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High-resolution seismic stratigraphy of Late Pleistocene Glacial Lake Iroquois and its Holocene successor: Oneida Lake, New York

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ABSTRACT

Oneida Lake, New York, is the remnant of Glacial Lake Iroquois, a large proglacial lake that delivered fresh water to the Atlantic Ocean during the last deglaciation. The formation of Glacial Lake Iroquois and its subsequent drainage into the Atlantic Ocean via the Mohawk Valley was a significant shift in the routing of Laurentide Ice Sheet meltwater to the east instead of south via the Allegheny or Susquehanna Rivers. Catastrophic drainage of Glacial Lake Iroquois into the Atlantic Ocean via the Champlain Valley is interpreted as the meltwater pulse responsible for the Intra-Allerod cold stadial. Therefore, understanding the evolution of Glacial Lake Iroquois has significant implications for understanding late Pleistocene paleoclimate.

High-resolution CHIRP seismic reflection data provides insight into the evolution of Glacial Lake Iroquois and Oneida Lake. Three seismic units image distinct stages of the Oneida Basin. Unit 1 is interpreted as proglacial lake deposits that overlie glacial till. Unit 2 is interpreted as sediments deposited when the Oneida Basin became isolated from Glacial Lake Iroquois and Unit 3 is interpreted as lacustrine sediments of the modern lake. Distally sourced turbidites possibly triggered by seismic activity or ice sheet meltwater pulses are represented as reflection-free acoustic facies that infill topographic lows and range in thickness from ~1–5 m within otherwise conformable proglacial lake deposits. Local slump deposits imaged at the boundary between Unit 1 and 2 were likely triggered by the drainage of Glacial Lake Iroquois. Wave cut terraces indicative of a low stand on the upper bounding surface of Unit 2 are likely the result of drier conditions during the Holocene Hypsithermal. Furthermore, preservation of this low stand suggests a rapid rise in lake level, possibly the result of the same transition to a wetter climate responsible for the Nipissing transgression observed in the Laurentian Great lakes.

1. Introduction

During termination of the last glacial period, retreat of the Laurentide Ice Sheet produced massive amounts of glacial meltwater forming Glacial Lake Iroquois (Muller and Prest, 1985; Muller and Calkin, 1993; Rayburn et al., 2005). Drainage of Glacial Lake Iroquois influenced global climate (Donnelly et al., 2005), however few studies have analyzed the late Pleistocene stratigraphy and evolution of the lake. Furthermore, formation of Glacial Lake Iroquois and its drainage via the Mohawk Valley (Fig. 1) was a significant change in the route of meltwater discharge. Before formation of Glacial Lake Iroquois glacial meltwater was routed through the Susquehanna and Allegheny Rivers, draining into the Atlantic Ocean at a lower latitude (Muller and Prest, 1985; Muller and Calkin, 1993; Marsh, 2017). Oneida Lake in central New York is the modern remnant of the southeastern section of Glacial Lake Iroquois, and is located adjacent to the Mohawk Valley (Fig. 1). Therefore, late Pleistocene sediments deposited within the Oneida Basin provide insight into the evolution of Glacial Lake Iroquois and its drainage through the Mohawk Valley until it catastrophically drained via the Covey Hill Gulf into the Champlain Valley. Here we present high-resolution seismic reflection data from Oneida Lake, which contains stratigraphic features and seismic stratigraphic units that provide insight into the evolution of Glacial Lake Iroquois and the Oneida Basin. Furthermore, the upper stratigraphic section provides insights into the Holocene hydroclimate of the Oneida Basin.

2. Geologic background

Oneida Lake in central New York is the largest body of water contained completely within New York State (Fig. 2). The lake measures ~34 km long (E-W) and ~8 km wide (N-S), with a total area of ~207 km^2. Oneida Lake has a maximum depth of 16 m and a mean depth of 6.8 m (Dean et al., 1981), and is relatively shallow compared to the Finger Lakes located to the west (Mullins et al., 1996). The lake's

