observed on four different cross-lines in the estuary, the influence of water depth, horizontal (paper feed rate) and vertical scales, and boat speed are excluded. Damuth and Hayes (1977) observed bedforms with similar hyperbolic echoes on the East Brazilian Margin, but their origin was not directly determined. In this case, it is impossible to identify the genetic nature of these reflectors due to lack of deep and strategically located core samples. The truncated reflectors of Nastapoka Sound and in the estuary imply that the reflector originally extended further but has been eroded by littoral or periglacial processes, such as sea ice erosion (Héquette et al. 1999; Hill et al. 1999).

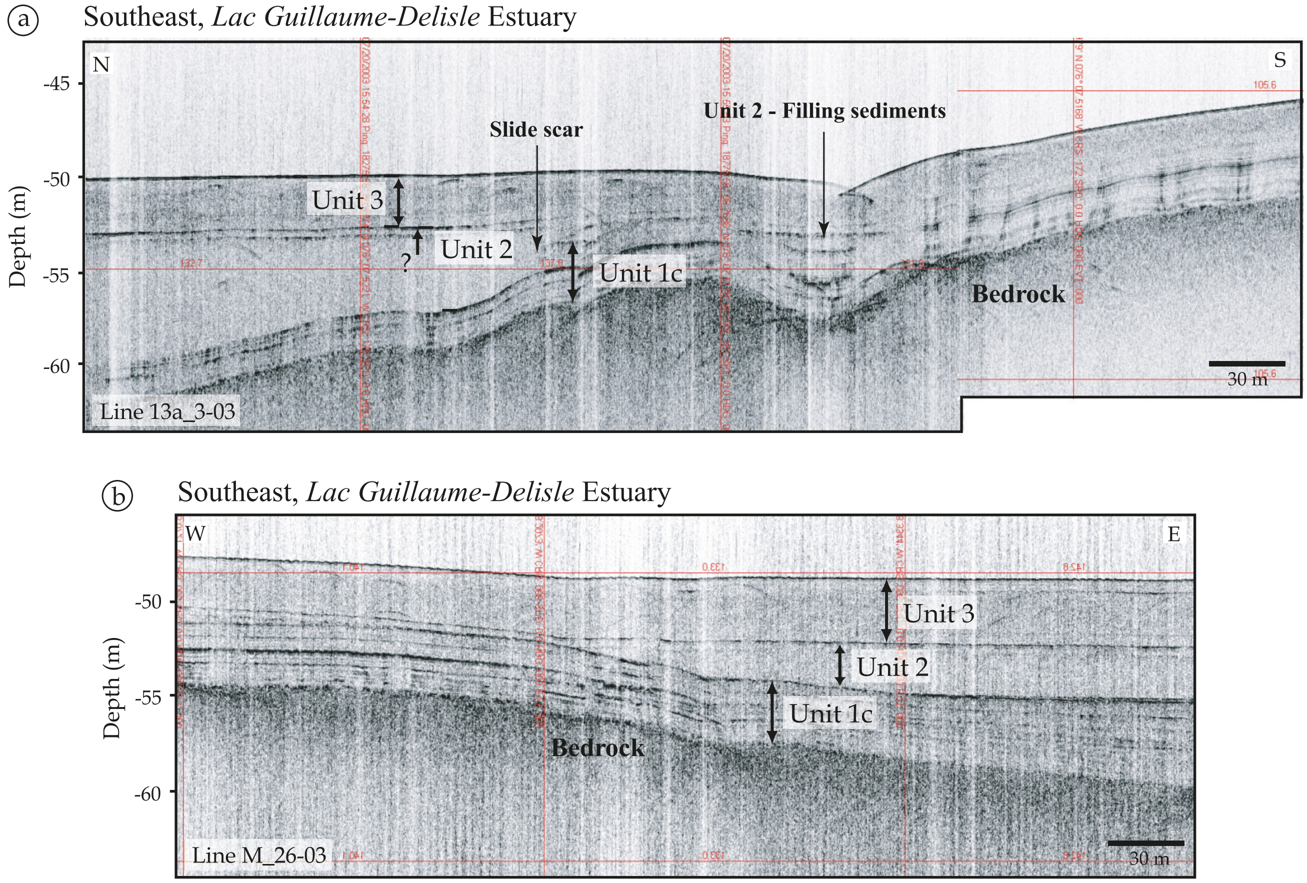
Based also on acoustic similarity and stratigraphic position, unit 1 from the study area may be correlated to the ice-contact and glaciomarine–glaciolacustrine sediments reported in Hudson Bay (Bilodeau et al. 1990; Josenhans et al. 1991), at the mouth of *Grande rivière de la Baleine* (Gonthier et al. 1993), in Manitounuk Sound (Hill et al. 1999) and at the mouth of *rivière Nastapoka* (Lavoie et al. 2002). A similar acoustic facies was also observed in acoustic data offshore of Umiujaq (Fraser 2001).

