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ARTICLE

Sedimentation in isolated glaciomarine embayments during glacio-isostatically induced relative sea level fall (northern Champlain Sea basin)

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Abstract: The nature of glaciomarine sediments deposited during ice margin retreat can vary according to physiographic setting and relative sea level fluctuations. To understand the effects of these two parameters on sedimentation, we analyzed the sediment records of four lakes located within former isolated glaciomarine embayments of the northern Champlain Sea basin. These lakes were initially inundated by marine water of the Champlain Sea, following deglaciation, and have subsequently experienced basin isolation owing to glacio-isostatic rebound. Three of these lakes reveal a common litho- and acoustic stratigraphic succession, characterized by an IRD-free glaciomarine to marine facies consisting of homogeneous to faintly laminated clayey silts grading into well-laminated silts with rapidly deposited layers. These two units recorded the transitional environment from glaciomarine sedimentation below multiyear shorefast ice to increased terrestrial runoff and rapid glacio-isostatic rebound once the ice margin retreated inland. During ice margin retreat, relative sea level fell concomitantly resulting in the deposition of coarser sediments in marine embayments. Upon the complete retreat of the ice margin, the supply of terrestrial sediments diminished and lake isolation, driven by relative sea level fall, led to higher biogenic content and increased bioturbation. This study provides a framework for sedimentation in isolated glaciomarine embayments which differs from deep-water sedimentation owing to the presence of shorefast sea-ice and their protected location from major ice-stream outlets.

Résumé : La nature des sédiments glaciomarins déposés durant le retrait des marges glaciaires peut varier selon le contexte physiographique et les fluctuations du niveau marin relatif. Afin de comprendre les effets de ces deux paramètres sur la sédimentation, nous avons analysé les sédiments de quatre lacs situés dans d'anciennes baies glaciomarines isolées de la partie nord de la mer de Champlain. Ces lacs étaient initialement inondés par de l'eau marine de la mer de Champlain, après la déglaciation, pour ensuite former des bassins isolés en raison du soulèvement glacio-isostatique. Trois de ces lacs révèlent une séquence lithostratigraphique et acoustique commune caractérisée par un faciès glaciomarin à marin sans débris glaciels consistant en des silts argileux homogènes à finement laminés passant progressivement à des silts bien laminés avec des couches déposées rapidement. Ces deux unités témoignent d'un milieu de transition entre une sédimentation glaciomarine sous de la glace de rive pluriannuelle à un ruissellement terrestre accru et un soulèvement glacio-isostatique rapide après que la marge glaciaire se soit retirée vers l'intérieur des terres. Durant le retrait de la marge glaciaire, le niveau marin relatif a baissé, entraînant le dépôt de sédiments plus grossiers dans des baies marines. Une fois le retrait de la marge glaciaire terminé, l'apport de sédiments terrestres a diminué et l'isolement des lacs, causé par la baisse du niveau marin relatif, s'est traduit par une teneur en matières biogéniques plus importante et plus de bioturbation. L'étude fournit un cadre pour la sédimentation dans des baies glaciomarines isolées qui se distingue de la sédimentation en eau profonde en raison de la présence de glace de rive marine et de leur emplacement protégé d'importants exutoires de coulées de glace. [Traduit par la Rédaction]

Introduction

Lake basins in formerly glaciated terrains can provide a continuous and high-resolution record of both abrupt events and gradual changes in sedimentation (Hodder et al. 2006) that can be used to reconstruct paleo-climates (e.g., Gajewski et al. 1997; Besonen et al. 2008), paleoseismicity (e.g., Doughty et al. 2014; Brooks 2016; Lajeunesse et al. 2017), and paleo-environments (Dix and Duck 2000; Chapron et al. 2007) from deglacial to modern times. Additionally, lake sediments are sometimes used to document environmental changes related to past sea level transgressions and (or) regressions (e.g., Snyder et al. 1997; Zwartz et al. 1998; Hutchinson et al. 2004; Nutz et al. 2013; Narancic et al. 2016). During regressions, topographic basins originally located below sea level can be isolated from marine water and record a transition towards a limnic environment.

The typical sedimentary succession observed in recently deglaciated marine basins consists of, from bottom to top, (*i*) ice-contact diamicton, followed by (*ii*) laminated mud and sand with ice-rafted debris (IRD), grading upwards into (*iii*) massive bioturbated muds (Syvitski 1993; Syvitski and Praeg 1989; Andrews et al. 1991; Josenhans and Lehman 1999; St-Onge et al. 2008; Duchesne et al. 2010). This succession, which is attributed to glaciomarine settings, is viewed as a transition from ice-proximal to ice-distal depositional environments. It mainly reflects a decrease in transport

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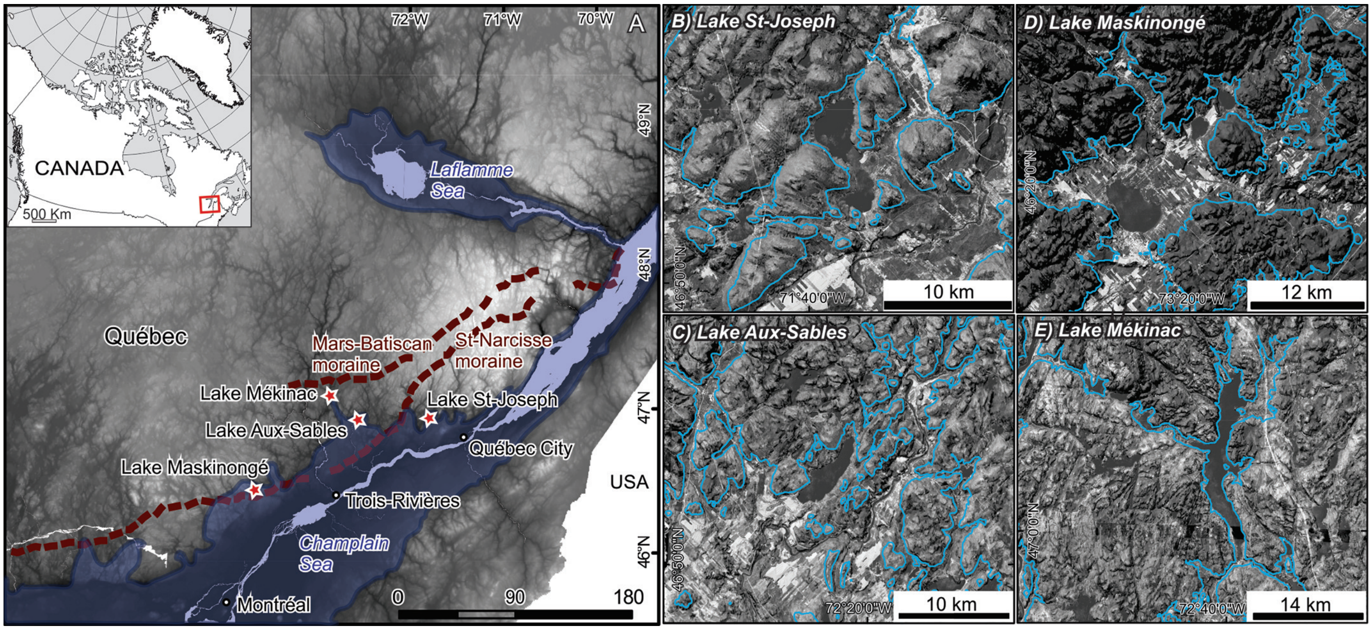
Fig. 1. (A) Location of the studied lakes in relation to the Champlain Sea limit and the Younger Dryas moraines. Red stars represent the study lakes while dashed red lines represent major morainic systems related to the Younger Dryas (YD) episode. (B–E) Approximate marine limit of the Champlain Sea around lakes (B) St-Joseph, (C) Aux-Sables, (D) Mékinac, and (E) Maskinongé. [Colour online.]



capacity and sedimentation rates as well as an increase in bioturbation resulting from an increase of macrofauna (benthos) as the ice margin retreats from the region (Ó Cofaigh and Dowdeswell 2001). However, this typical succession reflects sedimentation at ice-stream outlets and in deep-water environments of glacial seas or fjords and do not necessarily reflect glaciomarine sedimentation in isolated bays of the nearshore environment. The latter is yet to be properly described.

Recent studies by Normandeau et al. (2013) and Nutz et al. (2013) were conducted on the acoustic stratigraphy of lakes of southern Québec located below marine limit, i.e, below the highest preserved shoreline from the Late Pleistocene transgression. These studies reconstructed the impact of deglaciation on the nature and pattern of sedimentation during a transition from a marine to a lacustrine environment. During the retreat of the Laurentide Ice Sheet (LIS), vast regions of northeastern America were inundated by large proglacial lakes (e.g., Agassiz-Ojibway, Vermont) and seas (e.g., Laflamme, Champlain, Goldthwait). These glacially influenced lakes and seas acted as sediment traps and now contain archives of past environmental change. The Laflamme and Goldthwait seas remained large bodies of water throughout the Holocene (Lake Saint-Jean and the St. Lawrence Estuary, respectively) that are easily studied using conventional hydroacoustic techniques (Syvitski and Praeg 1989; Praeg et al. 1992; Josenhans and Lehman 1999; St-Onge et al. 2008; Duchesne et al. 2010; Nutz et al. 2013). Conversely, the Champlain Sea retreated from the region and was replaced by the St. Lawrence River hydrographic system, which altered its sedimentary record. Nevertheless, small lakes on its northern margin remained mostly unaltered by Holocene erosion and geomorphic processes, allowing them to hold a complete and continuous sedimentary record of the evolution from the Champlain Sea during deglaciation to the establishment of modern lakes. They thus yield unaffected records of a marine to lacustrine deglacial succession deposited during glacio-isostatic rebound. In this respect, they hold a continuous record of glaciomarine to lacustrine sedimentation in isolated bays.

