Deglacial and postglacial paleoseismological archives in mass-movement deposits of lakes of south-central Québec

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ABSTRACT

Investigation of seismic activity in eastern Canada is important for natural hazard management since two major active seismic zones with many historical records are located in the region: the Western Québec and the Charlevoix-Kamouraska seismic zones, with the latter being the most active in northeastern America. This paper describes and analyses a dataset of high-resolution swath bathymetric imagery, sub-bottom profiles and sediments cores collected in three lakes (Maskinongé, Aux-Sables and St-Joseph) located between two active seismic zones. The geomorphology observed on high-resolution swath bathymetric imagery, the acoustic sub-bottom profiles and the sediment analysis indicate that the lakes were disturbed by three phases of seismically-induced mass-movements since deglaciation : 1) during the deglacial Champlain Sea transgression and the rapid initial glacio-isostatic rebound between ~13 and 10.5 ka cal. BP; 2) around 1180 AD; and 3) the well documented CKSZ 1663 AD M>7 historical earthquake. The second phase of earthquake events (1180 AD) corresponds chronologically to a previously documented large-landslide in western Québec, dated at ~1020 yr BP. This earthquake is responsible for remobilizing the largest volume of sediments in the entire stratigraphic sequence of Lake Maskinongé, the westernmost lake. This earthquake was not recorded in Lake Aux-Sables and St-Joseph, which are located eastward from Maskinongé, but the largest MMDs are associated with the well-known 1663 AD event of eastern Québec. Therefore, both earthquake events are interpreted to have different epicenters and the lakes of southeastern Québec recorded earthquakes from both seismic zones.

Key words: Mass-movement deposits, earthquakes, lakes, geomorphology, stratigraphy

INTRODUCTION

The record of seismic activity prior to colonisation is poorly documented in northeastern North America, as historic testimonials are limited to the past ~450 years (at best) and data availability is closely linked to the locations of historical European settlements (Gouin, 2001). Since the early 20th century, geological investigations and instrumental monitoring systems improved the understanding of seismic activity, providing valuable information on magnitude, location and recurrence intervals of earthquakes (e.g., Lamontagne, 1987; Adams and Basham, 1989). However, only limited information is presently available on pre-colonization seismic events, even though it is critical for determining the recurrence interval of large infrequent earthquakes (St-Onge et al., 2004; Locat, 2008).

Lacustrine basins are depositional environments that can provide detailed information on significant earthquake events (Sims, 1975; Doig, 1986; Shilts and Clague, 1992; Ouellet, 1997; Chapron et al., 1996, 1999; Schnellmann et al., 2002; Nomade et al., 2005; Strasser et al., 2006; Arnaud et al., 2007; Chapron et al., 2007; Bertrand et al., 2008; Doughty et al., 2010a, 2010b; Ledoux et al., 2010; Moernaut and De Batist, 2011; Lauterbach et al., 2012; Brooks, 2013a, 2013b; Doughty et al., 2014; Brooks., 2016; Locat et al., 2016; Lajeunesse et al., 2017; Normandeau et al., 2017). The high water content and the poor consolidation of lacustrine sediments make them sensitive to external disturbance, causing failures (Shilts, 1984; Shilts and Clague, 1992). Many mechanisms can trigger slope disturbances and subaquatic mass-movements such as water level fluctuations, wave loading, high sedimentation rates, anthropogenic disturbances and earthquakes (Shilts, 1984; Shilts and Clague, 1992; De Blasio et al., 2004; Cauchon-Voyer et al., 2008; Fanetti et al., 2008;

Duchesne et al., 2010; Normandeau et al., 2013; Smith et al., 2013). Mass-movement deposits (MMDs) in lakes located near active seismic zones can be a proxy to identify Late-Pleistocene and Holocene earthquakes (e.g., Brooks, 2016). Many factors can link MMDs to a seismological trigger, but the key signature is multiple, synchronous-triggered MMDs (Shilts and Clague, 1992; Schnellmann et al., 2002; Bertrand et al., 2008; Smith et al., 2013; Brooks, 2015, 2016).

MMDs are common in lakes located within and near active seismic zones of eastern Québec (e.g., Shilts et al. 1992; Ouellet, 1997; Lajeunesse et al., 2008; Doughty et al., 2010a, 2010b, 2013, 2014; Locat et al., 2016; Lajeunesse et al., 2017) where they can be present at multiple stratigraphic levels. In southern Québec, postglacial MMDs are observed in lakes located near the CKSZ and are absent in lakes located away from it (Ouellet, 1997), suggesting that they have been triggered by earthquake events. Ouellet (1997) and Lajeunesse et al. (2017) proposed that paleoseismological research in eastern Canada should focus on MMDs occurring outside and away from very active seismic zones to identify high magnitude seismic events and avoid the background noise induced by frequent smaller earthquakes.

High-resolution swath bathymetric imagery allows full-bottom coverage of lacustrine basins and provides detailed information on lake-bottom morphology and sedimentary processes such as mass-movements (Locat and Lee, 2002; Hilbe et al., 2011; Strasser et al., 2011; Normandeau et al., 2013; Smith et al., 2013; Hilbe and Anselmetti, 2014). Older deglacial and postglacial MMDs in the stratigraphy can be identified on sub-bottom profiles. An approach combining high-resolution swath bathymetric imagery and sub-bottom profiles can provide valuable information on the spatial distribution of MMDs over an entire lake basin (e.g., Praet et al., 2016; Lajeunesse et al., 2017). In addition, sediment core data allow dating possibilities through depositional rates and can thus lead to a better understanding of paleoearthquakes.

This paper presents a morpho-stratigraphic analysis of three lakes located north of the St. Lawrence River, southern Québec (Canada), within the limits of the former deglacial Champlain Sea. The lakes are located between the WQSZ and the CKSZ (Fig. 1b) and provide insights into the deglacial and postglacial history of paleoseismic activity for the area between the major urban centres of Québec City and Montréal. More specifically, it aims to 1) describe the geomorphology and distribution of MMDs in these lacustrine basins; 2) identify the triggering factors of mass-movements; and 3) provide a chronostratigraphic framework for mass-movements in these lakes.

STUDY AREA

Physical setting

Lakes Maskinongé, Aux-Sables and St-Joseph, southern Québec (Table 1), are located within the Grenville geological province of the Canadian Shield, where bedrock mainly consists of Precambrian metamorphic and igneous rock (Geological Survey of Canada, 2008). During the last glaciation, the lake basins were all covered by the Laurentide Ice-Sheet (LIS) and were entirely deglaciated by ~13 ka cal. (Occhietti et al., 2011). The small and shallow basins are all located below marine limit (≤ 210 m asl in the region) (Parent and Occhietti, 1988; Normandeau et al., 2013, 2017) (Fig. 1b) and were emerged from the sea by ~10 ka cal BP (Parent and Occhietti, 1988). The lakes were selected for this study because previous investigations highlighted the widespread occurrence of MMDs on their floors (Ouellet, 1997; Normandeau et al., 2013, 2017).

Table 1

Physical characteristics of the investigated lakes.

Lake Maskinongé is a circle-shaped basin and its main tributary is the Mastigouche River located at the northern end of the lake. Lake Aux-Sables is 5.2 km long, has a maximum width of 1 km and is oriented from NE to SW. Its sedimentary input comes from multiple small streams, but there is no major tributary. Lake St-Joseph has a length of 7 km and a maximum width of 3 km. The lake is composed of two main basins. Its main tributary is the Rivière-aux-Pins that discharges into the northern basin of the lake. The three lakes stratigraphic successions were previously investigated and seven Late-Pleistocene and Holocene units were identified ranging from deglacial marine to postglacial lacustrine sediments (Normandeau et al., 2013, 2017).

Regional seismicity

Eastern Canada is part of a mostly aseismic stable craton with some restricted zones showing seismological activity (Fig. 1a). Three of these zones are partly located in the province of Québec and are all related to the reactivation of the Iapetan rift fault system, known as the St. Lawrence rift system (Adams and Basham, 1989; Tremblay et al., 2013). These three zones are: i) the Western Québec seismic zone (WQSZ), where earthquake epicentres are mostly distributed in eastern Ontario, western Québec and northern New-York state; ii) the Charlevoix-Kamouraska seismic zone (CKSZ), centered in the St. Lawrence Estuary, south of the Saguenay fjord (Fig. 1), and iii) the Lower St. Lawrence seismic zone (LSLSZ), located in the eastern part of the St. Lawrence Estuary, which has a low activity of small magnitude earthquakes (Adams and Basham, 1989; Locat, 2011). The WQSZ and the CKSZ are also partly due to local crustal fractures resulting from a passage over a hot spot during the Cretaceous and a meteoritic impact structure, respectively (Adams and Basham, 1989). The WQSZ is divided in two areas: a SE-NW band extending from Montréal to the upper Gatineau River and a less active southern band with epicenters located along the Ottawa River (Adams & Basham, 1989). Many historical earthquakes have been documented in the WQSZ, with events reaching M=5 to M=6 (Fig. 1: 1732 AD, M5.8; 1935 AD, M6.2; 1944 AD, M5.8) (Natural Resources Canada, 2018). The CKSZ, southeastern Québec, is the most active seismic zone in eastern Canada (Fig. 1a), with many historical earthquakes reaching M ≥ 6 (Fig. 1: 1663 AD, M>7; 1860 AD, M6; 1870 AD, M6.5; 1925 AD, M6.2; 1971 AD, M6) (Lamontagne, 1987; Adams and Basham, 1989; Doig, 1998; Tuttle and Atkinson, 2010; Locat, 2011).