Unit 2

Description

Unit 2 consists of two or more transparent beds that fill depressions and onlap underlying deposits of unit 1 (Fig. 6). The top of each bed is defined by a relatively strong reflector; reflectors form a thin condensed section where the

Fig. 6. Profiles showing acoustic character of buried acoustic basement and units 1c, 2, and 3. Location of profiles is shown on Fig. 2.



underlying surface is sloping. The thickness of unit 2 ranges from 2 to >12 m, the latter in depressions (generally in glacial valleys) where the basal reflector is not visible due to a lack of penetration (Fig. 7*a*, 7*c*). Unit 2 is found near the mouths of *rivière à l'Eau-Claire* and *rivière de Troyes* and extends toward Nastapoka Sound in the main subaqueous valley (Fig. 5*b*). This valley averages 1.3 km in width and 60 m depth, with troughs reaching 150 m deep. In Nastapoka Sound, this unit is observed also in submarine troughs and reaches up to 30 m in thickness.

Interpretation

The basin-fill character of this unit indicates a sedimentation process different than for unit 1. Unit 2 has a typical rapid basin-fill reflector configuration, as described by Syvitski (1991), that is interpreted as a paraglacial fluvio-deltaic accumulation, formed by the reworking and resedimentation of emerged glacigenic and terrestrial fluvio-glacial sediments. Relatively high sediment supply was associated with the rapid initial fall in RSL because of progressive cannibalization of emerged sediments as the fluvial base level was lowered.

Unit 2 has only one equivalent in the other study sites on the east coast of Hudson Bay. It is correlated to seismo-stratigraphic unit 2 in depressions of Manitounuk Sound, interpreted as a rapid basin-filling deposit that occurred in the transition from glaciomarine to modern conditions (Hill et al. 1999). No equivalent unit was observed at the mouths of *rivière Nastapoka*, Umiujaq, and *Grande rivière de la Baleine*, and no lithostratigaphic data from cores are available to confirm its origin.