In this study, we report on the geomorphology, stratigraphy, and sedimentary infill of four lakes (Maskinongé, Mékinac, Aux-Sables, and St-Joseph) located below marine limit in the northern sector of the Champlain Sea basin to document the sedimentary succession and architecture of isolated glaciomarine embayments as well as the transition from a deglacial to a postglacial sequence during a forced regression. The main objectives of this study are to (*i*) examine the spatial distribution of sedimentation in lakes located along the northern St. Lawrence River Valley between Québec City and Montréal, (*ii*) infer environmental conditions that led to the deposition of contrasting sedimentary units, and (*iii*) provide a conceptual framework for the deposition of sediments in isolated glaciomarine embayments that are progressively isolated by relative sea level (RSL) fall to become lakes.

Table 1. Characteristics of the four studied lakes.

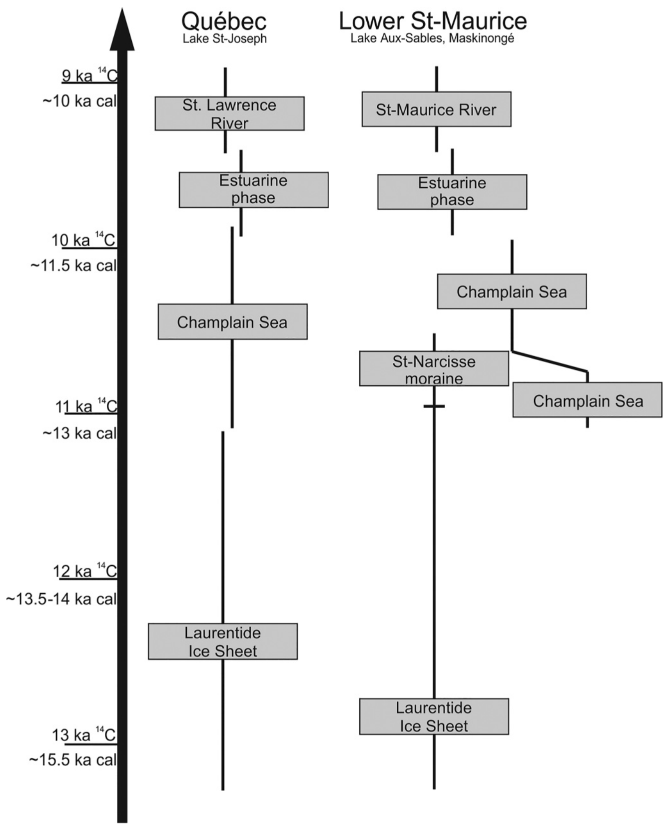
Lake	Maximum depth (m)	Surface area (km^2)	Elevation (m)
Maskinongé	36	10.2	140
Mékinac	145	23	165
Aux-Sables	42	5.2	150
St-Joseph	36	11.3	160

Regional setting

Location of lakes

The studied lakes are located along the southern limit of the Laurentian Highlands (Fig. 1) near the northern limit of the former Champlain Sea basin (marine limit ≤250 m above sea level (asl)). Lake Maskinongé is the southernmost lake of the study area (46.32°N, 73.39°W) and is located 60 km west of Trois-Rivières at 140 m asl (Table 1). Lake Mékinac is the northernmost lake (47.05°N, 72.68°W) and is located at the limit of the Champlain Sea basin, at an elevation of 165 m (Table 1). Lake Aux-Sables is located between Québec City and Trois-Rivières (46.88°N, 72.37°W) at 150 m asl, while the easternmost Lake St-Joseph (46.92°N, 71.64°W) is located 30 km northwest of Québec City at 160 m asl (Table 1). The lakes are considered as gravity-driven water bodies because their morphology is dominated by mass movement deposits instead of aeolian or deltaic landforms (Nutz et al. 2017). Neverthe-

Fig. 2. History of deglaciation and Champlain Sea inundation in Québec and the lower St-Maurice (Trois-Rivières area) (modified from Parent and Occhietti 1988). Ages are from Richard and Occhietti (2005) and Occhietti et al. (2001). The St-Narcisse moraine was not in contact with the Champlain Sea near Québec City while it was in the lower St-Maurice region.



less, their sedimentary infill provides valuable insights into the deglacial dynamics of southern Québec.

Deglacial history

The epicontinental Champlain Sea is of glacio-isostatic origin and lasted from 13 to 10.6 ka cal BP (Richard and Occhietti 2005). It extended over the entire St. Lawrence River Valley, from Québec City to the Lake Champlain Valley and west to the Ottawa Valley (Cronin 1977; Gadd 1988) (Fig. 1), although it never covered the entire basin simultaneously (Elson 1969). Indeed, while the marine limit along the southern shore of the Champlain Sea was occupied almost instantly at the onset, the northern limit was reached later and is widely diachronic (Parent and Occhietti 1988). The diachronic aspect of the northern marine limit is due to a standstill of the LIS margin after a rapid retreat across the St. Lawrence River Lowlands and to variations in RSL owing to glacio-isostatic rebound rates of ca. 12 cm/yr during land emergence (Hillaire-Marcel and Occhietti 1980).

Prior to the invasion of the Champlain Sea, the St-Maurice lobe likely blocked glacial Lake Candona that originated from the coalescence of glacial lakes Iroquois and Vermont (Occhietti and Richard 2003) (Fig. 2). When this lobe retreated north-west, glacial Lake Candona drained into the Goldthwait Sea and marine water invaded the St. Lawrence valley at ca. 13 ka cal BP (Richard and Occhietti 2005; Cronin et al. 2008). During the Younger Dryas (YD) cold episode (12.9–11.4 ka cal BP; Parent and Occhietti 1988; Occhietti 2007) the LIS margin was in contact with the Champlain Sea along most of the northern basin and deposited the St-Narcisse morainic complex, except near Québec City where it was located ≥50 km inland (Fig. 1) (Lasalle and Elson 1975; Occhietti 2007). Surficial waters of the Champlain Sea were brackish at that time while the deeper waters were more saline, except near the ice margin, according to isotopic composition of sediments (Hillaire-Marcel 1981). With time, the sea became fresher owing to the input of glacial meltwater. The retreat of the LIS margin from the St-Narcisse moraine then led to the invasion of the river valleys and to subsequent regression over the entire basin. In the Québec City region, the Champlain Sea retreated from the Lake St-Joseph sector at ca. 11–10.5 ka cal BP (Lamarche 2011).

According to Parent and Occhietti (1988), the Champlain Sea inundation/regression deposited (*i*) glacial diamictons, (*ii*) glaciomarine sediments, and (*iii*) marine sediments (Fig. 2). Glacial sediments consist mainly of till, whereas glaciomarine sediments consist primarily of proximal outwash fans and clayey diamictons. Glaciomarine sediments also consist of massive to laminated clays, silts, and sands and were deposited by suspension settling of glacial meltwater plumes. Marine sediments consist of stratified sands and gravels related to littoral sands, alluvial fans and bars (Prichonet 1988). Some coastal and estuarine regions consist of sediments deposited in brackish waters (Parent and Occhietti 1988).

Data and methods

High-resolution bathymetric maps of lakes Maskinongé, Mékinac, Aux-Sables, and St-Joseph were produced from hydroacoustic surveys using a GeoAcoustics Geoswath Plus compact (250 kHz) swath sonar deployed on a 4.5 m inflated boat and a Reson Seabat 8101 on board R/V Louis-Edmond Hamelin. The Geoswath system was coupled with a SMC motion sensor and a Hemisphere V101 DGPS (~60 cm precision), while the Reson system was coupled with a IXSea Octans III motion sensor and the same Hemisphere V101 DGPS. GS+® and Hypack® softwares were used for navigation and data acquisition. Sub-bottom data were acquired using a Knudsen 3212 echosounder operating at a frequency of 3.5 and 12 kHz, also deployed alternately on the inflated boat. This coverage allowed a detailed analysis of the geometry, extent, and distribution of the acoustic units present in the lakes (Fig. 3). The sub-bottom data were interpreted using The Kingdom Suite® software. The picked lines were exported to ArcGIS® to produce isopach maps of the units.

Sediment cores were collected in the lakes using an Aquatic Research® percussion corer. The coring sites were carefully selected from the analysis of the sub-bottom profiles to sample outcropping units. The cores were analyzed through a Siemens SOMATOM Definition CT-Scan, allowing for a non-destructive rapid visualization of sedimentary structures (St-Onge and Long 2009). CT-numbers (HU) were extracted using the ImageJ® software and proved to have an excellent correlation with density measurements (Fortin et al. 2013). The CT-numbers were thus converted into bulk density values (γ_t). The HU values were first converted into positive CT-numbers (Amos et al. 1996)