The region in which the three studied lakes are located is bounded by the two most important seismic zones of eastern Canada (WQSZ and CKSZ) (Fig. 1a, b), exposing it to a recurrence of seismic events since deglaciation. Although only few historical earthquakes occurred in the WQSZ, analysis of the disturbance of lacustrine sediment has linked deposits in the Outaouais region to the 1935 AD seismic event (Shilts, 1984; Shilts and Clague, 1992; Doughty et al., 2010a, 2010b). Cores analysis from lacustrine basins also allow Doig (1986, 1991, 1998) to identify past earthquakes. Additionally, pre-historical seismic events (7060 yr BP, 4550 yr BP and 1020 yr BP) from the WQSZ were identified by analysing and dating large terrestrial landslides (Aylsworth et al., 2000; Brooks, 2013a, 2013b). By contrast, the CKSZ has an approximate recurrence rate of 70 years for earthquakes of magnitude $M \geq 6$ (Ouellet, 1997; Natural Resources Canada, 2018). Ouellet (1997) observed that the largest sublacustrine disturbances occurred usually within a radius of 34.5 ± 5 km from the CKSZ. Physical damage to infrastructures has also been reported in the literature at a distance of 180 km to over 800 km from the epicenter of an earthquake of magnitude ≥ 7 (Ouellet, 1997; Geological Survey of Canada, 2001). Deglacial and postglacial seismic events were also identified by Tuttle and Atkinson (2010) dated at 10.12-9.41 ka yr BP and 5.04 ka yr BP in the Charlevoix region, and an event around 7.25 ka yr BP was dated by Cauchon-Voyer (2008) in the St. Lawrence Estuary.

MATERIAL AND METHODS

Hydroacoustic survey

Hydroacoustic surveys were undertaken in the three lakes between 2011 and 2014 to acquire high-resolution swath bathymetry imagery and sub-bottom profiles. The hydroacoustic database presented in this paper is the same as the one used by Normandeau et al. (2013, 2017). Data was acquired using two different swath bathymetric systems, depending on lake depth and accessibility. In the shallow southern basin of Lake St-Joseph (< 20 m), data was acquired with an *Odom ES3* multibeam echosounder (240 kHz), together with an *Ixsea Octans III* motion sensor and an *SX Blue* DGPS (~ 60 cm precision). The other lakes were mapped with a *GeoAcoustics GeoSwath Plus Compact* interferometric bathymetric sonar (250 kHz), coupled with a *Valeport SMC* motion sensor and a *Hemisphere V101* DGPS (~ 60 cm precision) for positioning. The instruments were mounted on two different platforms;

an inflated boat (Zodiac) and a pontoon boat. Bathymetric data were post-processed using *Caris Hips and Sips 8.1* software.

Acoustic stratigraphy data was acquired using a dual frequency *Knudsen 3212* (3.5 and 12 kHz) sub-bottom profiler; refer to Figures 3A, C, D of Normandeau et al. (2017) for the profiling survey pattern. Survey lines were planned perpendicularly to each other in order to better visualize the distribution of the acoustic units in the lake basins. A sound velocity of 1500 m s^{-1} was used to compute depths and sediment thickness. The *SegyJp2Viewer* software from Natural Resources Canada (NRCan) and *SonarWiz 5.0* were used to analyze the sub-bottom profiles which were then coupled to the high-resolution bathymetric imagery using the *QPS Fledermaus* software.

Sedimentological analysis

Short cores (< 1.5 m; Table 2) were collected with a percussion corer from an ice surface during winter at all of the studied lakes. Based on the sub-bottom profile dataset, one coring site in each lake was chosen to sample recent undisturbed sediments to get a deposition rate through ^{210}Pb radiometric activity. Cores were analyzed through a CT-Scan at the Institut National de la Recherche Scientifique Centre Eau Terre Environnement (INRS-ETE) in Québec City and then split, visually described and photographed. Magnetic susceptibility (MS) was measured manually every centimeter using a *Bartington MS3*.

Samples were collected in cores at every centimeter on the upper 15 cm for ^{137}Cs and ^{210}Pb radiometric analyses. The sedimentation rates (SR), assuming a constant rate, were calculated using:

$$SR = - [(\ln(2)/(Slope*22.3)]$$

(e.g., Gagné et al., 2009; Duboc et al., 2016). No samples from a depth deeper than where the non-supported ^{210}Pb activity values reach the supported ^{210}Pb activity values were used to calculate each respective sedimentation rates. On the other hand, the radiometric activity of ^{137}Cs allowing sediment deposited in 1963 AD to be identified by the peak activity of ^{137}Cs attributed to the atmospheric nuclear bomb testing (Arnaud et al., 2002). Radiometric activity was measured on every samples at the Laboratoire de Radiochronologie of the Centre d'études nordiques (U. Laval).

Table 2

Description and location of cores collected in the investigated lakes.

RESULTS

Lake bottom morphology

High-resolution swath bathymetric imagery reveals similar morphologies on the lake basin floors at all three lakes: headwall scarps, gullies, lobe of hummocky debris and hummocky topographies (Fig. 2). These morphologies are typical of lacustrine basins affected by mass-movements (e.g., Hampton and Locat, 1996; Moernaut and De Batist, 2011). These observations are also coherent with results of previous studies that highlighted that the studied lakes are affected by mass-movements (Ouellet, 1996; Normandeau et al., 2013, 2017). Therefore, the above morphological criteria (Fig. 2) are here used to identify MMDs on the high-resolution swath bathymetric imagery.

Acoustic stratigraphy

For the purpose of this study, the seven acoustic units previously identified in the three lakes by Normandeau et al. (2013, 2017) have been grouped into three main depositional units, providing a stratigraphic framework (Fig. 3). Ua located at the bottom of the stratigraphic sequence lacks acoustic penetration and is interpreted as ice-contact sediments (till) or bedrock. Ub is a thick acoustically transparent unit overlaid by high amplitude parallel reflections and groups U3 and U4 of Normandeau et al. (2013). This unit results from the high sedimentation rates of the glaciomarine environment of the Champlain Sea during rapid ice margin retreat (Normandeau et al., 2013). Uc has low amplitude parallel reflections and is associated with paraglacial and postglacial sedimentation; it groups U5, U6 and U7 of Normandeau et al. (2013, 2017).

These three units are observed in Lake Aux-Sables and Lake St-Joseph, but the acoustic attenuation in the sediments limited the signal penetration down to Ua in Lake Maskinongé. However, Ub and Uc are identified in every investigated lake. MMD acoustic facies is observed in Ub and Uc: it is acoustically transparent to chaotic, has a hummocky topography, an erosive base and a lense geometry (Fig. 3).

Lake Maskinongé

The high-resolution bathymetric map of Lake Maskinongé (Fig. 4a) reveals three distinct types of lake floor morphologies (Fig. 4b): 1) a flat smooth surface; 2) linear to sinuous structures from 50 to 100 m wide and ~600 m long, appearing slightly shallower (≤ 1 m) and in topographic unconformity with the flat bottom floor; and 3) widespread mass-movement surface morphologies, such as hummocky topography, displaced blocks, scarps on the southeastern margins and lobes of hummocky debris extending away from the lateral slopes. The linear to sinuous structures all converge towards the deep basin and are located on the northern slope at the front of the Mastigouche River mouth. MMDs are all coalescent, forming one large-scale chaotic area on the lake bottom, covering the base of the western, southern and eastern slopes of the lake (Fig. 4b). MMD morphologies cover 4.09 km^2, which represents 40% of the lake basin surface.

The sub-bottom profiles show the acoustic facies of the deposits underlying the topographic morphologies (Fig. 5). Below the smooth flat bottom floor lies 4 m of continuous parallel reflections (Uc). Sub-bottom profiles show a lateral unconformity under the morphological linear to sinuous structures where the parallel reflections are acoustically chaotic and vertically offset. Lenses of acoustically chaotic sediments associated with MMD facies are visible at three different intervals within the acoustic sequence. These lenses are observed at depth of 5.5-6.0 m (Event ME1 within Ub), 1.5 m (Event ME2 within Uc) and 0.5-1.0 m (Event ME3 within Uc), indicating three distinct mass-movement events. The acoustic attenuation in the sediment made it impossible to delineate the base of the first and second deposit of mass-movement on all of the sub-bottom profiles. In this case, MMDs overly directly the acoustically transparent glaciomarine unit (Ub). However, ME2 deposit underlies the extensive hummocky topography observed on the swath bathymetric imagery (Fig 6), as ME3 is associated with small MMD lenses located only at the base of slopes. Based on the sub-bottom profiles where the bottom of ME2 is observed, the deposits ME2 and ME3 reach a maximal thickness of 7 m and 1.5 m, respectively. The isolated displaced blocks are characterized on sub-bottom profiles by high-amplitude parallel reflections and sharp vertical sidewalls. The displaced blocks rise up 4.5 m above the MMDs (Fig. 5b) and the parallel reflections indicate that they are areas of remnant sediments not displaced by mass-movements.