Unit 3

Description

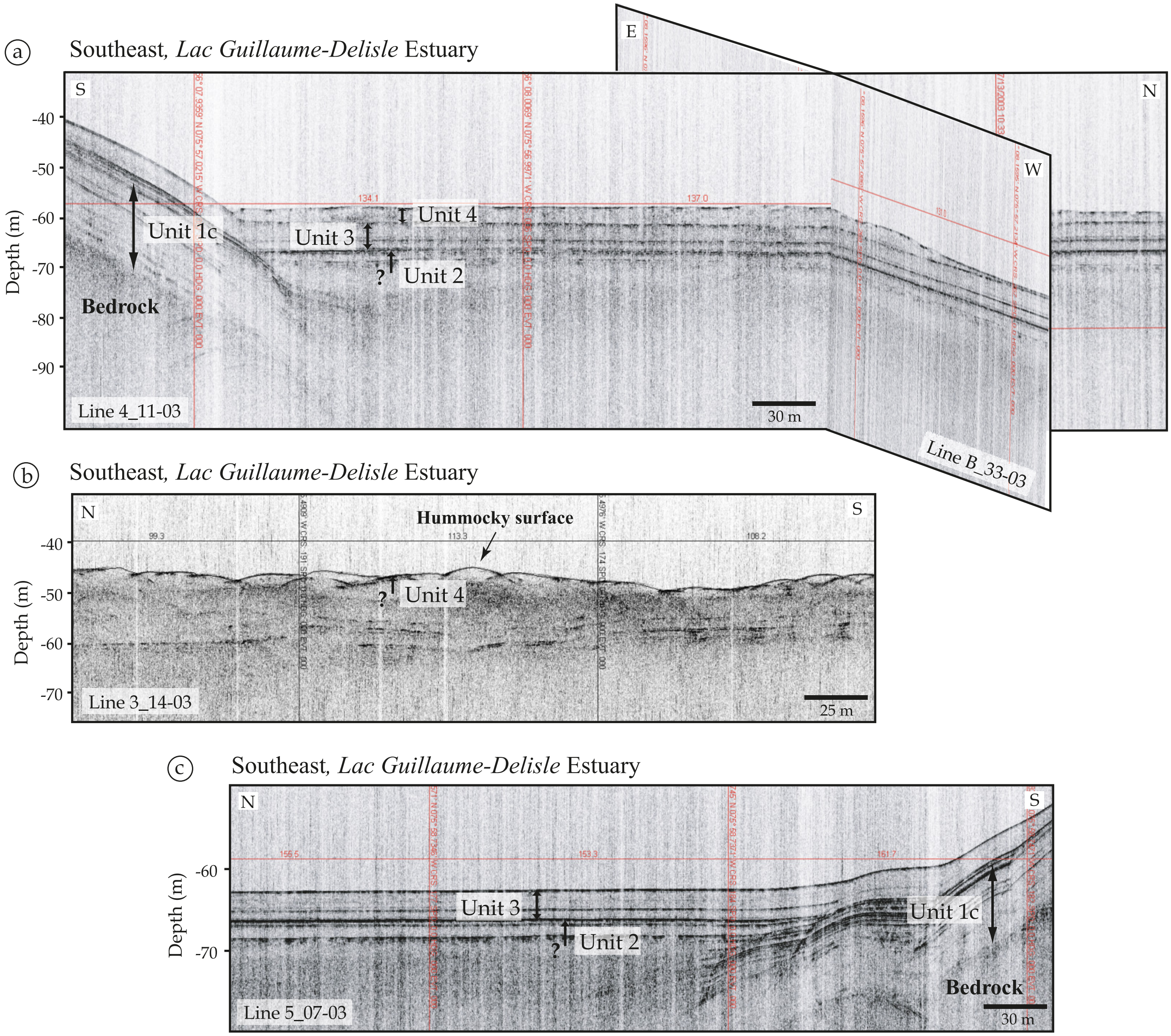
Unit 3 is typically the uppermost unit in *Lac Guillaume-Delisle* Estuary and Nastapoka Sound. It shows a transparent to poorly stratified acoustic signature showing a divergent-fill relationship with the underlying surface (Figs. 3, 6, 7*a*, 7*c*). Unit 3 has an average thickness of 4–7 m and is characterized by an insufficient acoustic contrast to generate strong reflectors, except for small and abundant internal hyperbolic reflectors.

Interpretation

Unit 3 represents postglacial hemipelagic estuarine sediments deposited from suspension under a low-energy sedimentary regime. While deposited under continuous falling RSL, there was no glacial influence after the final ablation of the QLIS. Many profiles show small and abundant internal hyperbolic reflectors that may be caused by erosional furrows, sediments waves, or ice-rafted material (Jakobsson 1999; Damuth 1980).

Unit 3 has a wide regional extent and a good continuity, which easily permited correlation to other studies (Fig. 5*c*). The internal reflection configuration of seismo-stratigraphic unit 3 is similar to the acoustic signature of postglacial acoustic units in eastern Hudson Bay (Bilodeau et al. 1990;

Fig. 7. Profiles showing acoustic character of units 1c, 2, 3, and 4. Location of profiles is shown on Fig. 2.



Josenhans et al. 1991; Gonthier et al. 1993; Hill et al. 1999; Fraser 2001; Lavoie et al. 2002).

Unit 4

Description

This acoustic unit consists of distinctly incoherent and chaotic reflections of about 1–2 m thickness (Figs. 7*a*, 7*b*). This facies is locally observed in the eastern part of the estuary (Fig. 5*c*).

Interpretation

Unit 4 is a localized postglacial deposit associated with a recent landslide event. This may have originated on land as the deposit is located close to the estuary shore and the nearshore slope is quite gentle.