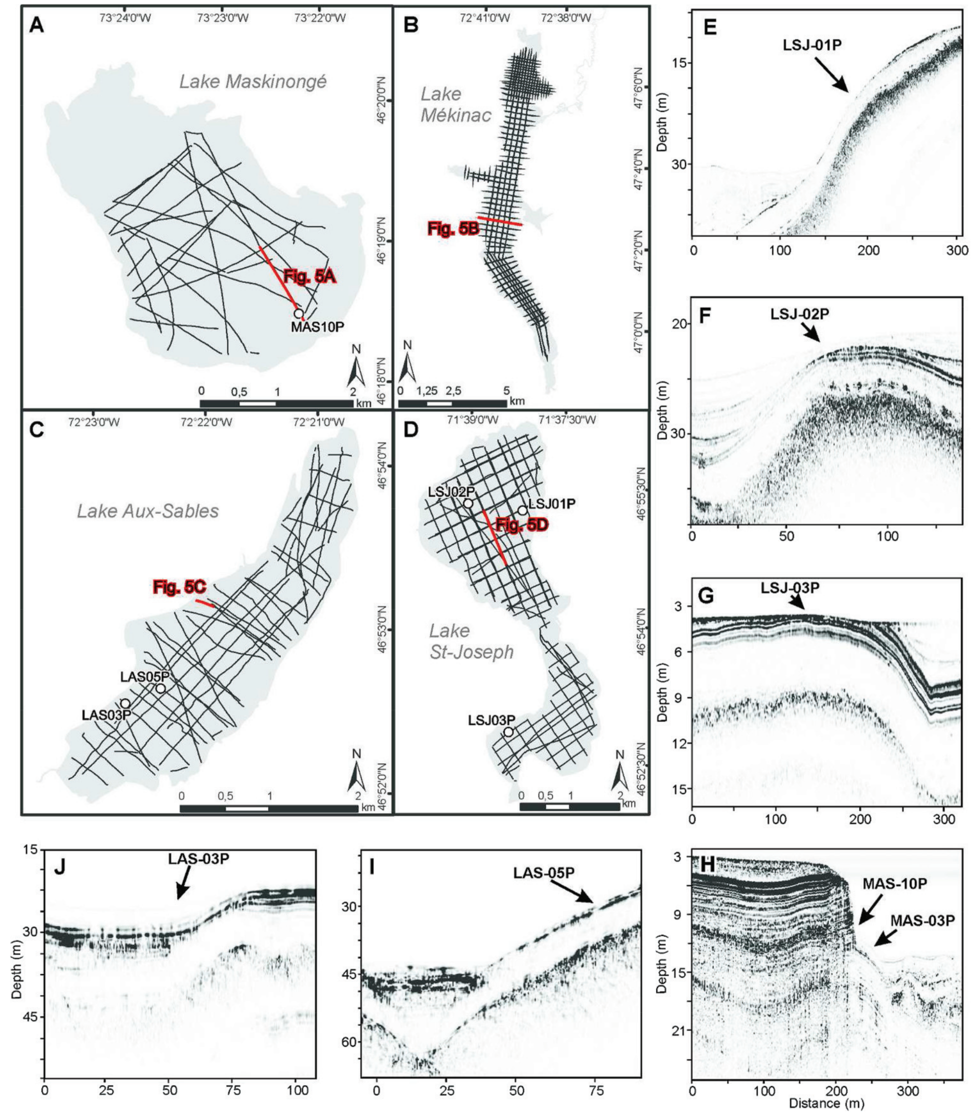
$$(1) \qquad \mathrm{CT} = \frac{1000 + \mathrm{HU}}{1000}$$

The bulk density estimates were then obtained using the following equation from Yamada et al. (2010):

$$(2) \qquad \gamma_t\ (\mathrm{g/cm^3}) = 1.32\mathrm{CT} - 0.39 \quad (R = 0.95)$$

Cores were then opened and visually described. Magnetic susceptibility, using a Bartington MS2E surface scanning sensor, was measured on the cores at 1 cm intervals. The cores were then sampled for grain-size measurements at 10 cm intervals and analyzed using a Horiba laser sizer. Samples were diluted into a

Fig. 3. Sub-bottom profile lines collected in the four studied lakes: (A) Maskinongé, (B) Mékinac, (C) Aux-Sables, and (D) St-Joseph. (E–J) Stratigraphic context of cores presented in Figs. 6, 7, 9, and 10. [Colour online.]



calgon solution for 24 h, submitted to an ultrasound bath, and at least three runs were averaged to obtain reliable grain-size distribution data. Statistical parameters of the sediments were then obtained using the Gradistat software (Blott and Pye 2001). End-member modelling analysis (EMMA) was used to quantify the grain-size characteristics of the samples following Dietze et al. (2012). The EMMA algorithm unmixes grain-size distributions to extract the processes and (or) the sources of sediment deposited in the lakes. Three end-members were sufficient to describe ~90% of the grain-size variability.

The absence of organic material within the Champlain Sea sediments precluded extensive dating in this study. A pine tree twig was sent to the Radiochronology Laboratory of the Centre d'études nordiques (Université Laval) for pre-treatment and preparation of the sample. The dating itself was done by accelerator mass spectrometry (AMS) at the Keck Carbon laboratory of the University of California (UCIAMS). The only date obtained was calibrated with Calib 7.0 (Stuiver and Reimer 1993) using the IntCal13 database (Reimer et al. 2013) and is shown with 2σ in Table 2.

Sediments sampled in different units of the Lake St-Joseph and Aux-Sables cores were used to examine fossil diatom assemblage composition for the reconstruction of past aquatic conditions (fresh versus brackish or salt water) that prevailed when sediments were deposited. In the Aquatic Paleoecology Laboratory at Centre d'études nordiques, fossil diatoms were extracted from core sediment samples with hydrogen peroxide (30% H_2O_2) digestion techniques, and microscope slides were mounted using Naphrax resin (Pienitz et al. 2003). Identification of diatom species was made using a Leica DMRB microscope at 1000× magnification under oil immersion objectives. The main reference floras used were Campeau et al. (1999), Fallu et al. (2000), and Pienitz et al. (2003). Diatoms were generally rare within the sediments and a quantitative analysis of the diatom remains was not possible. Therefore, this diatom analysis was a qualitative investigation

Table 2. Accelerator mass spectrometry ^{14}C age of the dated material collected in Lake Aux-Sables.

Core name	Depth (cm)	^{14}C age (BP)	Calibrated age (cal BP)	Material	Laboratory No.
LAS2013-03P	120	8930±30	9920–10 195	Twig	UCIAMS-137209

Note: Calibration was done using the IntCal13 curve and is presented with 2σ.

where the presence or absence of species allowed the characterization of paleo-environments.

Results

Lake morphology

Lake Maskinongé is a relatively shallow lake with a maximum depth of 36 m. Two main rivers, the Mastigouche and Matambin rivers, flow into the lake along its northern shore. The shores are generally steep (≥10°), favouring the presence of mass movement deposits (MMD) (Fig. 4A). A particularly large MMD is observed in the eastern part of the lake, near the Maskinongé River, the lake outlet. Otherwise, most of the central part of the lake is undisturbed and relatively flat.

Lake Mékinac is a fjord-lake with steep sidewalls and a maximum depth of 145 m (Fig. 4B). Its morphology can be divided into two parts: (1) the southern sector of the lake, consisting of a chaotic surface typical of hummocky moraines with two apparent sills; and (2) the northern part of the lake, presenting a smoother surface reflecting draping sedimentation. Two rivers also discharge into the northern sector of the lake and contribute to the shallower and smoother bottom morphology by delivering sediments to the basin plain. This draping sedimentation is disturbed by MMDs to the north and by crescentic bedforms on the Du Milieu River delta that are interpreted as cyclic steps (e.g., Normandeau et al. 2016).

Lake Aux-Sables is also a relatively shallow lake with a maximum depth of 42 m (Fig. 4C). Half of the lake is disturbed by MMDs, especially in the southern half where slopes are steeper. Residual mounds are observed in the sector affected by the largest mass movement of the lake (Fig. 4C). Other small-scale mass movement morphologies are present on the shores and on the different plateaus bordering the lake. Lake Aux-Sables does not receive considerable amounts of sediment from its tributaries, which are mostly small rivers and streams.

Lake St-Joseph is composed of two very different basins. The northern basin has a maximum depth of 36 m, whereas the southern one has a maximum depth of 12 m (Normandeau et al. 2013) (Fig. 4D). The southern basin has a smooth morphology, whereas the northern one is disturbed by MMDs on half of its surface. Residual mounds are also apparent within the MMDs.

Acoustic and litho-stratigraphy

Unit 1 is the lowermost unit and underlies the entire sedimentary succession of the lakes. Acoustic penetration is limited to absent and its surface morphology can be smooth or rugged (Table 3; Fig. 5), representing the acoustic basement. This unit was not cored during our surveys.

Unit 2 is a transparent acoustic facies and is observed only in Lake St-Joseph (Table 3). It has a basin-fill geometry with a sharp upper reflection. It is observed exclusively in the deeper parts of the lake basin (Fig. 5D). Its thickness varies according to the depth of the basin that it fills (0–10 m thick). This unit was not cored.

Unit 3 is a generally transparent acoustic facies containing a few low amplitude reflections (Table 3) and is observed primarily in lakes Aux-Sables and St-Joseph and appears to be present in Lake Maskinongé (Fig. 5). The upper boundary of Unit 3 is sharp and consists of a high amplitude reflection. It has a draping geometry and has a mean thickness of 4 m, but it can reach greater thicknesses locally (~7 m) at greater lake depths. Unit 3 was cored in lakes St-Joseph and Aux-Sables and reveals similar lithofacies (Fig. 6). In Lake St-Joseph, it consists of massive dark grey clayey silt; in Lake Aux-Sables, it consists of fine and faint parallel laminated dark grey clayey silt. The faintly laminated sediments are gradational and individual laminae are generally ≤5 mm thick. Density (derived from CT-numbers) and magnetic susceptibility are relatively low and homogeneous in these two lakes, with values averaging 1.85–2 g/cm³ (700–800 HU) and 400 SI, respectively (Fig. 6). Grain-size distributions are mostly unimodal in the clayey silt fraction (Fig. 7). EMMA reveals that EM1, centered on 5–10 μm is predominant in this unit. No diatoms were observed in core LAS05P (Lake Aux-Sables) while clastic particles were abundant. In core LSJ-01P (Lake St-Joseph), one sample revealed the presence of elongate benthic freshwater diatoms (*Fragilaria* ssp.) (Fig. 6B).