At a location selected from the analysis of the sub-bottom profiles, a short core (MAS15-1aP), 105 cm long, was collected at a strategic undisturbed location in Uc (Fig. 7). Structures caused by the freezing of the sediment during core collection appear as black areas on the CT-Scan images. ^{210}Pb profile of Lake Maskinongé is non-linear and the values between the depth of 6.25 cm and 8.25 cm are probably related to a rapid sedimentation event and were excluded from the calculation of the depositional rate (Fig. 8). The peak activity of ^{137}Cs measured in the core is observed at a depth of 7.25 cm, while the ^{210}Pb radiometric activity reveals a depositional rate of 0.18 cm yr^{-1} (Fig. 8). The depositional rate obtained by the ^{210}Pb radiometric dating methods is in good agreement with ^{137}Cs peak activity. A layer (ML1) with high CT-numbers values is observed in the upper part at a depth of 8.5 cm (~ 12 cm thick) and also corresponds to high MS values (Table 3, Fig. 7). Such high values indicate a detrital source of sediment rather than organogenic material. According to the calculated depositional rate, the layer ML1 is dated at ~1969 AD.

Table 3

Depth, thickness and date of the layers observed in each core.

Lake Aux-Sables

Analysis of the high-resolution swath bathymetric imagery of Lake Aux-Sables (Fig. 9a) reveals two main types of lake bottom morphologies (Fig. 9b): 1) a smooth lake bed surface, present on the flat basin floor and on the slopes; and 2) the widespread occurrence of MMD surface features in the basin. The smooth lake bed surface is observed in southeastern and northern sectors of the lake. MMD features are mostly concentrated in the south-central sector of the lake, but a few small isolated morphologies are also observed in its northern sector. MMD structures are located at the base of the slopes and are characterized by a hummocky topography. Headscarps and gullies are typical morphologies observed on the lake slopes (Fig. 10). Lobes of hummocky debris are also splayed from the lateral sidewalls onto the central basin. MMD surface morphologies cover 1.8 km^2, representing 35% of the lake surface.

Sub-bottom profiles (Fig. 11) show an uppermost unit (Uc) acoustically transparent on the lake lateral shelves, as MMDs facies are observed in the deep basin (Event SE1 within Uc). Uc has a smooth topography and drapes the underlying glaciomarine unit (UB) conformably, while MMDs facies has a hummocky topography and a sharp erosive contact at its base. MMDs of the event SE1 reach a maximum thickness of 5 m on the sub-bottom profiles. No sediment apparent on the sub-bottom profileare observed over the MMDs of event SE1, suggesting that the MMDs are modern in age or have the same acoustic signature as the overlying gyttja deposit.

A sediment core (LAS15-1P), 131 cm long, was collected in Lake Aux-Sables in the undisturbed Uc (Fig. 7). ^{210}Pb profile of Lake Aux-Sables is non-linear due to biological mixing at the surface (Fig. 8). Thus, the two surficial values were excluded from the calculation of the sedimentation rate. The ^{210}Pb radiometric activity reveals a depositional rate of 0.08 cm yr^{-1}, which is in general agreement with the peak activity of ^{137}Cs observed at a depth of 5.75 cm (Fig. 8). Layers of high CT-numbers values are observed at a depth of 5.5 cm (SL1), 23 cm (SL2) and 35 cm (SL3) in LAS15-1P, with a respective thickness of 4.5 cm, 5.5 cm and 6 cm (Table 3, Fig. 7). Such depths suggest a deposition of the detrital layers around 1947 AD (SL1), 1785 AD (SL2) and 1704 AD (SL3); note that the thickness of the layers was subtracted from the depth to calculate the ages. The MS in core LAS15-1P is highly variable and only the second layer of high CT-number values (SL2, 23 cm) corresponds to a small increase of MS.

Lake St-Joseph

The northern and southern basins of Lake St-Joseph are isolated from each other by a 2-m deep central sill (Fig. 12a, b); both have distinct morphologies and bathymetries. The southern basin has a flat and uniform shallow lake bottom morphology (≤ 12 m); the northern basin is deeper (≤ 37 m) with widespread MMD surface morphologies. Mass-movement morphologies observed on the bathymetry imagery include headscarps, residual mounds, hummocky topography and compression ridges caused by frontal thrusting (Fig. 12b, 13). The hummocky areas of MMDs in the northern basin originated from the northeastern, southern and eastern slopes and coalesce on the basin-floor. They cover 2.8 km^2, representing 36% of the basin surface.

Three different stratigraphic levels of MMDs are observed on the sub-bottom profiles in Ub and Uc, indicating distinct mass-movement events (Fig. 14). Two stacked transparent to chaotic lenses (MMD Facies) are observed in a topographic depression at the base of the western slope, buried under 5.5 m of sediments (Events JE1 & JE2 within Ub). A third acoustically transparent to chaotic lens associated with MMD facies is located at the base of the eastern slope (Event JE3 within UC). This thick (≤ 10 m) lens underlies hummocky topography and has a sharp erosive base. The interface between the uppermost MMDs (JE3) and Ub is characterized by a high-amplitude acoustic reflection. Compression ridges associated with frontal thrusting are located at the distal part of MMDs. These ridges make a lateral transition between MMDs facies and the undisturbed acoustically laminated Uc. The thick JE3 MMD is covered by 0.5-1.0 m of sediment (Fig. 14a, c).

Core LJS15-1bP, 123 cm long, was collected in the northern basin in an undisturbed sector of Uc (Fig. 7). The ^{210}Pb activity indicates a depositional rate of 0.07 cm yr^{-1}, which is in good agreement with the ^{137}Cs activity at a depth of 3.25 cm (Fig. 8). Layers of high CT-number and MS values are observed at a depth of 19 cm (JL1) and 49 cm (JL2), with a respective thickness of 3.5 cm and 1 cm (Table 3, Fig. 7). According to the depositional rate, these layers are dated at ~1745 AD (JL1) and ~1366 AD (JL2).

DISCUSSION

Seismicity as a trigger of mass-movements

Sediments of the three lakes show evidence of mass-movements that, in terms of area and volume, mostly affected the late-deglacial and postglacial units (Uc: ME2, ME3, SE1 & JE3), although buried MMDs were observed in the glaciomarine unit (Ub: ME1, JE1 & JE2) deposited during deglaciation. Even though the basins are all located within the area of two active seismic zones and are all widely affected by mass-movements, it is necessary to consider every possible trigger mechanism before concluding to a seismic trigger.

High water level variations can trigger slope failures. In the studied area, such variations were limited to the deglacial Champlain Sea transgression and forced regression (from 11.1 cal. Ka BP to 10.5 cal. ka BP) (Occhietti and Richard, 2003), and no major water level fluctuation occurred since the establishment of the postglacial drainage network. Additionally, in contrast to open sea water, lacustrine environments are not subject to high wave energy on shoreline. The studied lakes also have a relatively small surface area (from 5.2 km^2 to 11.3 km^2) reducing the fetch and the possibility to generate strong erosive waves. Therefore, the modern-aged MMDs observed in Uc were most probably not triggered by major water level variations or wave loading on the shoreline. Conversely, it is not excluded that the MMDs observed within the glaciomarine unit (Ub) could have been triggered by a major water level variation although wave loading would be unlikely since the basins were situated in isolated bays during the regression.

The MMDs surface morphologies observed on the swath bathymetric imagery indicate that the disturbed slopes of Lake Maskinongé are not connected to sectors receiving a higher sedimentary input. In fact, the disturbed slopes are located on the opposite side of the lake, whereas the slopes located at the river mouth are the only ones that do not show scarps or MMDs. Lake Aux-Sables disturbed slopes are also not associated with a high sedimentation rate, having no main river input but many small streams instead. The northern basin of Lake St-Joseph is also widely affected by mass-movements but, even though scars are observed on the swath bathymetric imagery near the river discharge, the disturbed area extends far from the delta. However, the surface features observed on the swath bathymetric imagery are only relevant to the modern-aged events. In the studied lakes, late postglacial slope failures deposited within Uc are not associated with an overload resulting from high depositional rates near a river discharge because 1) the majority of the disturbed slopes observed on the swath bathymetric imagery are located far from deltas and 2) the lakes are all characterized by modern low depositional rates (from 0.07 cm yr^{-1} to 0.18 cm yr^{-1}). However, overloading is not excluded as a trigger for the buried MMDs observed within the glaciomarine unit (Ub: ME1, JE1 & JE2), since 1) deglacial times were characterized by higher sedimentation rates (Normandeau et al., 2013, 2016) and 2) the setting of each lake was different at that time, being deeper basins during the Champlain Sea transgression and having different location of sedimentary input.

From the analysis of the swath bathymetric imagery, MMDs are widespread in the lake basins: they extend over a total of 34% to 40% of the surface of the three lakes. According to the high-resolution swath bathymetric imagery and the acoustic sub-bottom profiles analysis, synchronous events occurred within each lake respectively: headwall scarps are observed on different slope orientations and many MMDs are observed within the same stratigraphic unit. The MMDs of events ME2, SE1 and JE3 corresponding to widespread disturbed topography on the lake floors indicate that synchronous events triggered the slopes failures of more than one sidewall and formed one large-scale coalescent MMD or many isolated smaller MMDs in each respective lake. The MMDs of event ME3 do not cover a wide surface area, but are observed at the base of many slopes indicating that small synchronous failures occurred.

Based on the synchronicity of multiple mass-movements (e.g. Schnellmann et al., 2002; Fanetti et al., 2008; Doughty et al., 2010b) and considering that the lakes are all located within the area of two active seismic zones, mass-movements events ME2, ME3, SE1 and JE3 are interpreted to be seismically induced. Similarly, *in situ* disrupted horizontal parallel reflections within a particular layer have been attributed to liquefaction induced by a nearby strong seismic shaking (Shilts et al., 1992; Beck, 2009; Tuttle and Atkinson, 2010). The linear to sinuous structures observed on the swath bathymetric imagery and on acoustic subbottom profiles at the Mastigouche River mouth in Lake Maskinongé are interpreted as liquefaction features since sub-bottom profiles show lateral uncomformity in the acoustic draping parallel reflections indicating that the sediments were fluidilized in situ (Shilt et al., 1992). These disrupted reflections in upper Uc suggest that a strong modern-aged earthquake might have disturbed the sedimentary infill in Lake Maskinongé. However, other possible aseismic triggers are still considered for the deglacial mass-movement events ME1, JE1 and JE2 since depositional environments were highly different at that time.