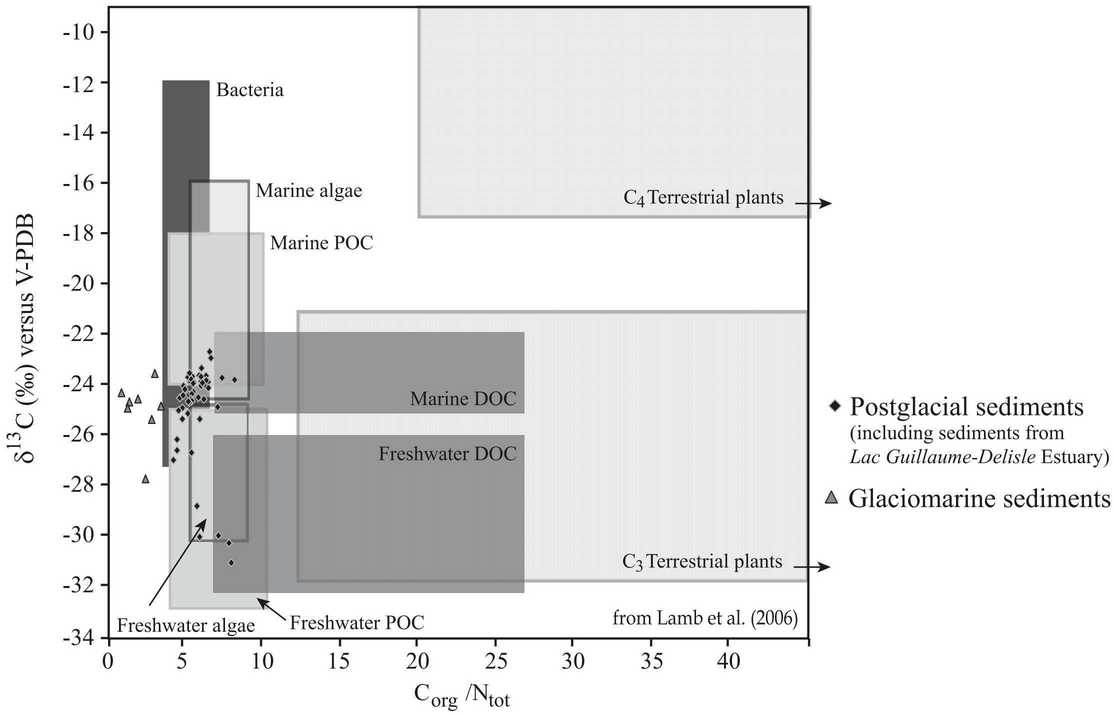
Lithology and geochemical and isotopic composition

Lac Guillaume-Delisle sediments

In general, the sampled sediments in *Lac Guillaume-Delisle* Estuary are visually similar. They are characterized by homogeneous compact grey silts without shell fragments. No recognizable stratification is visible in the cores and only some minimal bioturbation is present. They contain fine to medium silt (mean between 14.97 and 4.59 μm) and their grain-size distributions are unimodal, symmetric and very poorly to poorly sorted (σ = between 5.27 and 2.77 μm). The distribution is platykurtic (flat).

Fossil diatoms were rare in sediments of *Lac Guillaume-Delisle*. Therefore, it was decided to use TN, carbon (OC and $CaCO_3$), and C/N along with $\delta^{13}C$ contents as paleo-

Fig. 8. $\delta^{13}C$ and weight ratio of C/N ranges for organic inputs to *Lac Guillaume-Delisle* Estuary in comparison with typical data in coastal environments compiled by Lamb et al. (2006). POC, particulate organic carbon; DOC, dissolved organic carbon; V-PDB, Vienna Pee Dee Belemnite standard.



environmental indicators (Table 1). TN and OC values in all cores are very low being < 0.1% and < 1%, respectively, and changes very little. In general, values are lower at the base of the cores and increase slightly toward the top, except for cores 04-4 and 04-5 (inverse pattern). All sediments have low $CaCO_3$ concentrations (<1%). C/N atomic ratios vary between 4.71 and 9.29. $\delta^{13}C$ values range from –31.12‰ to –23.06‰ (Table 1).