Unit 4 consists of high amplitude reflections and drapes conformably the underlying Unit 3. These high-amplitude reflections are present in the four lakes (Fig. 5). The thickness of Unit 4 is generally between 3 and 4 m (Table 3) but reaches ~7 m in Lake St-Joseph and ~30 m in the central part of Lake Aux-Sables (Fig. 8). Unit 4 is not present throughout the entire lake floor, as it is absent in some cases on steep nearshore slopes. Additionally, several transparent to chaotic lens-shaped facies interpreted as MMDs or rapidly deposited layers (RDL) are observed within this unit (Figs. 5D, 8). For example, nine MMDs are stacked within Unit 4 in Lake Aux-Sables, increasing the thickness of the unit to >20 m in the deeper areas (Fig. 8). Unit 4 was cored in lakes Maskinongé, Aux-Sables, and St-Joseph and consists of grayish silt and clay rhythmites responsible for a wide range of density and magnetic susceptibility values (Fig. 6). Density values vary between 1.7 and 2.25 g/cm³ (600 and 1000 HU) while magnetic susceptibility varies between 500 and 1700 SI. Grain-size distributions are mostly bimodal, especially in Lake Aux-Sables, reflecting the laminated nature of the sediments (Fig. 7). EM1, centered on 5–10 μm, and EM2, centered on 20 μm, are predominant within this unit with the occasional presence of EM3 where coarser particles are present (centered on 40–70 μm). The grain-size distributions generally have a broad mode centred on 5–10 μm and a narrower mode centred on 40–70 μm, indicating fine clayey silt laminae alternating with medium to coarse silts. The grain size (D50) also shows an upward coarsening trend when compared to Unit 3 (Fig. 6). CT-scan imagery reveals erosional surfaces, disturbed bedding, and coarse layers of gravels within the unit (Fig. 9). Diatoms are rare or absent within this unit, which is mainly composed of clastic material. However, *Diploneis smithii* ssp. and sponge spicules, typically observed in brackish waters, were observed at the base of core LSJ-02P (Fig. 10B).

Unit 5 consists of medium amplitude acoustic reflections and drapes the underlying unit (Table 3; Fig. 5). It is generally less than 2 m thick and in some cases cannot be differentiated from the underlying Unit 4. Cores LAS-03P and LSJ-02P reveal faintly laminated gray sediments with density and magnetic susceptibility values decreasing upwards from 1.4 to 1 g/cm³ (400–40 HU) and 400 to 10 SI (Fig. 10). Laminations are clearly visible at the base of the unit and gradually become faint to absent upcore. The laminated facies is replaced upcore by a more homogeneous one. Consequently, the grain-size distribution becomes more unimodal in the medium silt fraction (Fig. 10). End-members vary from one core to the other, where in Lake Aux-Sables EM2 is predominant, whereas in Lake St-Joseph EM1 and EM2 are present. Diatom assemblages identified within this unit are diverse and composed of brackish water (e.g., *Rhopalodia* ssp., *Tabularia* ssp.) and freshwater (e.g., *Fragilaria* ssp., *Achnanthes* ssp., *Tabellaria* ssp.) species. A pine tree twig sampled at 120 cm depth in core LAS-03P (Lake Aux-Sables) provided an age of 10 045 cal BP (Table 2), which indicates that the deposition of Unit 5 occurred during the early Holocene.

The uppermost Unit 6 observed in the four lakes consists of transparent to low amplitude reflections (Table 3; Fig. 5). It is generally less than 4 m thick and conformably drapes the underlying units. The top of this unit (= lake bottom) is in some cases difficult to identify on the subbottom profiles owing to the low acoustic impedance of the surficial sediments (Fig. 5C). In Lake Maskinongé, this unit is composed of low amplitude reflections whereas it is completely transparent in Lake Aux-Sables and in the southern basin of Lake St-Joseph. Sediment cores reveal homogeneous to faintly laminated silt (Fig. 10). Density and magnetic susceptibility values are very low and homogeneous in the order

Fig. 4. High-resolution swath bathymetric maps (2–5 m grid resolution) of the four study lakes: (A) Maskinongé, (B) Mékinac, (C) Aux-Sables, and (D) St-Joseph (Normandeau et al. 2013). DS, draping sedimentation; MMD, mass movement deposit; HM, hummocky morphology; D, delta; RM, residual mound; UB, undisturbed blocks. [Colour online.]

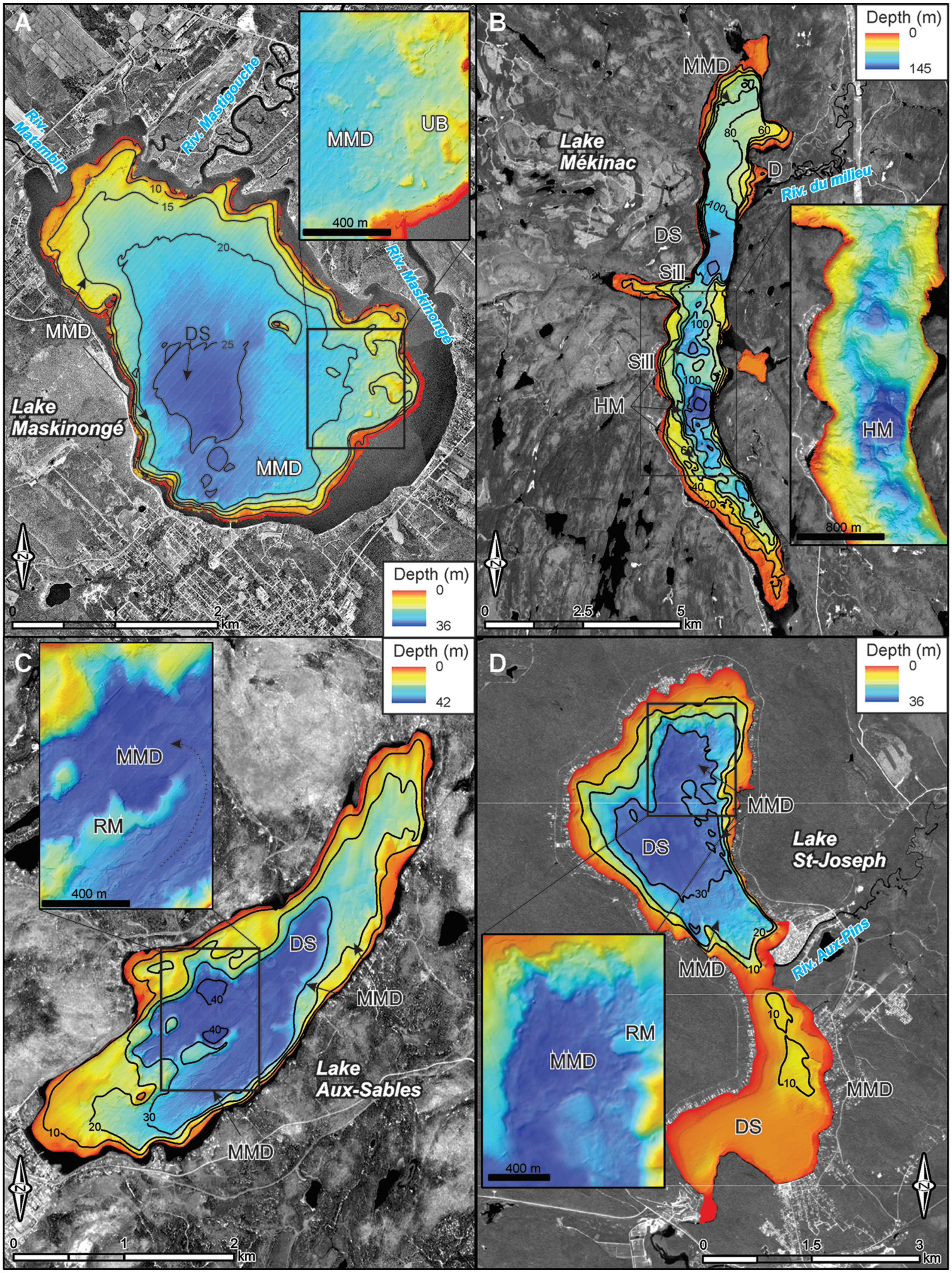


Table 3. Description and interpretation of acoustic units with their lithofacies description, from oldest (Unit 1) to youngest (Unit 6).

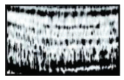
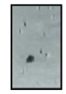
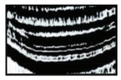
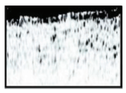
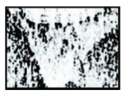
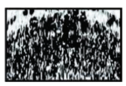
Unit	Acoustic properties	Acoustic profile	Mean thickness (m)	Lithofacies description	CT-scan lithofacies	Interpretation
6	Reflection free to medium amplitude reflections Drapes lower unit		0–4	Dark brown silt, rich in organic matter		Gyttja/postglacial sediments
5	Transitional unit Low to medium amplitude reflections Drapes lower unit		0–2	Silty laminations transitioning to dark brown silt, rich in organic matter		Marine to lacustrine transition/high paraglacial sedimentation rates
4	High amplitude reflections Drapes lower unit Interbedded with transparent lenses		3–4	Gray silt rythmites with occasional coarse rapidly deposited layers		Glaciomarine sediment deposited during high glaciofluvial discharge
3	Reflection-free to low amplitude reflections Drapes lower unit		2–4	Massive to finely laminated clay and silt		Glaciomarine sediment deposited below multiyear ice
2	Reflection-free Basin fill geometry Upper erosive contact?		0–10	N/A	N/A	Pre-Champlain Sea sediments
1	Absence of penetration, irregular morphology		N/A	N/A	N/A	Glacial diamicton and (or) bedrock

Fig. 5. Typical acoustic stratigraphy succession of the study lakes: (A) Profile from Lake Maskinongé. Unit 3 (U3) could only be observed near the shores as acoustic penetration is not sufficient at the centre of the lake. (B) Profile from Lake Mékinac illustrating Unit 4 and Unit 5. (C) Profile from Lake Aux-Sables illustrating the main units. (D) Profile from Lake St-Joseph illustrating the six main units. Note the presence of Unit 2 as well as mass movement deposits (MMDs) and rapidly deposited layers (RDLs) within Unit 4. [Colour online.]