Deglacial and postglacial seismicity

The stratigraphy and distribution of MMDs in the investigated lakes are here used to reconstruct the history of major seismic events since deglaciation. The ^{210}Pb depositional rates provided a chronological framework, but the proposed chronology represents a minimal age of the events because: 1) only the upper 15 cm of sediments were used to calculate the mean depositional rates and then applied to a depth ranges of 0.5-1.5 m; 2) compaction in the sediments occur with time, implying that the ^{210}Pb radiometric dating overestimates the depositional rates; 3) a mean sound velocity of 1500 m/s was used to calculate the time-travelling depths and no sound velocity correction was applied for the sedimentary column; and 4) measures of depths on the sub-bottom profiles have a precision of ~0.5 m.

MMDs in the lakes occur along three distinct stratigraphic levels, indicating three different phases of mass-movements (Fig. 5 & 14, Table 4): deposits of Phase 1 (ME1, JE1 & JE2) are in the glaciomarine unit (Ub), and deposits of phases 2 (ME2) and 3 (ME3 & JE3) are in the upper part of the paraglacial and postglacial unit (Uc) and are separated by 0.5-1.0 m of undisturbed sediments. The stratigraphic position of the MMDs of Phase 1 observed in Ub in Lake Maskinongé and St-Joseph indicates a triggering mechanism during the deglacial Champlain Sea probably related to the rapid initial glacio-isostatic rebound (Normandeau et al., 2013; Lajeunesse, 2016). Normandeau et al (2017) also highlighted 9 stacked MMDs buried in Ub in Lake Aux-Sables. Brooks (2016) suggested that seismic activity can be increased during deglaciation due to the crustal deformation during glacio-isostatic rebound. The buried MMDs are probably associated with the same series of diachronic events that took place during the retreat of the LIS margin, according to each lake basin respective timing of deglaciation. A phase of enhance mass-movement events thus likely occurred around 11.1 to 10.5 cal. Ka BP, during the deglacial Champlain Sea episode, most probably triggered by local seismic activity caused by the rapid initial glacio-isostatic rebound. However, deglacial times were characterised by depositional environments of higher energy, sedimentation rates and water level variation (Normandeau et al., 2013, 2017), which could also precondition the sediments to slope failures (Lajeunesse and Allard, 2002).

The MMD associated to Phase 2 (ME2) is only observed in Lake Maskinongé (Table 4), at a depth of 1.5 m in the postglacial unit (Uc). The extrapolated ^{210}Pb depositional rate over the sedimentary column in the Lake Maskinongé indicates that an earthquake occurred around or before 1180 AD. Brooks (2013a) also dated a large-scale terrestrial landslide (~ 31 km^2) in Quyon Valley, near the WQSZ, at ~1020 yr BP and a minimal magnitude of M ~ 6.1 was estimated. Based on the dating proximity and the intensity of the seismic shock, we suggest that the MMD associated to Phase 2 (ME2) relates to the same event recorded in Quyon Valley, indicating that a strong earthquake ($M \geq 6.1$) from the WQSZ disturbed Lake Maskinongé sedimentary sequence around ~ 1020 yr BP. However, Lake Aux-Sables and Lake St-Joseph stratigraphic sequences did not record that event most probably because they are located farther away from the WQSZ (235 km and 290 km, respectively).

Similarly, the deposit of the third and last phase of mass-movement (ME3 & JE3) is observed in the same paraglacial and postglacial unit (Uc) at a depth of 0.5-1.0 m in Lake Maskinongé and St-Joseph (Table 4). This MMD was cored by Normandeau et al (2013) at a depth of 0.23 cm in Lake Saint-Joseph and dated with bulk sediment at 1250 AD. However, we revise this date since the correlation between bulk sediment dating and a given MMD can be low and such a depth indicate a timing event around 1685 AD using our new depositional rate of 0.07 cm yr^{-1}. According to the depth of the MMDs ME3 & JE3, it seems unlikely that those events relate to the strong (M 6.2) historical earthquake that occurred in 1935 AD in the WQSZ (Doughty et al., 2010b). We rather suggest that the deposits of ME3 & JE3 are associated with the $M > 7$ 1663 AD CKSZ earthquake, since it was the strongest historical event ever recorded in eastern Canada (Locat, 2002). The MMDs of event SE1 in Lake Aux-Sables are most probably related to the same earthquake (CKSZ $M > 7$, 1663 AD) since 1) the lake is located between Lake Maskinongé and St-Joseph, which basins recorded the seismic shock, and 2) the highly chaotic topography of Lake Aux-Sables indicates a modern-aged event. However, it is not clear if the MMDs either are recent or have the same acoustic signature as the overlying gyttja deposit because no sediment apparent on the sub-bottom profile returns are observed over the MMDs.

Table 4

Summarize of the three phases of mass-movements with their respective deposits, date and seismic trigger event.

The seismic events reported by Tuttle and Atkinson (2010) dated at 5.04 ka yr BP in the Charlevoix region and the one reported by Cauchon-Voyer (2008) at 7.25 ka yr BP in the St. Lawrence Estuary are not observed in the sedimentary record of the three studied lakes, suggesting epicenters located farther to the east. The pre-historic WQSZ events reported by Aylsworth et al. (2000) dated at 7060 yr BP and 4550 yr BP were not recorded in the stratigraphy of the studied lakes, neither is the strong recent historical earthquakes of the WQSZ (1935 AD, M 6.2).

Scale of the deposits

The deposits related to Phase 2 in Lake Maskinongé (ME2) represent the main mass-movement structures in its entire acoustic stratigraphy. The deposits of phase 2 (ME2) is thicker than the deposits of Phase 3 (ME3) (7 m v.s 1.5 m thick, respectively), even if the earthquake of Phase 2 is believe to be of smaller magnitude than the event of Phase 3 ($M \geq 6.1$ vs $M \geq 7$, respectively). Conversely, the CKSZ $M > 7$ 1663 AD event triggered the biggest MMD structures in Lake Aux-Sables (SE1, ≤ 5 m thick) and in Lake St-Joseph (JE3, ≤ 10 m thick). It was previously mentioned that Lake Aux-Sables and St-Joseph were not submitted to seismic disturbances during the event of phase 2 of the WQSZ because the lakes are located too far away. The difference of thickness between the deposits of each seismic events indicate that the recurrence rate of strong earthquakes controls the ability of a lacustrine basin to record seismic shaking by reducing the sediment availability to form wide mass-movement deposits under strong seismic shaking (Wilhelm et al., 2016), in favor of frequent smaller deposits instead. In Lake Maskinongé, MMDs of the event ME3 are much smaller than the MMDs of the event ME2 because the failure that occurred some 600 years earlier reduced the sediment availability to generate a large-scale MMDs. Therefore, MMDs associated with a seismic event are not necessarily representative of the intensity or the proximity of an earthquake because the recurrence interval affects sediment availability. In order to identify the intensity of past earthquakes, investigations need to contextualize the seismically induced MMDs in a regional stratigraphic framework and to consider the recurrence rates of strong earthquakes.

RAPIDLY DEPOSITED LAYERS

In contrast with the normal organogenic lacustrine sedimentation, high MS values associated with high CT-numbers values in cores indicate a detrital source of material. These layers are referred here as rapidly deposited layers (RDLs). Similar thin silt layers were observed by Doig (1986) in lakes located in southern Québec and were interpreted to result from the fine grained particles kept in suspension by water oscillation during a sublacustrine mass-movement. Doig (1986) interpreted the RDL as seismically induced due to the proximity of an active seismic zone and to the absence of organic material near the layers, excluding the possibility of flooding. RDLs are also reported in the Saguenay Fjord and were interpreted as turbidites (St-Onge et al., 2004; St-Onge et al., 2012).

In Lake Maskinongé, the RDL ML1 observed at a depth of 8.5 cm (1969 AD) in core MAS15-1aP could result from a terrestrial 1950 AD mass-movement (ArchivesCanada) that occurred in the glaciomarine silty-clay along the shore of the Mastigouche River, the main tributary of the lake. RDLs observed in lacustrine basins are thus not systematically associated with an earthquake, even if the lakes are located near active seismic zones as the entire watershed dynamics need to be considered in order to identify the trigger of such layers in a lake basin. Conversely, the RDL SL1 dated at ~1947 AD in Lake Aux-Sables could be of seismic origin because two significant earthquakes occurred in the WQSZ during the first half of the 20th century (1935 AD, M 6.1; 1944 AD, M 5.8) (Natural Resources Canada, 2018). Similarly, the RDL JL1 in Lake St-Joseph dated at ~1745 AD could have been trigger by the WQSZ 1732 AD (M 5.8) event. No historical earthquakes seem to relate to the RDLs SL2 and SL3 in Lake Aux-Sables and JL2 in Lake St-Joseph, dated at ~1785 AD, ~1704 AD and ~1366 AD, respectively. However, even if a seismic trigger is possible for the RDLs SL1, SL2 and JL1, other local or inter-basin trigger mechanisms such as flood or anthropogenic disturbances are also possible. The RDLs do not show the synchronously-aged multiple deposits key signature of a seismic trigger and our investigations were aimed on only one core from each lake. RDLs might not be recorded in the entire lake basin area, suggesting that single coring investigations do not necessarily provide information on the disturbance rate of a lacustrine basin and paleoseismological investigations should focus on multiple cores sampled from different sites. Coring investigations aiming to reconstruct the history of seismically induced RDLs should also take place away from the sedimentary input of the river mouth.