Glaciolacustrine, glaciomarine, and postglacial sediments

Emerged glaciolacustrine sediments from James Bay are composed of fine to medium silt (Table 2). Their distributions are very poorly to poorly sorted (σ = between 8.72 and 2.66 μm) and are unimodal, symmetric, and platykurtic. TN and OC values in these sediments are either nil or extremely low (<0.03%). These sediments have low $CaCO_3$ concentrations (<0.1%), where their $\delta^{13}C$ values vary between –27.42 and –25.06 ‰ (Table 2). Because the values of TN are nil, C/N atomic ratios cannot be calculated.

In general, emerged glaciomarine sediments from *rivière Nastapoka* (Hudson Bay) are composed of very find sand to fine silt, and those from James Bay are defined by fine to medium silt (Table 2) with distributions similar to glaciolacustrine sediments. Glaciomarine sediments have TN values < 0.07% and OC values between 0.03% and 0.22%. $CaCO_3$ contents are very low in sediments from *rivière Nastapoka* (mean 0.05%) and higher in sediments from James Bay (between 3.03% and 10.19%). C/N atomic ratios vary between 0.83 and 3.75. $\delta^{13}C$ varies between –27.83‰ and –23.70‰.

Four postglacial marine sediment samples were also analysed. These sediments from James Bay (on land) and Hudson Bay (offshore) are composed of fine silt (Table 2). TN and OC values are low, <0.1% and <1%, respectively. $CaCO_3$ contents vary between 2.54% and 9.54%. C/N atomic ratios are similar to those in *Lac Guillaume-Delisle* estuarine sediments (mean 6.24), and $\delta^{13}C$ values vary between –26.70‰ and –23.65‰.

Interpretation

Conservation of organic matter in sediments is not always uniform. There is the potential for alteration of carbon as a result of decompositional process during transport, settling, and diagenesis (which can also modify carbon isotope compositions depending on oxygen availability) (e.g., Thornton and McManus 1994; Meyers 1994, 1997; Muzuka and Hillaire-Marcel 1999; Lamb et al. 2006). However, on the other hand, as the grain size of studied sediments is comparable, the vertical distribution of C/N atomic ratios is likely to be uniform (Gearing et al. 1977; Thompson and Eglinton 1978; Keil et al. 1994; Meyers 1997). In this study, geochemical and isotopic analyses are used to provide information about the origin of organic material preserved in different coastal environments. The local variations in *Lac Guillaume-Delisle* Estuary cores are not discussed.

The results indicate that sediments in all our cores are postglacial–estuarine deposits with no glacial influence. C/N atomic ratios show an average value of 6.5 that likely originates from a mixture of marine and lacustrine algae, which typically range between 4 and 10 (Meyers 1997). C/N atomic ratios from postglacial sediments in Hudson Bay and emerged sediments in the James Bay region are similar to those in *Lac Guillaume-Delsile* Estuary. In comparison, C/N ratios are lower in glaciomarine sediments (average value of 2.3), and known glaciolacustrine sediments contain no measurable nitrogen (Table 2).

δ^{13}C values in *Lac Guillaume-Delsile* estuarine sediments (between –31.12‰ and –23.06‰) fall across the isotopic composition ranges of C_3 terrestrial plants (Calvin photosynthetic pathway) and marine phytoplankton production (Kelly et al. 2005). Therefore, δ^{13}C results alone do not show a good discrimination between depositional environments. A similar conclusion was reached in sediments from the Saguenay Fjord by St-Onge and Hillaire-Marcel (2001).