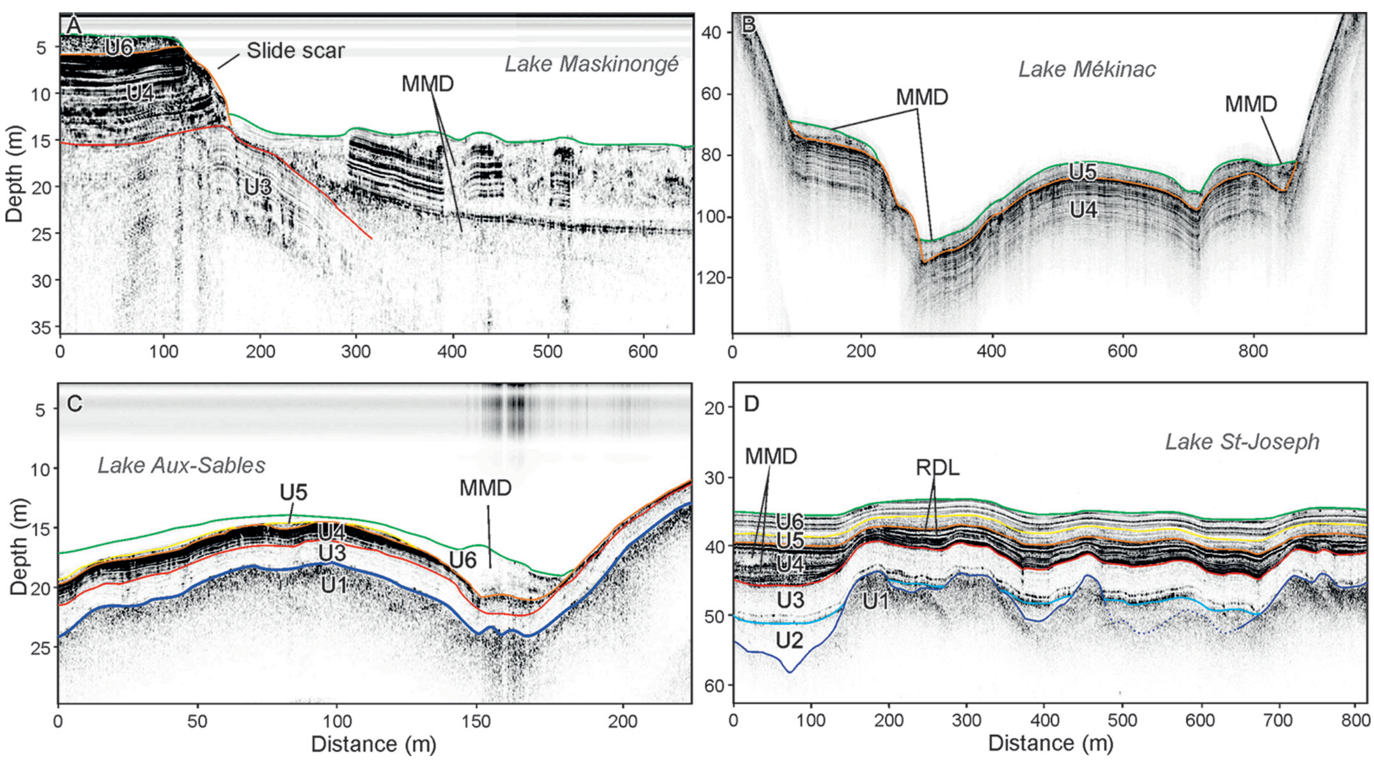
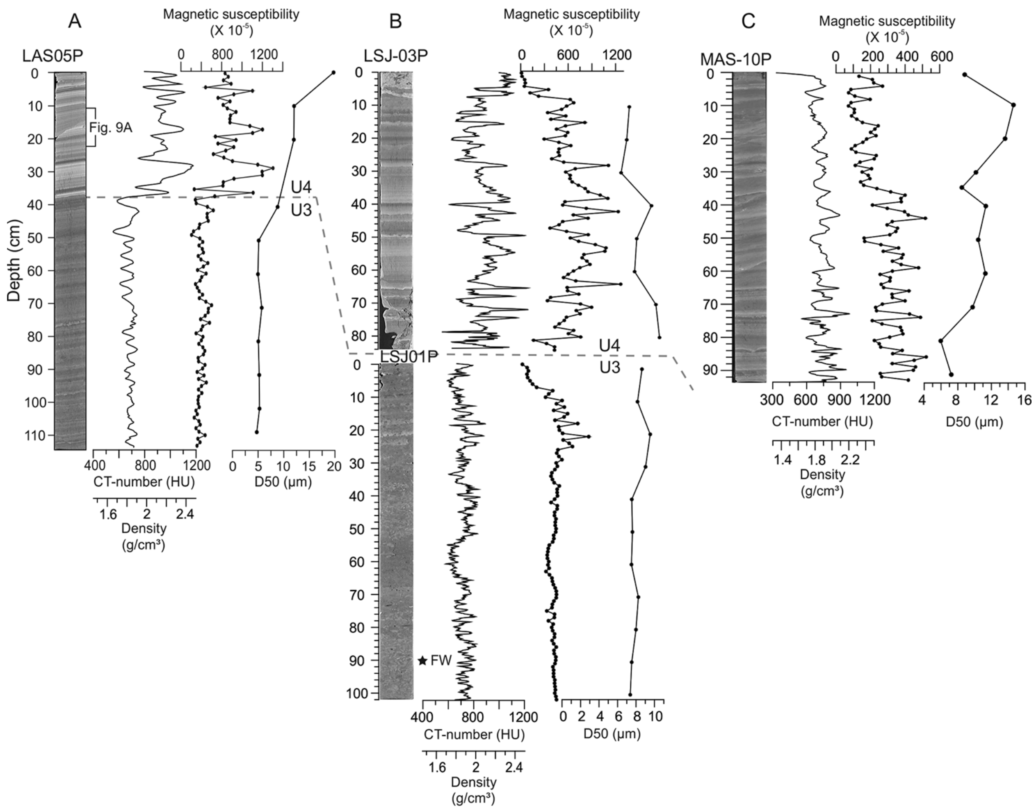


Fig. 6. Physical sediment properties of Unit 3 and Unit 4 in lakes (A) Aux-Sables, (B) St-Joseph, and (C) Maskinongé. FW, freshwater diatoms.



of 1 g/cm³ (40 HU) and 0–20 SI, respectively (Fig. 10). Grain-size distributions are mostly unimodal with D50 between 30 and 40 μm. EM2 and EM3 generally predominate within this unit. Diatom assemblages in this facies are species-rich and well preserved. Planktonic and benthic freshwater diatoms are observed, including the centric plankters *Cyclotella bodanica* and *Aulacoseira* ssp., as well as benthic and epiphytic *Pinnularia* ssp., *Surirella* ssp., *Diploneis* ssp., and *Amphora* ssp.

Discussion

Depositional environments

Although the local chronology of deglaciation differs from one lake to another according to LIS margin retreat models (Dyke 2004; Richard and Occhietti 2005; Occhietti et al. 2011), the overall stratigraphy and architecture of their Late Quaternary sediment infill is similar, indicating comparable sedimentation processes and sequence of events along the northern margin of the Champlain Sea basin. A conceptual model of sedimentation can thus be developed for former isolated glaciomarine embayments that gradually transitioned to limnic environments in the context of glacio-isostatic rebound (Fig. 11). This conceptual model of sedimentation consists of (*i*) a glacial phase, (*ii*) a glaciomarine with sub-multiyear floating ice sedimentation to open marine phase, (*iii*) a transitional postglacial marine to lacustrine phase, and (*iv*) a full postglacial limnic phase. Some of these depositional environments have previously been described by Normandeau et al. (2013) for the Lake St-Joseph basin. We nevertheless review them and discuss their similarities and differences between lakes before presenting a conceptual framework of sedimentation for isolated glaciomarine embayments that are progressively isolated from the sea.

Glacial phase

The pre-deglacial phase of the lakes is not well recorded nor constrained. Its interpretation is solely based on the acoustic stratigraphy analysis because sediment cores could not be collected. Based on the absence of acoustic penetration at the base of the sedimentary successions, the basal Unit 1 is interpreted as a deposit consisting of coarse-grained sediments that could be either glacial diamicton and (or) glaciofluvial sands.

In Lake Mékinac, the morphological expression of the southern part of the lake is typical of hummocky terrains consisting of till (e.g., Eyles et al. 1999) (Fig. 4B). The fjord heritage of this lake and the hummocky terrain suggest that during the retreat of the LIS, an ice tongue remained in the Mékinac Valley. Sills are present on the lake bottom where the valley narrows, suggesting that the ice tongue stabilized in these sectors during its retreat. As the lake is located at marine limit and residual ice likely remained in this valley during deglaciation, it appears that the Champlain Sea may have invaded only the southern part of the lake basin for a limited time while it did not invade its northern part.