CONCLUSIONS

High resolution swath bathymetric imagery, sub-bottom profiler and sediment core data collected in three lakes (Maskinongé, Aux-Sables and St-Joseph) located near two active seismic zones (WQSZ and CKSZ) in south-central Québec reveal that the lacustrine basins were highly disturbed by three distinct phases of seismically-induced mass-movements since deglaciation, without any event between late-deglacial and late postglacial times. These mass-movements are interpreted to have a seismic triggering due to 1) the widespread distribution of MMDs, covering ≥ 34% of each lacustrine basin area; 2) the presence of disturbed slopes with headwall scarps located far from a sedimentary input; 3) the occurrence of many MMDs along the same stratigraphic level, suggesting synchronous events; and 4) the presence of liquefaction structures observed on sub-bottom profiles.

MMDs were observed at different stratigraphic levels on sub-bottom profiles of the investigated lakes, allowing the identification of three different phases of seismic events. Taken together, the stratigraphic position of the MMDs and the depositional rates suggest that: Phase 1 occurred during the deglacial Champlain Sea episode (11.1 to 10.5 cal. Ka BP) and produced many mass-movements, when rates of glacio-isostatic rebound were high; Phase 2 around 1180 AD, which is in agreement with a large-scale terrestrial landslide observed in Quyon Valley (western Québec) dated at ~1020 cal. yr BP (Brooks, 2013a); and Phase 3 corresponding to the well documented CKSZ 1663 AD historical earthquake. However, aseismic triggers are still considered for the first phase of mass-movement deposits because deglacial environments were characterized by high sedimentation rates and water level variation. The ^{210}Pb analysis revealing a depositional rate of 0.07 cm yr^{-1} in Lake St-Joseph allow us to revise the Normandeau et al (2013) date for a large-scale MMD to the M ≥ 7 historical 1663 AD event.

Even though the dating represents a minimal age due to errors induced by the sediment compaction and time-traveling-depth variations in the sediments, taken together, our dataset leads us to conclude that a high magnitude seismic event occurred a few hundred years before the CKSZ 1663 AD historical earthquake. We observed that a large-scale MMDs event (ME2: 4.09 km^2, ≤ 7 m thick) recorded in Lake Maskinongé was seismically-induced by the WQSZ M ≥ 6.3 earthquake previously reported by Brooks (2013a) and dated at ~ 1020 yr BP.

The largest MMDs in the three lakes do not correspond to the same phases (Phase 2 in Lake Maskinongé vs Phase 3 in Lake Aux-Sables and St-Joseph) suggesting that the seismological events epicenters occured at different location (WQSZ vs CKSZ). Although Phase 2 (~ 1020 yr BP) MMDs are more extensive in Lake Maskinongé than those of Phase 3 (1663 AD, M>7) MMDs, the event of Phase 2 was not necessarily of a higher magnitude because the occurrence of a mass-movement a few hundred years prior to the 1663 AD historical earthquake must have reduced the sediment availability. Investigations aiming to reconstruct paleoearthquakes must contextualized MMDs in a regional stratigraphic framework and consider the recurrence of slope failures. More morphostratigraphic and sediment core data are needed in eastern Canada to define the extent, exact timing and geomorphological impact of the events of phases 2 & 3.

This study has demonstrated that hydroacoustic investigations coupled with the analysis of sediment cores in lakes located farther away from an active seismic zone provide a reliable record of strong earthquakes in a context of frequent lower magnitudes earthquakes and low sedimentation rates. Different levels of MMDs can be identified in the lakes basin infill, but these deposits must all be separated by normal sedimentation to deduce their thickness and depth.

The coring data show that RDLs are not necessarily related to seismically-induced sublacustrine mass-movements, but can be generated by different events occurring in a lake basin and watershed. Moreover, RDL analysis does not provide information on the disturbance rate of a lacustrine basin since they might not always be observed in the cores. Therefore, sediment core data are considered complementary to swath bathymetric imagery and sub-bottom profiler data and contextualizing them in a morphostratigraphic framework enhances the detail of paleoseismological reconstructions. Further investigations using a lower frequency subbottom profiler (e.g., boomer) showing the entire Quaternary stratigraphic sequence and multiple long sediment cores should be undertaken in these lakes as well as others of eastern Canada in order to extend the sedimentary archives of mass-movements.

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Table 1

Physical characteristics of the investigated lakes.

Lake	Coordinates	Elevation (m) asl	Distance from WQSZ *(km)	Distance from CKSZ *(km)	Maximum depth (m)	Area (km^2)
Maskinongé	46°19.78N 73°23.92W	140	140	285	25	10.2
Aux-Sables	46°52.93N 72°21.95W	150	235	185	41	5.2
St-Joseph	46°55.00N 71°39.00W	160	290	135	37	11.3

* Distances were measured from the center of the seismic zones to the center of each respective lake.

Table 2

Description and location of cores collected in the investigated lakes.

Core number	Lake	Coordinates	Depth (m)	Length (cm)
MAS15-1aP	Maskinongé	46°18.73N 73°23.43W	18.5	105
LAS15-1P	Aux-Sables	46°53.12N 72°22.00W	39	131
LSJ15-1bP	St-Joseph	46°54.82N 71°38.76W	37	123

Table 3

Depth, thickness and date of the layers observed in each core.

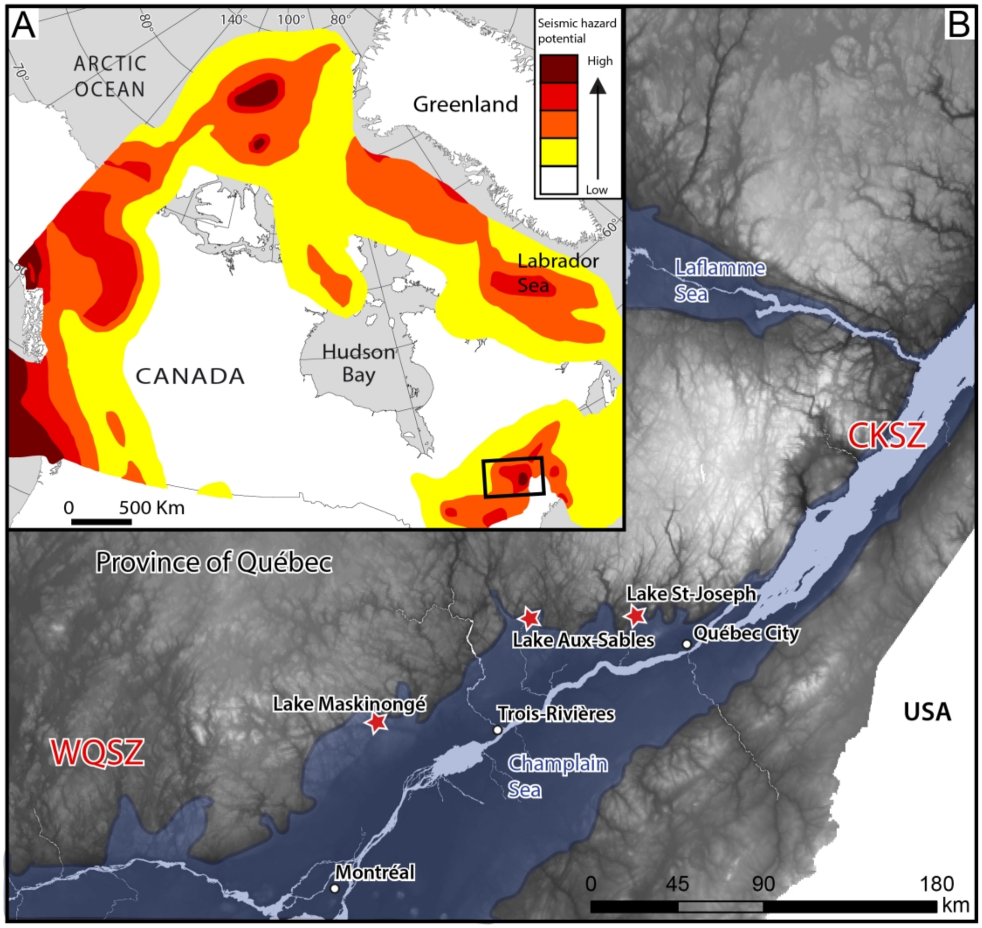
Core number	Layer	Depth (cm)	Thickness (cm)	Depositional rate (cm yr^{-1})	Calendar age (AD)
MAS15-1aP	ML1	8.5	3.0	0.18	1969
LAS15-1P	SL1	5.5	4.5	0.08	1947
LAS15-1P	SL2	23	3.5	0.08	1785
LAS15-1P	SL3	35	6.0	0.08	1704
LSJ15-1bP	JL1	19	3.5	0.07	1745
LSJ15-1bP	JL2	49	1.0	0.07	1366

Table 4

Summarize of the three phases of mass-movements with their respective deposits, date and seismic trigger event.

Phase	MMDs event	Depth (m)	Maximal thickness (m)	Calculated calendar age* (AD)	Seismic event	Seismic zone
1	ME1	5.5 - 6.0	-	Deglacial Champlain Sea transgression	11.1 to 10.5 Ka yr BP	-
	JE1	> 5.5	4			
	JE2	5.5	3			
2	ME2	1.5	7	1180	~ 1020 yr BP	WQSZ
3	ME3	0.5 - 1.0	1.5	1739	1663 AD	CKSZ
	SE1	-	5	-		
	JE3	0.5 – 1.0	10	1685		

*Note that the calculated age represent a minimal age.