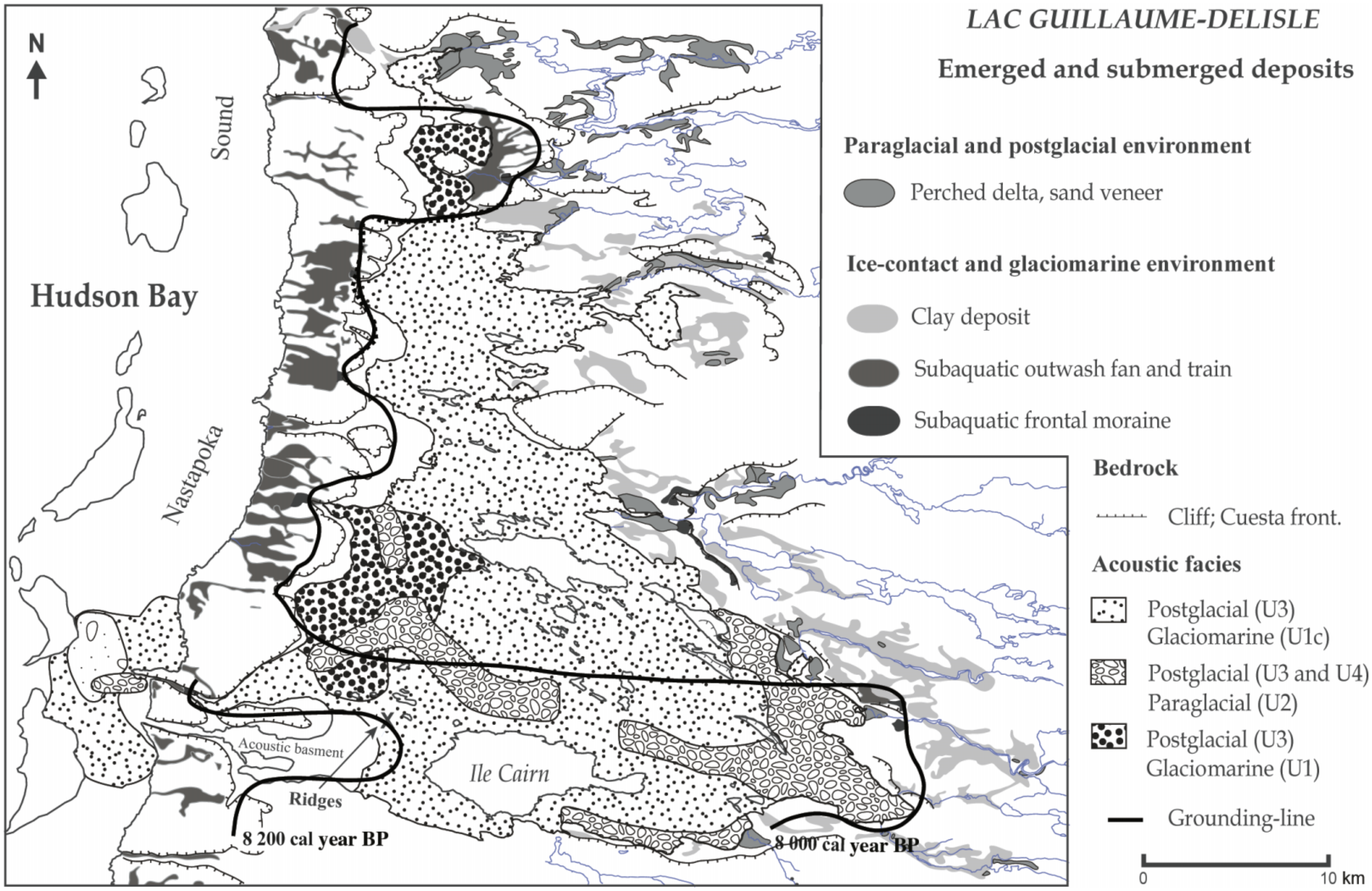
However, when viewed together, the δ^{13}C and C/N values provide a clear distinction between postglacial and glaciomarine depositional environments (Fig. 8) and indicate that the discriminatory element is the TN content. Weight atomic ratio C/N values alongside δ^{13}C measurements in the estuary were compared with typical data in coastal environments compiled by Lamb et al. (2006). The graph shows that our estuarine postglacial sediments probably received organic material from both autochthonous and allochthonous sources, most of it being derived from marine algae and particulate organic carbon (POC, suspended organic matter such as phytoplankton). Glaciomarine sediments are situated in a blank zone, i.e., without reference data. We assume that these results indicate an unvegetated surrounding landscape under a glacial influence and (or) possible diagenetic effects. During deglaciation of the eastern coast of Hudson Bay, the relative contribution of terrestrial carbon increased steadily as soils and forests developed (Miltner et al. 2005). Additionally, neither plots of OC or $CaCO_3$ against δ^{13}C permit discrimination between sediments from different depositional environments. Higher values of $CaCO_3$ in glaciomarine sediments from James Bay, as compared with Hudson Bay (see Table 2), originate from the presence of known Paleozoic limestone in that region.