In Lake St-Joseph, the basin-fill geometry of acoustically transparent Unit 2 was previously interpreted as homogeneous fine-grained sediment (mud) deposited prior to final deglaciation (Normandeau et al. 2013). It could thus consist of preserved sediments dating from an earlier phase of marine invasion, for example, preceding the LIS margin stabilization and (or) readvance of the YD (Occhietti 2007), or it could have been preserved throughout the entire Wisconsinan glaciation and be of Upper Wisconsinan or Sangamonien age. Unit 2 was not observed in the other lakes, either owing to the absence of acoustic penetration (e.g., Maskinongé, Mékinac) or because they were not preserved owing to the absence of deep and narrow basins (e.g., Aux-Sables).

Glaciomarine with multiyear shorefast ice to open marine phase

Unit 3 and Unit 4 are observed in lakes Maskinongé, Aux-Sables, and St-Joseph and are interpreted as having been deposited in a glaciomarine to marine environment (Fig. 11). In Lake Mékinac, only Unit 4 is present, which is interpreted as glaciolacustrine in origin.

Fig. 7. End-member modelling analysis (EMMA) of sediments from lakes (A) Aux-Sables and (B) St-Joseph. End-member loadings represent the three end-members used for each lake while the end-member scores represent the percentage of each end-member in each sample. The coefficient of determination (r^2) represents the error estimate that compares modeled results to the original datasets. The EMMA shows an increase in coarse particle up-core in both lake sequences as well as the prevalence of EM1 and EM2 in Unit 3 (U3) and Unit 4 and EM2 and EM3 in Unit 5 and Unit 6.

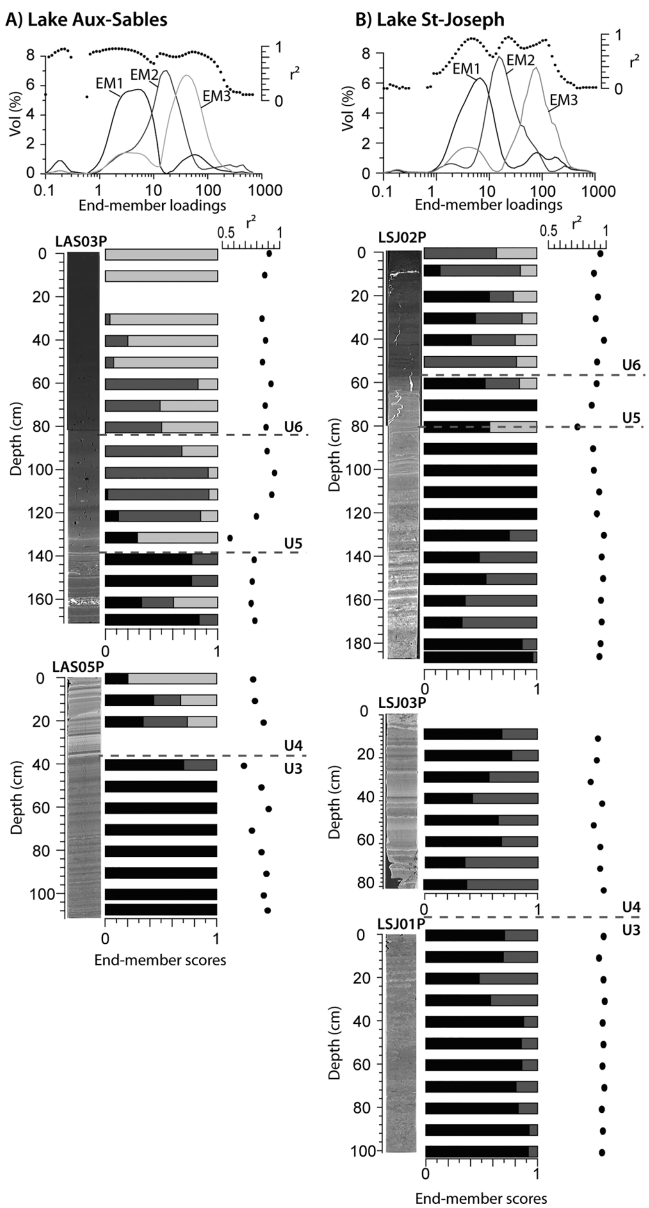


Fig. 8. (A) Isopach map of mass movement deposits (MMDs) within Unit 4 (U4) in Lake Aux-Sables superimposed on a shaded relief image of the bathymetry. Note that the isopach map is surrounded by thick black lines. The important thickness of this unit is due to the presence of stacked mass movement deposits (B). [Colour online.]

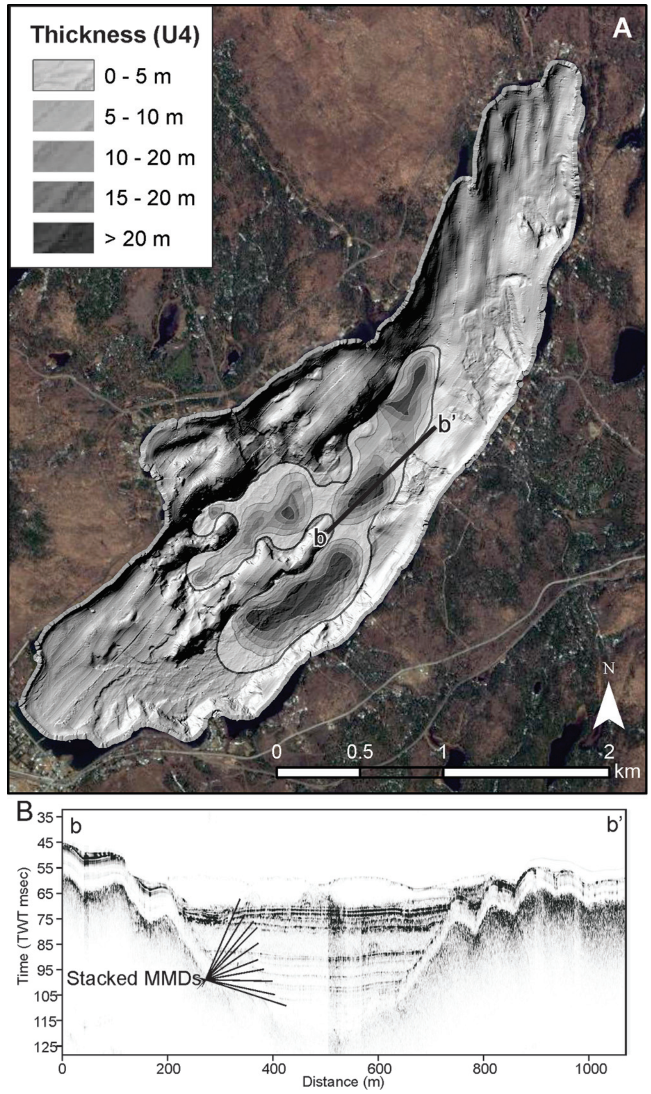
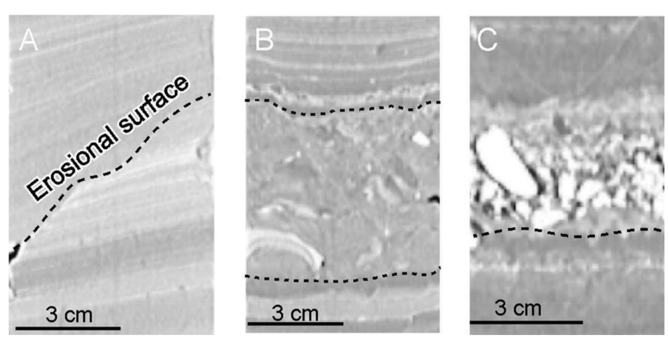


Fig. 9. (A) Erosional surface, (B) disturbed bedding, and (C) rapidly deposited layer within Unit 4 in Lake Aux-Sables. Location of facies in Figs. 6 and 10.



The faintly laminated to homogeneous appearance and blanket-like draping of Unit 3 over the lake floors indicate that the sediments were deposited through suspension settling potentially enhanced by flocculation (Normandeau et al. 2013). The presence of faint laminations in the Aux-Sables cores precludes sediment reworking by biological activity, hinting at hypoxic conditions (Jenny et al. 2016). We suggest that these sediments were deposited in a proximal setting relative to the ice margin because macrofauna is unlikely within several hundred metres of the ice margin (Syvitski et al. 1996), which prevents bioturbation (Jaeger and Nittrouer 1999). The presence of freshwater diatoms also

Fig. 10. Physical sediment properties of Unit 4 (U4), Unit 5, and Unit 6 in lakes (A) Aux-Sables, (B) St-Joseph, and (C) Maskinongé. BW, brackish water diatoms; FW, freshwater diatoms.