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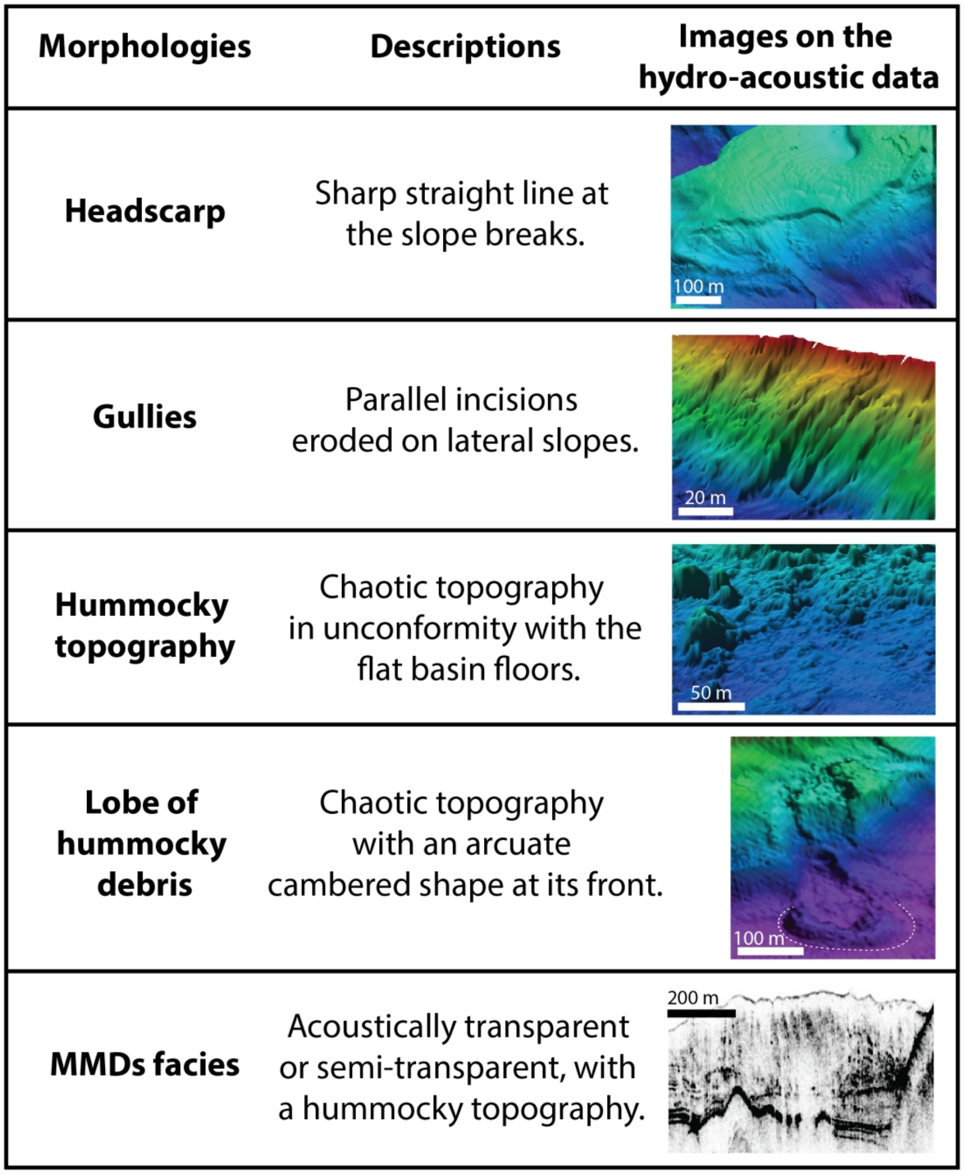

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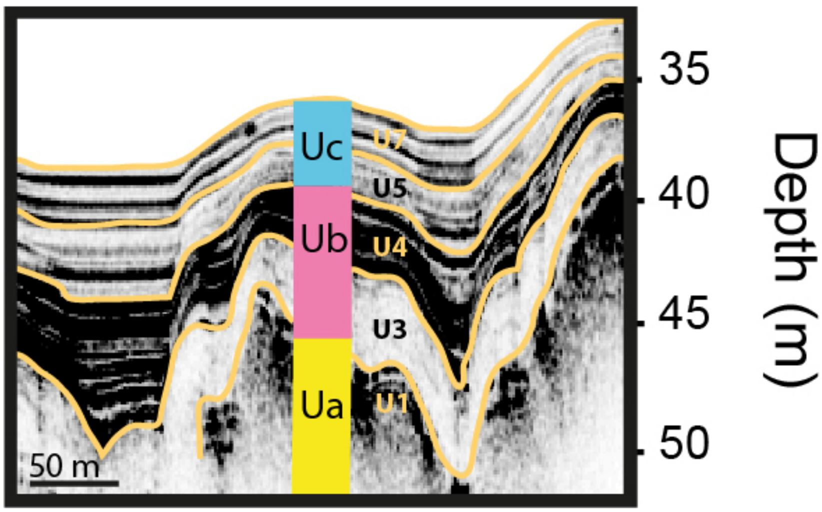

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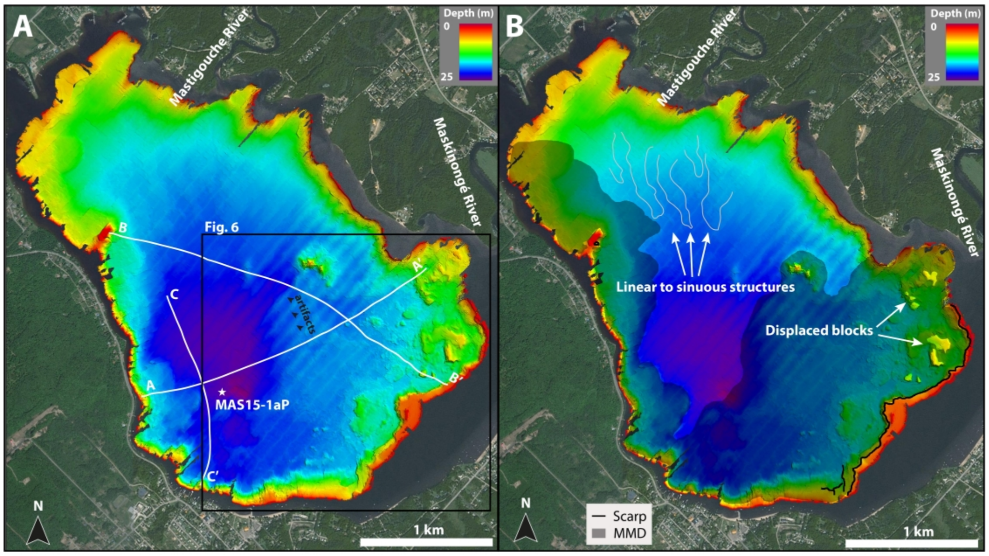

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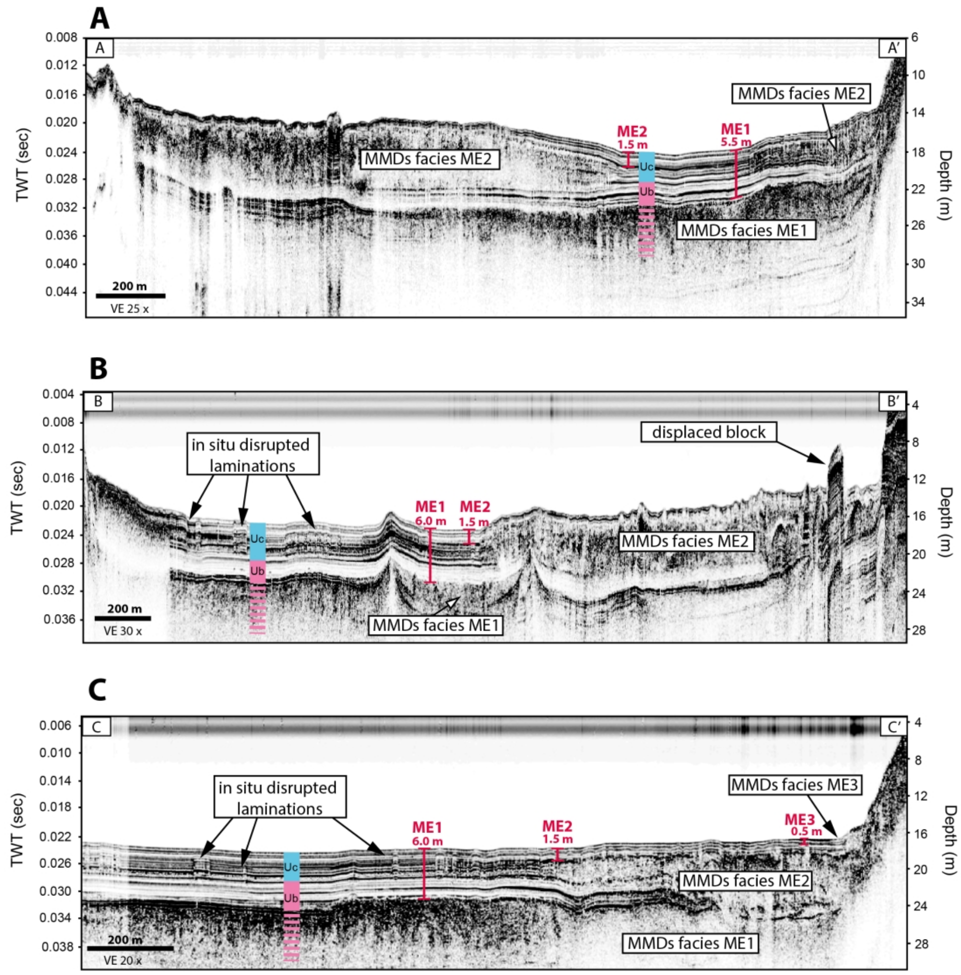