Discussion

The late Quaternary deposits in *Lac Guillaume-Delisle* Estuary and Nastapoka Sound provide a continuous and well-preserved record of deglaciation of the region. The variable thickness of units identified in the study area was likely controlled by a combination of the glacial dynamics, antecedent topography, sediment supply, and forced regression (a regression brought by RSL fall, in this case in consequence of the glacio-isostatic rebound, rather than an excess of sediment supply over accommodation space; Posamentier et al. 1992). In general, sediments are thicker in the study area than in the Hudson Bay basin because of the increasingly enclosed nature of basins, which limited the offshore dispersal of sediments during the forced regression. It appears that pre-existing sediments from the last interglacial cycle in the study area are completely eroded and the deposition of the glaciomarine sediments started directly at the time of the deglaciation. Although *Lac Guillaume-Delisle* Estuary is the largest coastal proglacial basin in Quebec that contains relatively thick late Quaternary deposits in its depressions, the sequence is much thinner than in other basins with a similar context, such as Lake Melville in Labrador (average thickness of 66 m and > 400 m in Grand Trough; Syvitski and Lee 1997). The lower sediment volume indicates that *Lac Guillaume-Delisle* Estuary was not the site of a concentrated ice stream or valley glacier with high local sediment supply, but rather formed a section of a broad retreating ice front.

The well-preserved late Quaternary seismo-stratigraphic units in the study area can be correlated with the extensive and well-described deposits now exposed on land and their associated geomorphologic features (Fig. 9). Unit 1 is interpreted to have been deposited at the western margin of the QLIS at the time the glacier was retreating and was in contact with the Tyrrell Sea waters between ca. 8200 and ca. 7700 cal BP. As no erosional surfaces were observed between the three subunits of unit 1, the transitions between them were rapid and sedimentation continuous. Acoustic facies 1a and 1b record the highly energetic sedimentation dynamics near the maximum elevation of RSL and by various processes, such as glaciofluvial meltwater discharge and glacial and submarine gravity flows. By comparison with modern acoustic analogues in Powell (1981), it seems that these sediments were deposited within a few hundred metres of the QLIS termini. These facies are related to different stillstands of the glacier front on Low peninsula and on the eastern side of *Lac Guillaume-Delisle* Estuary (Fig. 9). The equivalent emerged sediments on eastern Hudson Bay are the ice-proximal glaciomarine deposits described by Lajeunesse and Allard (2003*a*) as subaqueous outwash fans and trains of stratified sand and silt defined by shell-rich layers with interbedded diamictons. In the study area, these emerged deposits are also located in front of ice-margin stillstand positions (Lavoie 2006). The underwater continuity of the emerged ice-proximal glaciomarine sediments is possible to see on many acoustic profiles. The acoustically well-stratified facies 1c was probably deposited from the buoyant meltwater plume and associated iceberg melting that would have occurred during the landward retreat of the QLIS margin, several kilometres from upland ice termini. Comparable sediments on land are composed of sand–silt layers (mud) that sporadically contain IRD and are interpreted to be deposited mainly by suspension settling through the water column (Lajeunesse and Allard 2002, 2003*a*; Lavoie 2006). Icebergs were probably the main mechanism by which coarse-grained sediments were transported offshore at the front of the QLIS. Because of the suspension deposition, these sediments were draped over older sediments with a conformable stratigraphic contact. Acoustic facies 1c is generally thinner than the equivalent emerged deposits, possibly because the emerged deposits were formed in more topographically constrained valleys. Bilodeau et al. (1990), Gonthier et al. (1993) and Hill et al. (1999) who analyzed offshore cores from their respective study areas, showed that subunit 1c is characterized by weakly stratified and poorly sorted gravelly mud with sand followed by rhythmically bedded clay and silty clay usually with little sand and gravel. Some of these deposits were interpreted as glaciolacustrine sediments from glacial Lake Ojibway on the basis that they are laminated and contain sparse to no marine microfauna and microflora. However, the glaciolacustrine origin of this facies is doubtful. The percentages of sulphur recorded in this deposit by Gonthier et al. (1993) are not characteristic of a lacustrine environment. Lajeunesse and

Fig. 9. Compilation map of emerged and submerged late- and postglacial deposits in the study area. Interpreted ice frontal positions at 8.2 cal. ka and 8.0 cal. ka from Lavoie (2006) are also shown. U, unit.