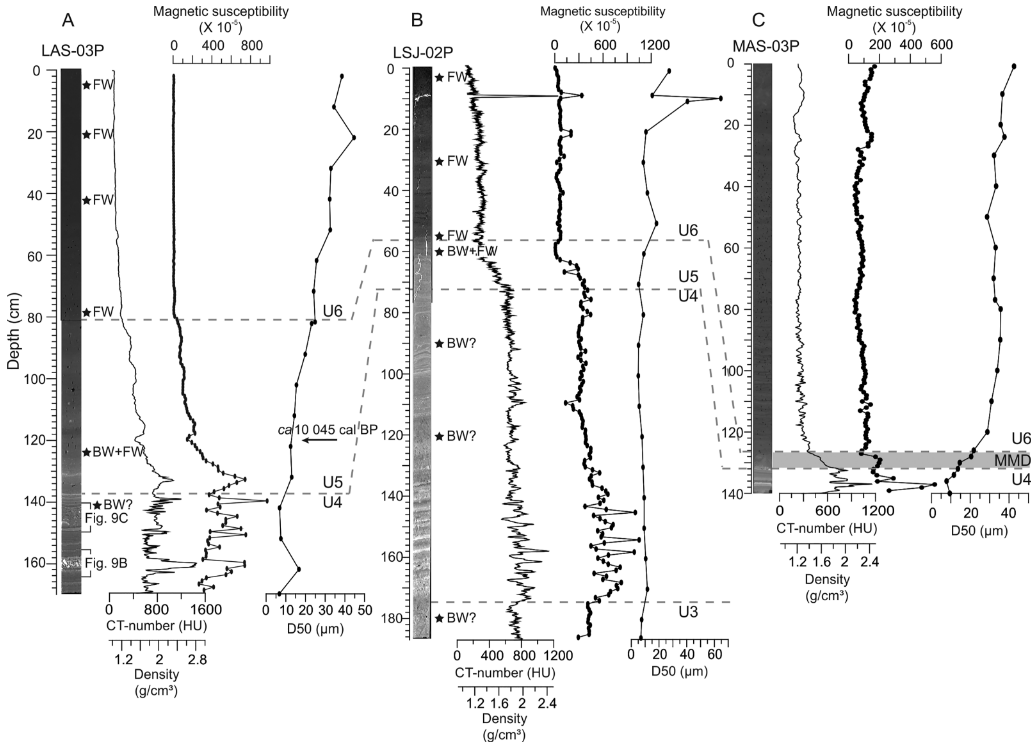
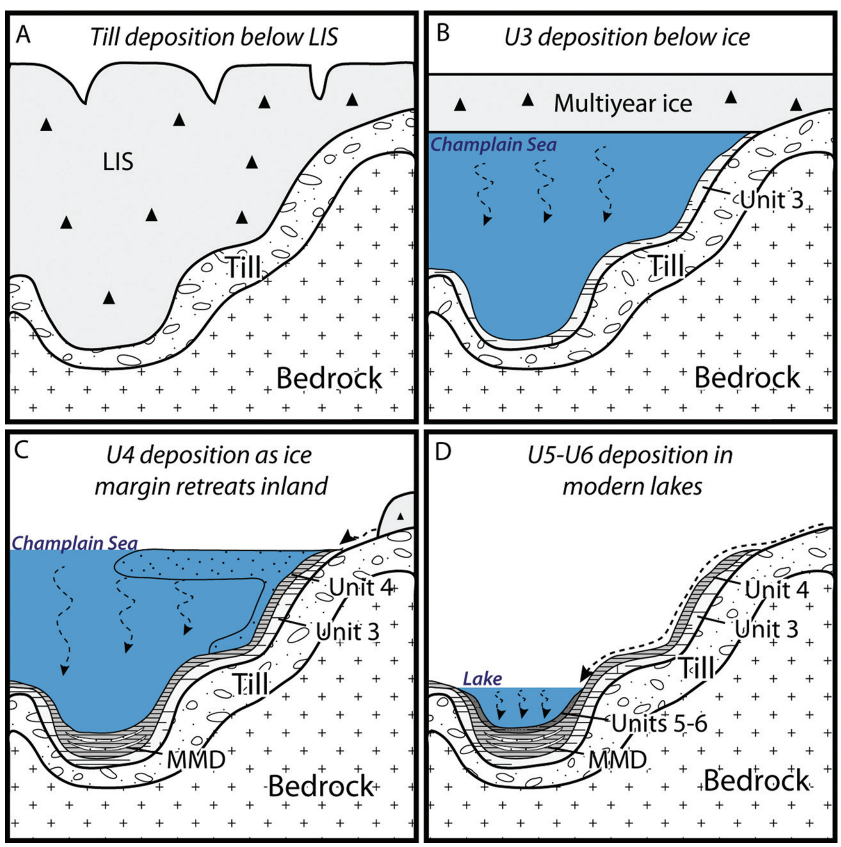


Fig. 11. Depositional environments of sediments in a glaciomarine to lacustrine transition in former embayments of the northern Champlain Sea basin. (A) Deposition of till below the Laurentide Ice Sheet (LIS); (B) Deposition of faintly laminated mud below multiyear shorefast sea-ice (Unit 3); (C) Deposition of laminated mud and fine sand during ice margin retreat as well as mass movement deposits (MMDs) owing to glacio-isostatic rebound (Unit 4); (D) Deposition of lacustrine sediments in modern lakes (Units 5-6). [Colour online.]



suggests dilution by abundant glacial meltwater inputs close to the ice margin.

Sedimentation in glaciomarine settings can be dominated by discharge plumes or melting of icebergs (Syvitski et al. 1996). Two important criteria distinguish both environments: (*i*) the presence versus absence of IRD, and (*ii*) the presence versus absence of biogenic material (Domack et al. 1995, 1999; Pudsey and Evans 2002). Sedimentation controlled by discharge is believed to have dominated the northern Champlain Sea embayments as no IRD were observed in any of the cores. The absence of IRD in glaciomarine settings suggests the presence of a floating ice cover (Reece 1950; Domack et al. 1995, 1999; Dowdeswell et al. 2000; Smith and Andrews 2000; Pudsey and Evans 2002; Pieńkowski et al. 2012), either as multiyear shorefast sea-ice or an ice-shelf (Fig. 11B). During cooler climate periods, the presence of ice prevents icebergs from reaching the shores, which in turn suppresses IRD in glaciomarine sediments (Dowdeswell et al. 2000; Pieńkowski et al. 2012). For example, multiyear shorefast sea-ice currently observed in many High Arctic regions (e.g., Syvitski et al. 1996; Dowdeswell et al. 2000) is believed to represent conditions analogous to those that prevailed during the Champlain Sea episode. The absence of icebergs can also be inferred from the absence of scouring on the acoustic profiles, even at paleo-depths shallower than 50 m (i.e., 5 m of the modern lake depths). This absence of scours and IRD contrasts sharply with sediments found at greater paleo-depths near the St. Lawrence River, for example, near Québec City (Occhietti et al. 2001). For all the abovementioned reasons and because the EMMA reveals the predominance of EM1 in Unit 3, we interpret EM1 as sediment deposited below sea-ice.

Two competing hypotheses may thus explain the deposition of Unit 3: sedimentation below an ice-shelf of below multiyear shorefast sea-ice. A floating ice-shelf extends across water from a land-based glacier. It is bounded upstream by a grounding zone wedge (GZW), some of which have been identified in the Estuary and Gulf of St. Lawrence (Syvitski and Praeg 1989; Lajeunesse 2016), but which have not been identified in the St. Lawrence River Valley to date. In the immediate regions of the lakes, no GZW were identified in our study. Assuming the deposition of sediment below an ice-shelf, the GWZ would have existed along the axis of major ice streams flowing into the Champlain Sea. Our study lakes are not located on this direct axis but in isolated bays next to the potential pathways of ice streams (major glacially carved rivers). The location of the lake basins in former embayments would also explain the presence of muds and the absence of coarse sediment (diamicton) related to the basal debris zone of the GZW, corresponding to a "null zone" as described by Domack et al., 1999. However, studies on the Antarctic ice-shelves reveal that following catastrophic ice break-up, sedimentation returns to coarse diamicton above the fine silts (Kilfeather et al. 2011; Reinardy and Lukas 2009), reflecting the release of supraglacial debris to the water column and the release of IRD from the calving ice-front. The absence of such a clast-rich layer favours the presence of landfast sea-ice rather than ice-shelf conditions, which would have prevented icebergs from entering the former bays. During the Champlain sea invasion, shorefast sea-ice could have been present (Harington et al. 2006; Paiement 2007), especially in low-energy, isolated glaciomarine bays.

The sharp but conformable transition between Unit 3 and Unit 4 indicates an increase in terrestrial runoff to the basins and a rapid change in suspension settling dynamics reflecting a sudden change in sea-ice dynamics. Unit 4 is believed to have been deposited when the ice margin retreated inland, allowing an increase in terrestrial runoff through enhanced glaciofluvial discharge to the Champlain Sea. Therefore, EM2 and EM3 are interpreted as sediments originating from river floods that were deposited by suspension settling and underflows (Fig. 11C). The presence of EM2 and EM3 indicates ice-free conditions during the summer months, whereas the presence of EM1, which is associated with sedimentation below a floating ice cover, reflects the presence of shorefast sea-ice during winter.

According to the diatom remains, waters were brackish at the time of deposition of Unit 4, which reinforces the interpretation of a retreating LIS margin. As the ice margin retreat progressed, the mixing of glacial meltwater with the Champlain Sea was reduced. As a result, coastal waters became more brackish.

Blanket-like draping indicates that Unit 4 was also deposited primarily by suspension settling (e.g., Gilbert et al. 2002). However, Unit 4 is also ponded in the deeper lake areas, especially in Lake Aux-Sables (Fig. 8B), owing to the presence of chaotic to transparent lenses that suggest sediment deposition when the LIS margin retreated towards the hinterland. These lenses are interpreted as mass movement deposits that were triggered by earthquakes related to rapid glacio-isostatic rebound (e.g., Hill et al. 1999; Lajeunesse and Allard 2002; Beck 2009; Brooks 2016) or by important meltwater discharges during the retreat of the LIS. Sediment cores collected within this unit also show typical erosional surfaces on the slopes that are associated with mass movements (Fig. 9). Lajeunesse and Allard (2002) and Hill et al. (1999) showed that MMDs related to glacio-isostatic rebound were frequent during the glaciomarine to marine transition in northern Québec, which is also where we observe them in our study.

Because the Champlain Sea did not reach the northern Lake Mékinac basin, the observed high amplitude reflections are rather associated with glaciolacustrine sediments that are similar in appearance to glaciomarine sediments in acoustic stratigraphy and widespread in southeastern Canadian lakes (e.g., Turgeon et al. 2003; Brooks 2016; Lajeunesse et al. 2017).