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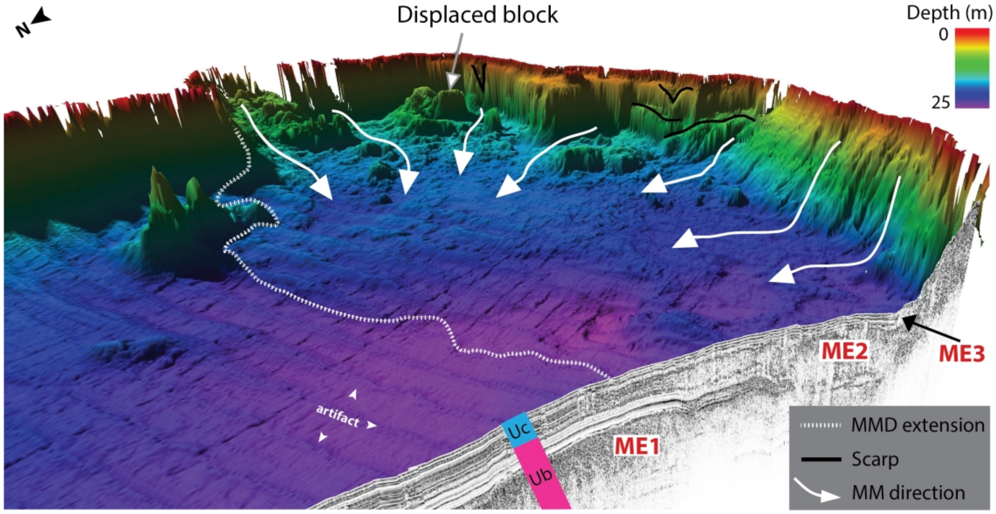

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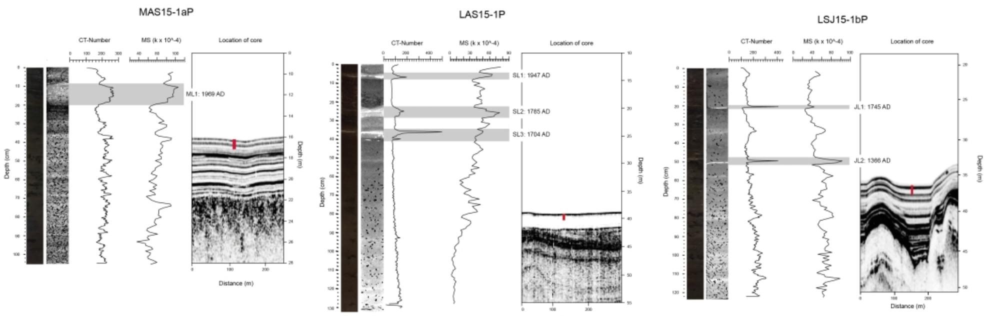

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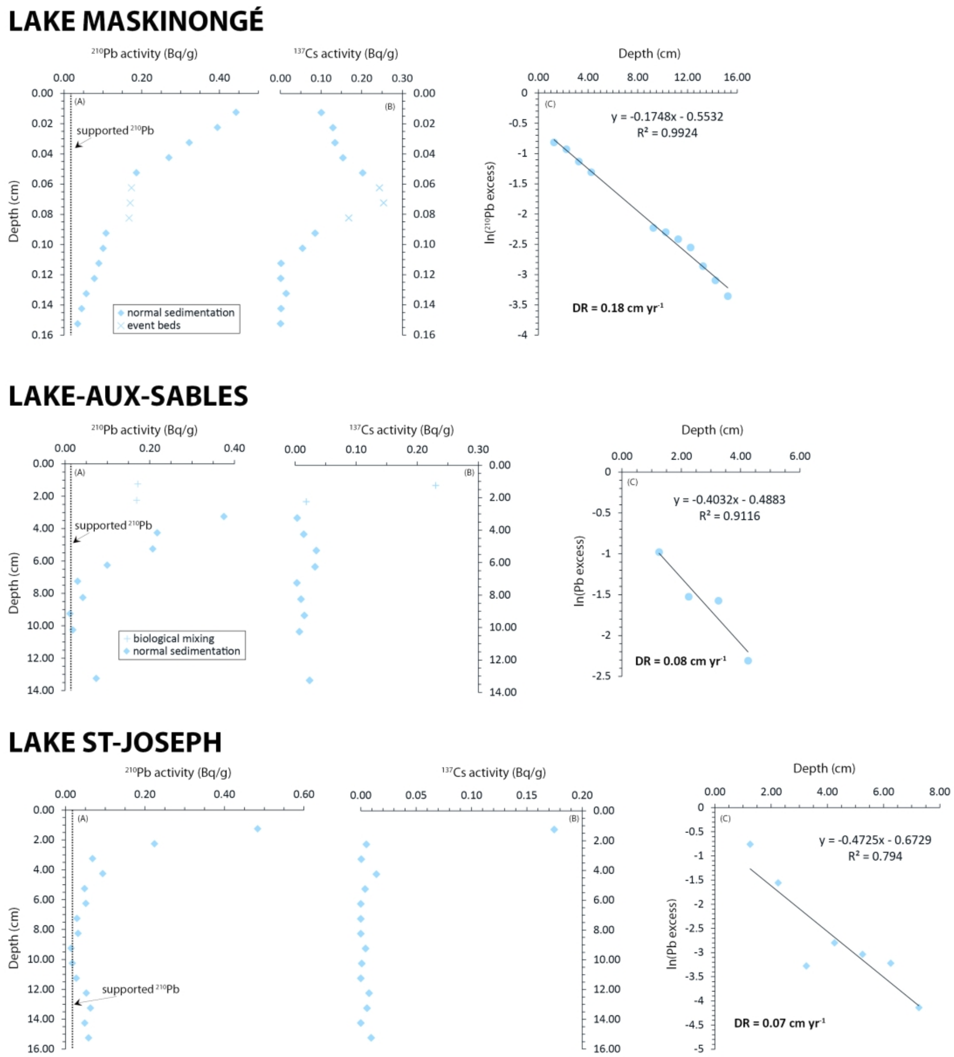

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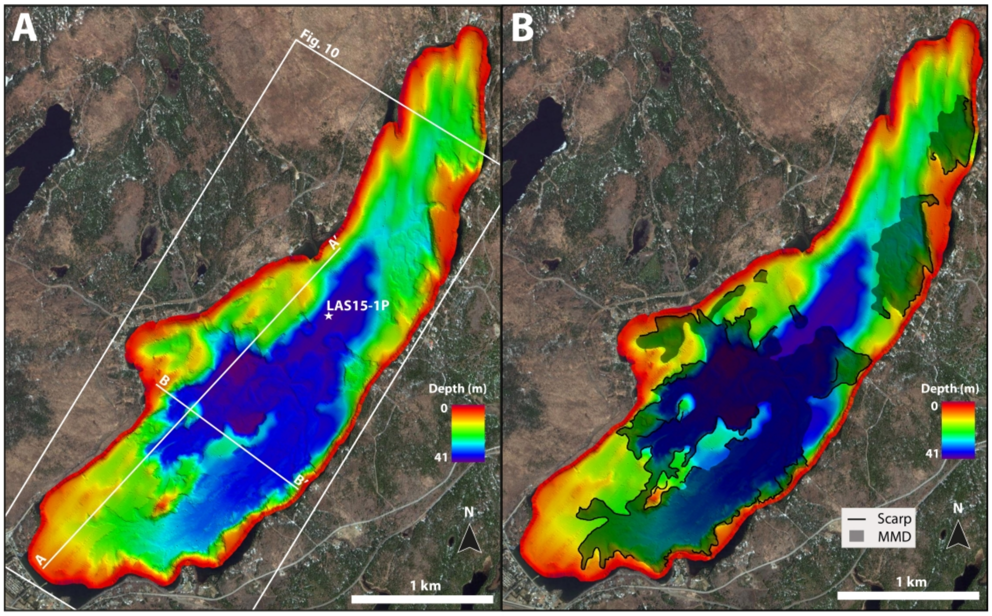

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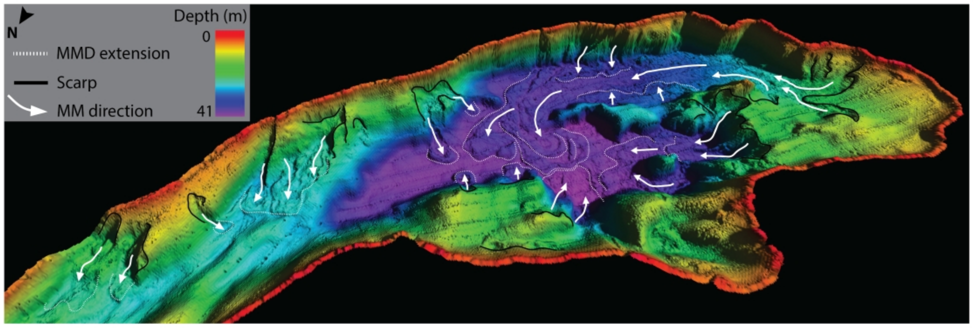