Allard (2003*a*) identified similar laminated silt exposed at *rivière Nastapoka* and unambiguously identified them as ice-distal glaciomarine deposits on the basis that marine shells were found in them. Laminated deposits observed on the east coast of James Bay are also identified as glaciomarine sediments. In summary, the evidence for glaciolacustrine deposits in the area seems to be weak. It is effectively impossible to distinguish glaciolacustrine and glaciomarine in acoustic records, so the northern extension of glacial Lake Ojibway beyond Kuujjuarapik-Whapmagoostui and *rivière Domachin* (Manitounuk Sound) remains unproven.

Overall, acoustic unit 1 and the presence of a ridge that has the acoustic appearance of a moraine document the deglaciation of *Le Goulet* that was previously interpreted only on the basis of marine limit elevations. Once detached from the coastal cuesta relief, the eastward retreat of the margin of the QLIS was probably rapid. Two sites along the Gulf of Alaska, the margins of the Bering Glacier (Lake Vitus), and La Perouse Glacier (Lingle et al. 1993) provide modern analogues for *Lac Guillaume-Delisle* during its deglaciation.

As the ice thinned and retreated inland simultaneously with the fall of RSL and the loss of contact between the glacier and the sea, glaciofluvial systems developed. At this time, paraglacial fluvio-deltaic deposits of unit 2 accumulated exclusively at the mouth of valleys when RSL was at ca. 125–120 m a.s.l. between ca. 6700 and ca. 6300 cal BP (Lavoie 2006). As the glacio-isostatic rebound gradually exposed substantial amounts of unlithified sediments to remobilization by coastal processes, these eroded sediments were redeposited near the mouths of most important rivers and along associated subaqueous valleys (Fig. 9). On land, these deposits are characterized by thick interbedded and interlaminated, coarsening-upward sand and gravel layers (Lavoie 2006).

Finally, the hemipelagic postglacial–estuarine sediments of unit 3 represent a low-energy sedimentary regime governed by nonglacial processes. They mark the period of contemporary marine sedimentation. The geochemical and isotopic results and interpretation above show that the sediments sampled in the estuary are of postglacial origin (unit 3) despite the fact that the intended acoustic targets were thought to be glaciomarine deposits. Given the difficult working conditions encountered during both marine operations and the winter sampling (blizzard conditions), it seems probable that positioning errors were to blame rather than misinterpretation. The exposed glaciomarine areas were small enough to be within the cumulative positioning errors between the acoustic and coring programs. Finally, despite the relatively low numbers of samples analyzed here, the geochemical and isotopic composition methods provide a potential tool to be used as an environmental indicator and may be useful for distinguishing the origin of similar sedimentary silty-clay deposits in future studies on the east coast of Hudson and James bays.

Conclusions

The dynamics of the retreat of the QLIS margin on the eastern coast of Hudson Bay was controlled by the pre-existing topography and exerted a major influence on the processes and patterns of late Quaternary sedimentation in marine basins. Four acoustic units were identified in *Lac Guillaume-Delisle* Estuary and Nastapoka Sound and are interpreted as ice-contact and glaciomarine (unit 1), paraglacial and postglacial (unit 2), and postglacial (units 3 and 4) units. This study suggests that the *Lac Guillaume-Delisle* Estuary contains a complete record of late Quaternary deglaciation on the east coast of Hudson Bay. Additionally, C/N atomic ratios in *Lac Guillaume-Delisle* sediments show a predominance of carbon from a mixture of marine and lacustrine algae sources indicating a postglacial origin (C/N atomic ratios vary between 4.71 and 9.29, and $\delta^{13}C$ values range from –31.12‰ and –23.06‰). Geochemical analysis enabled the identification of TN content as the most effective marker to differentiate between two types of waterlaid late-glacial sediments, namely glaciolacustrine and glaciomarine sediments.

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