Transitional phase

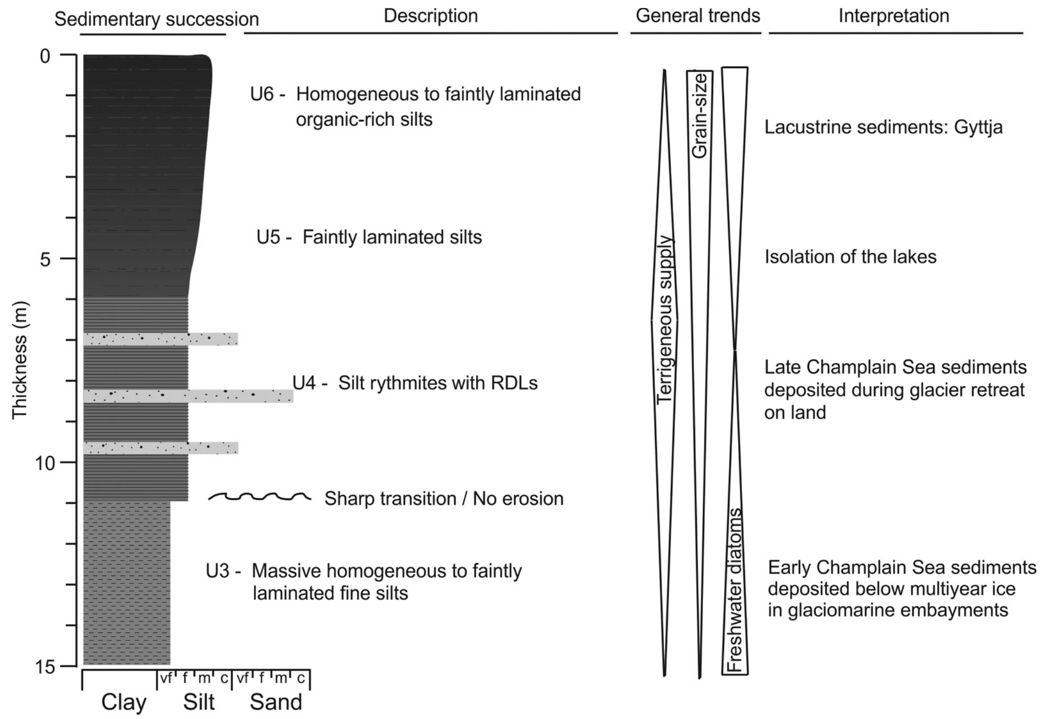
As the LIS margin retreated inland, sedimentation rates were reduced while glacio-isostatic rebound caused relative sea level to fall over the lake areas. With increasing distance from a glaciofluvial sediment source and RSL fall, laminated sediments graded into massive bioturbated mud (Unit 5), reflecting reduced influence of meltwater fluxes, lower sedimentation rates, and an increase in macrofaunal colonization (e.g., Ó Cofaigh and Dowdeswell 2001).

In Lake Aux-Sables, the deposition of Unit 5 occurred at ca. 10 045 ka cal BP. At that time, brackish and freshwater diatoms were deposited in the lake, representing the progressive isolation of the lake which likely occurred earlier during the Holocene based on known sea levels (Lamarche 2011), yet brackish waters remained trapped in the lake as it was stratified with a residual salty dense water at the bottom, until replacement with freshwater was complete.

Lacustrine phase

The lacustrine phase in each lake is characterized by the deposition of organic-rich gyttja (Fig. 11D). However, the stratigraphy revealed that these sediments have a transparent acoustic appearance in Lake Aux-Sables and the southern basin of Lake St-Joseph, whereas they have a laminated appearance in lakes Maskinongé, Mékinac, and the northern basin of Lake St-Joseph. In these three latter cases, rivers flowing on a relatively large delta plain deliver sediments to the lakes during the spring snow melt, which transport coarser sediments to the lake bottom. In contrast, the Lake Aux-Sables watershed is much smaller and does not contain delta plain sediments that can be flushed into the lake during floods. Therefore, the difference in acoustic stratigraphy properties between lakes is mainly related to the surficial geology of their watersheds and the rivers delivering clastic sediments. During the lacustrine phase, large mass movements also occurred, although infrequently, especially during the late Holocene, suggesting a common trigger such as earthquakes.

Fig. 12. Typical deglacial succession in the emerged study lakes owing to glacio-isostatic rebound. This succession reflects a retreating ice margin combined with a forced marine regression. vf, very fine; f, fine; m, medium; c, coarse.



Sedimentary succession in isolated glaciomarine embayments during relative sea level fall

The depositional environments described above allow us to compare the sedimentary succession of isolated glaciomarine bays to those of deep-water glaciomarine environments. In deep-water glaciomarine settings, typical deglaciation successions consist of ice-proximal to ice-distal laminated sediments, reflecting energetic sedimentation dynamic near the ice margin, followed by paraglacial homogeneous to massive sediment that reflect increased bioturbation and the ablation of the terrestrial ice margin (Syvitski 1993; Jaeger and Nittrouer 1999). Sediment grain-size and sedimentation rates decrease as the ice margin retreats, favouring bioturbation (Syvitski 1993; Aitken and Bell 1998). Additionally, ice-proximal environments are often composed of IRD, reflecting calving of the ice margin. For example, in the deeper water of the nearby former Goldthwait Sea, the typical succession consists of highly laminated sediments followed by finely laminated sediment representing ice-proximal to ice-distal environments (St-Onge et al. 2008). This typical deglacial succession is not observed in the isolated embayments of the northern Champlain Sea basin owing to its particular physiographic setting and glacio-isostatic rebound dynamics that led to important changes in water depth with time. In glaciomarine embayments, multiyear shorefast sea-ice is more likely to occur than in deep-water environments or near ice-stream outlets. The presence of shorefast sea-ice thus prevents the deposition of relatively ice-proximal coarse sediments, leading to an initial reversed sedimentary succession. Therefore, the sedimentary succession in former glaciomarine embayments (Fig. 12) rather consists of the following:

(1) IRD-free, finely laminated sediments below multiyear ice in relatively ice-proximal environments. This unit is believed to have been deposited in embayments while outwash fans are being constructed at the front of ice streams in adjacent valleys and while coarse glaciomarine diamicton are being deposited in deeper waters.
(2) Well-laminated sediment with rapidly deposited layers, erosional surfaces, and mass movement deposits put in place during the inland retreat of the LIS margin. The melting of shorefast sea-ice during the summer allows small streams and rivers fed by glaciogenic sediments to supply contrasting sediment layers in the embayments. Additionally, the retreat of the LIS margin leads to an initial rapid glacio-isostatic rebound, generating numerous mass movements along the shores of the sea.
(3) Finely laminated to homogeneous sediment deposited during RSL fall and LIS margin retreat from the watersheds. These homogenous muds represent the progressive isolation of the basins and the reworking of the sediment by macrofauna (bioturbation).
(4) Finely laminated to homogenous gyttja deposited in postglacial lakes, which represents the establishment of modern conditions.

In addition to this sedimentation framework, the progressive retreat of the LIS margin during a RSL fall leads to a slight increase in grain size with time. Therefore, the nearshore sediment of the Champlain Sea reflects sea-ice breakup and the continued glacio-isostatic rebound that favour the deposition of coarser sediments in increasingly shallower areas. The effect of glacio-isostatic rebound counteracts the effect of a retreating ice-sheet margin in the grain-size distribution of the sediments. The sediments then gradually change from marine to lacustrine as the individual basins/bays progressively emerge from the Champlain Sea in response to glacio-isostatic rebound. Under this forced marine regression, water depth continues to diminish and leads to a slight increase in grain size, even in lacustrine settings. This increase in grain size appears to be observed in other glacio-isostatically uplifted lakes, such as in the High Arctic (e.g., Cuven et al. 2011).

Conlusions

The morphological, stratigraphic, and sedimentary data collected from four lakes located within the northern sector of the former Champlain Sea basin (southern Québec) provide new information on the depositional environments that marked deglaciation and land emergence in the region. These results demonstrate the following:

(1) Lakes St-Joseph, Aux-Sables, and Maskinongé contain a sedimentary infill of similar stratigraphy and architecture marked by sedimentation below multiyear ice, LIS margin retreat, and the deposition of terrestrially derived event beds (e.g., MMD and turbidites) and lacustrine sediments. This similar succession in the lakes of the northern Champlain Sea suggests a similar sequence of events, despite diachronic marine inundation and regression.
(2) Glaciomarine to marine sediments consist of homogeneous to faintly laminated muds without IRD followed by a laminated facies. End-member modelling analysis combined with a lack of IRD suggest that the lowermost glaciomarine unit (Unit 3) was deposited below multiyear ice, more likely to be shorefast sea-ice then an ice-shelf. Conversely, the sudden input of coarser materials (Unit 4) is interpreted as being associated with the break-up of multiyear ice and open seawater conditions during summer months, allowing the deposition of coarser terrestrially derived sediments while the ice margin was retreating inland.
(3) The transition from marine to lacustrine environments is characterized by increasing bioturbation (i.e., increasing primary production), decreasing terrestrial runoff, and increasing grain size. The latter is attributed to land emergence owing to glacio-isostatic rebound. Although glacial influence gradually diminishes, the falling RSL favoured the deposition of coarser sediment with time.

The deglacial succession of the northern Champlain Sea sediments is slightly different than that observed in conventional deglacial successions, which is attributed to the location of the study lakes in former embayments and to postglacial land emergence. Hence, sedimentary facies successions in embayments in the context of glacio-isostatic rebound are notably different from deep-water facies successions. This conceptual model based on the northern Champlain Sea sediment records should provide help in identifying sediment deposited in former shallow nearshore embayments.

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