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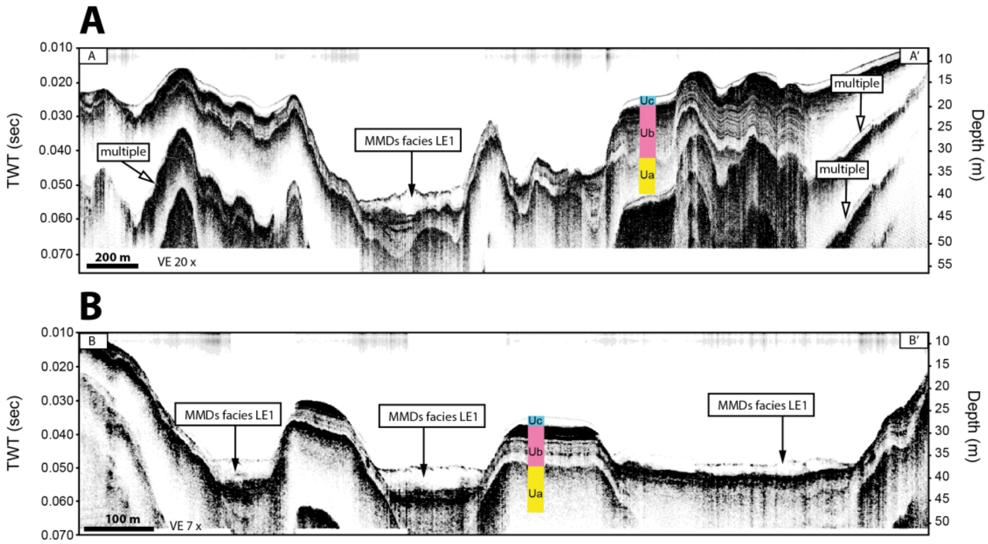

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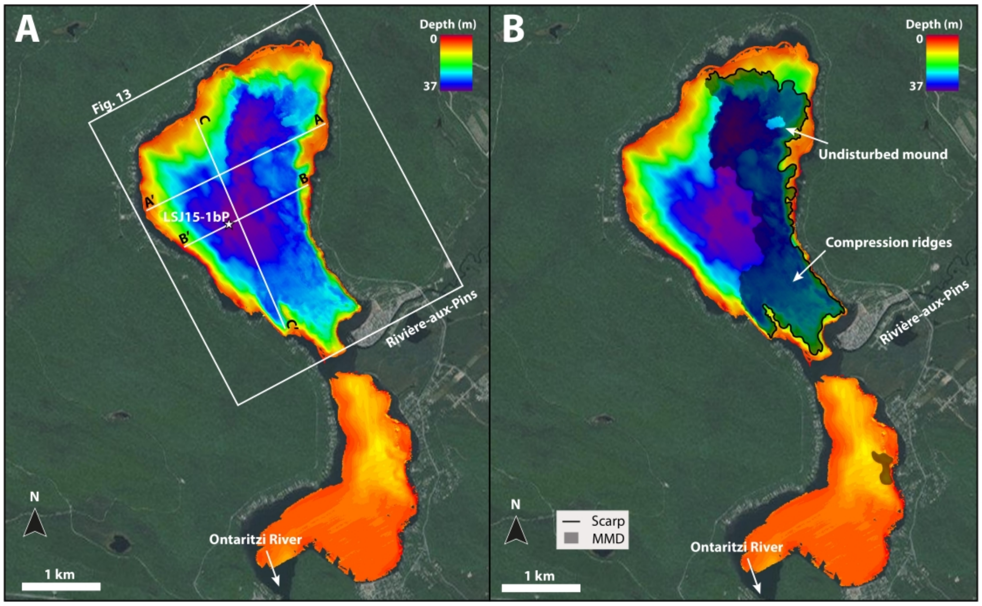

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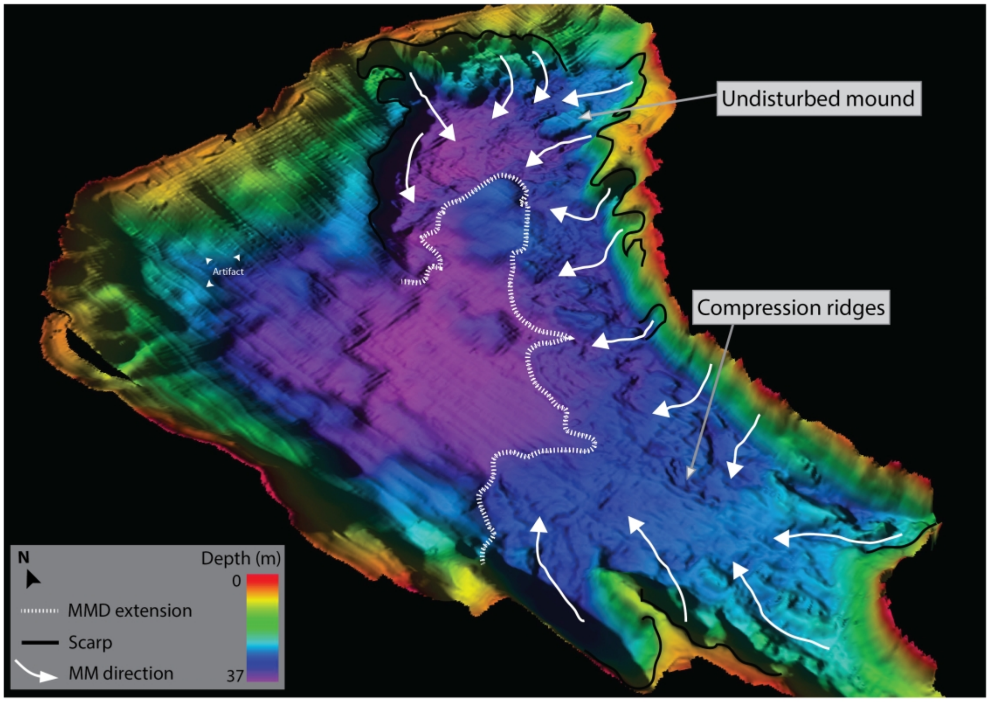

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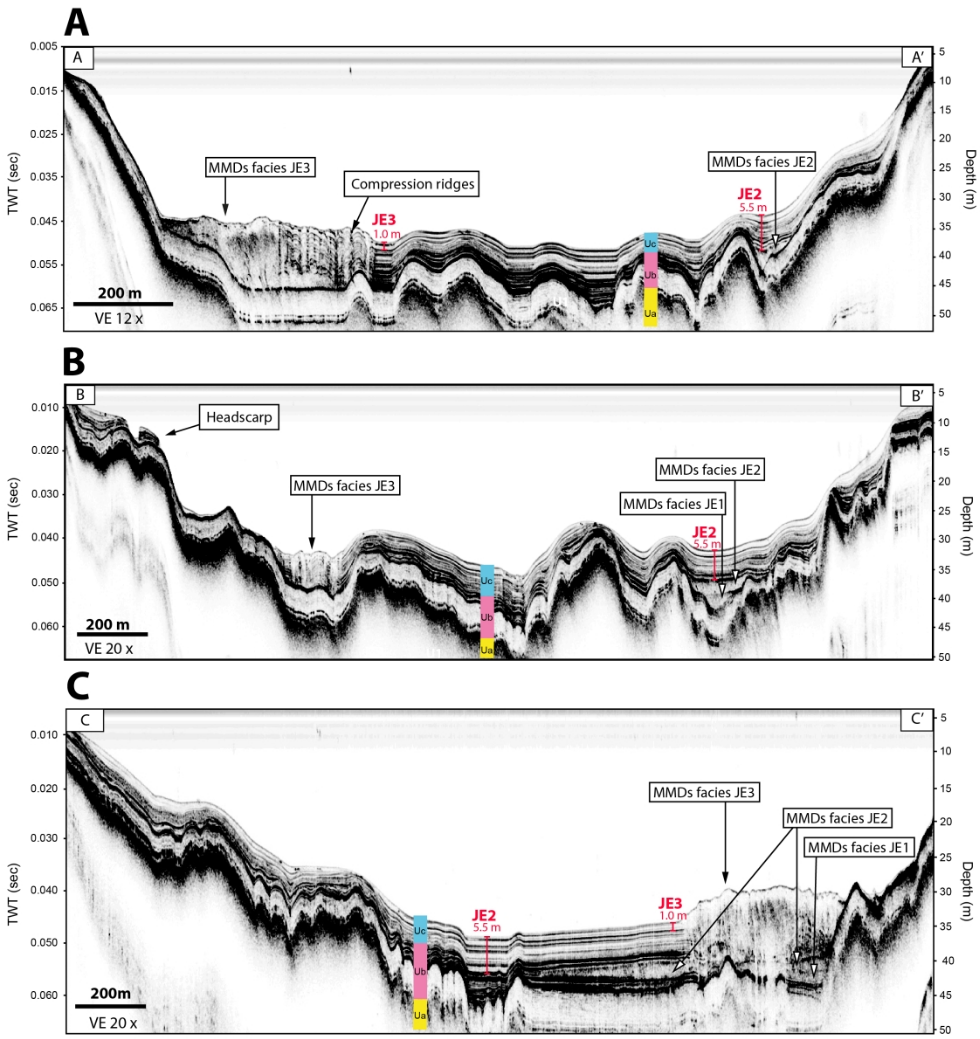
279x199mm (300 x 300 DPI)



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