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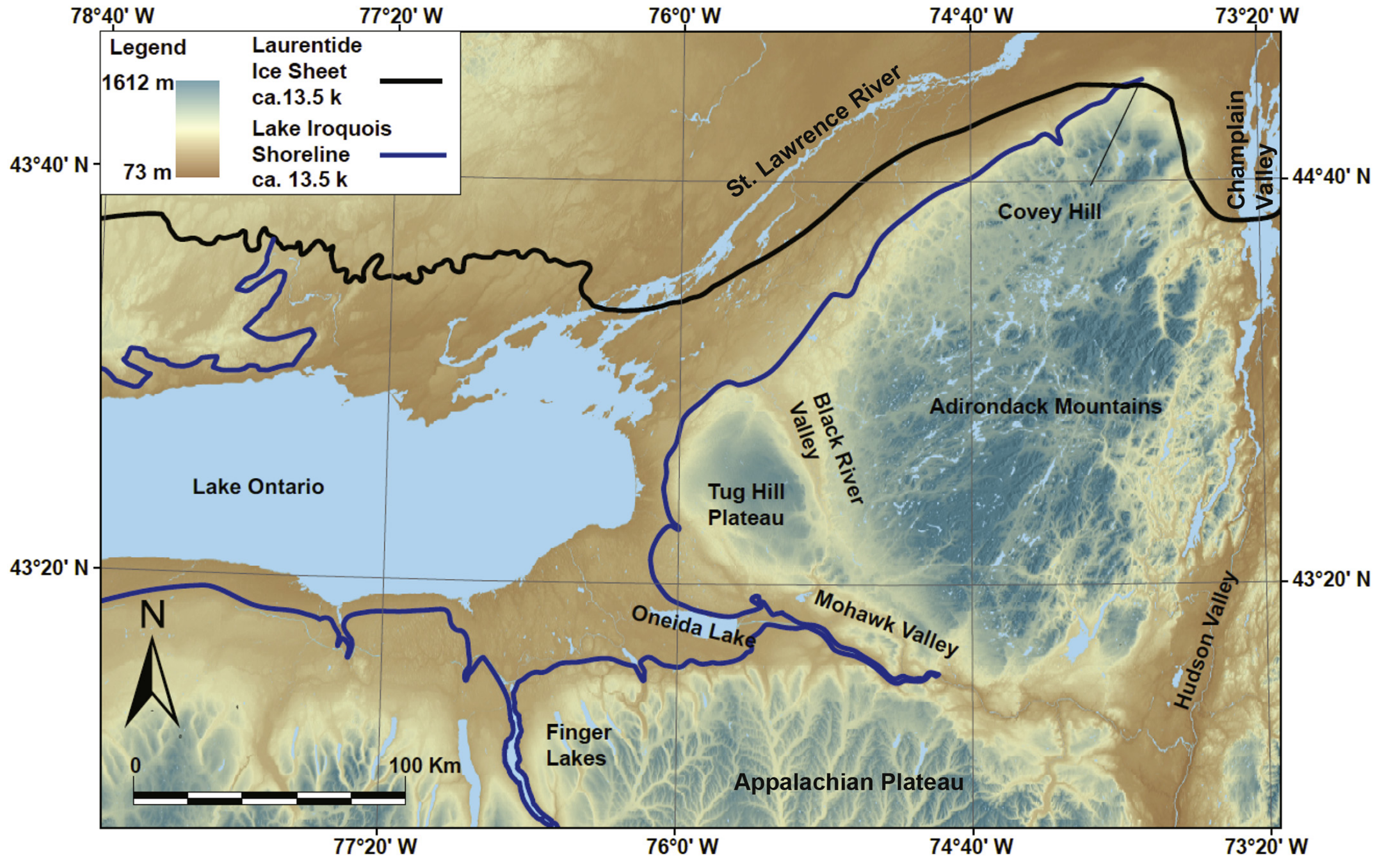

Fig. 1. Regional digital elevation model of the study area. The shoreline of Glacial Lake Iroquois indicated by the blue line and the approximate location of the Laurentide Ice Sheet indicated by the black line (Bird and Kozlowski, 2016) ca. 13.5 k cal BP (Lothrop et al., 2016). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

outlet drains to the west into the Seneca River and eventually into Lake Ontario. Wood Creek, located on the eastern shore is the largest input into Oneida Lake. Oneida Lake is the remnant of a major impoundment of glacial meltwater formed during the late Pleistocene known as Glacial Lake Iroquois (Fairchild, 1909; Donnelly et al., 2005; Rayburn et al., 2005). Glacial Lake Iroquois's northern border was the Laurentide Ice Sheet, and its southern border is defined by topographic highs including the Appalachian Plateau (Fig. 1). Meltwater from Glacial Lake Iroquois was first released to the Atlantic Ocean via the Hudson Valley and then through the St. Lawrence River (Donnelly et al., 2005). The lake initially drained into the Hudson Valley via the Mohawk Valley until drainage was redirected to the Champlain Lowlands after recession of the Laurentide Ice Sheet north of the Covey Hill Gulf (Fig. 1). As the Ontario Lobe of the Laurentide Ice Sheet retreated to the north, other topographic lows opened until the system drained through the St. Lawrence River (Donnelly et al., 2005). The formation of the lake and alterations in drainage occurred over a time period that included the Older Dryas (ca. 14.3–14 cal kyr BP), Intra-Allerod (ca. 13.35–13.1 cal kyr BP), and Younger Dryas (ca. 12.9–11.8 k cal kyr BP) events, all significant paleoclimate fluctuations (Stuiver et al., 1995; Rasmussen et al., 2006; Ridge et al., 2012; Rasmussen et al., 2014). Lake level within the Oneida Basin was presumably affected by changes in the location of key drainage points, but also by isostatic tilting from glacial unloading, similar to what has been documented in Lake Ontario and Lake of the Woods (Dyke, 2004; Rayburn et al., 2005; Lewis and Anderson, 2012; Hougardy and Colman, 2018).

3. Methods

Approximately 305 km of high-resolution seismic reflection data were collected using an Edgetech SB424 (4 to 24 kHz) CHIRP (Compressed High Intensity Radiated Pulse) sub-bottom profiler and Discover™ acquisition software. The CHIRP profiler was towed at ~0.5 m below the water surface at a speed of ~4 knots. Positioning data for all shots were acquired using a Trimble AG132 GPS Navigation system in autonomous mode. Initially, 80 km of widely-spaced seismic lines (~2–4 km line spacing) were collected in 2013 and 2014 in a reconnaissance grid, designed to cover as much of the lake as possible. In the summer of 2018 an additional 180 km of seismic data were collected over regional profiles and in three high density grids. The locations of the three high density grids were selected based on the identification of various stratigraphic features in the 2013 and 2014 datasets; the high density grids have line spacings of 250–500 m. An additional 45 km of seismic data with a spacing of approximately 1.5 km were collected in the fall of 2018 (Fig. 2A). All data were analyzed and interpreted using DecisionSpace™ seismic interpretation software.

4. Results

The high-resolution seismic reflection data from Oneida Lake reveal three main depositional units above a lake-wide acoustic basement reflection (Figs. 2B, 3). Each of these units reveals markedly different internal acoustic attributes, external morphologies, and extents, reflecting important transitions in the late-glacial through modern history of Glacial Lake Iroquois and Oneida Lake (Fig. 1).

4.1. Acoustic basement, Reflection 1

The basal reflection (acoustic basement) in these high-resolution

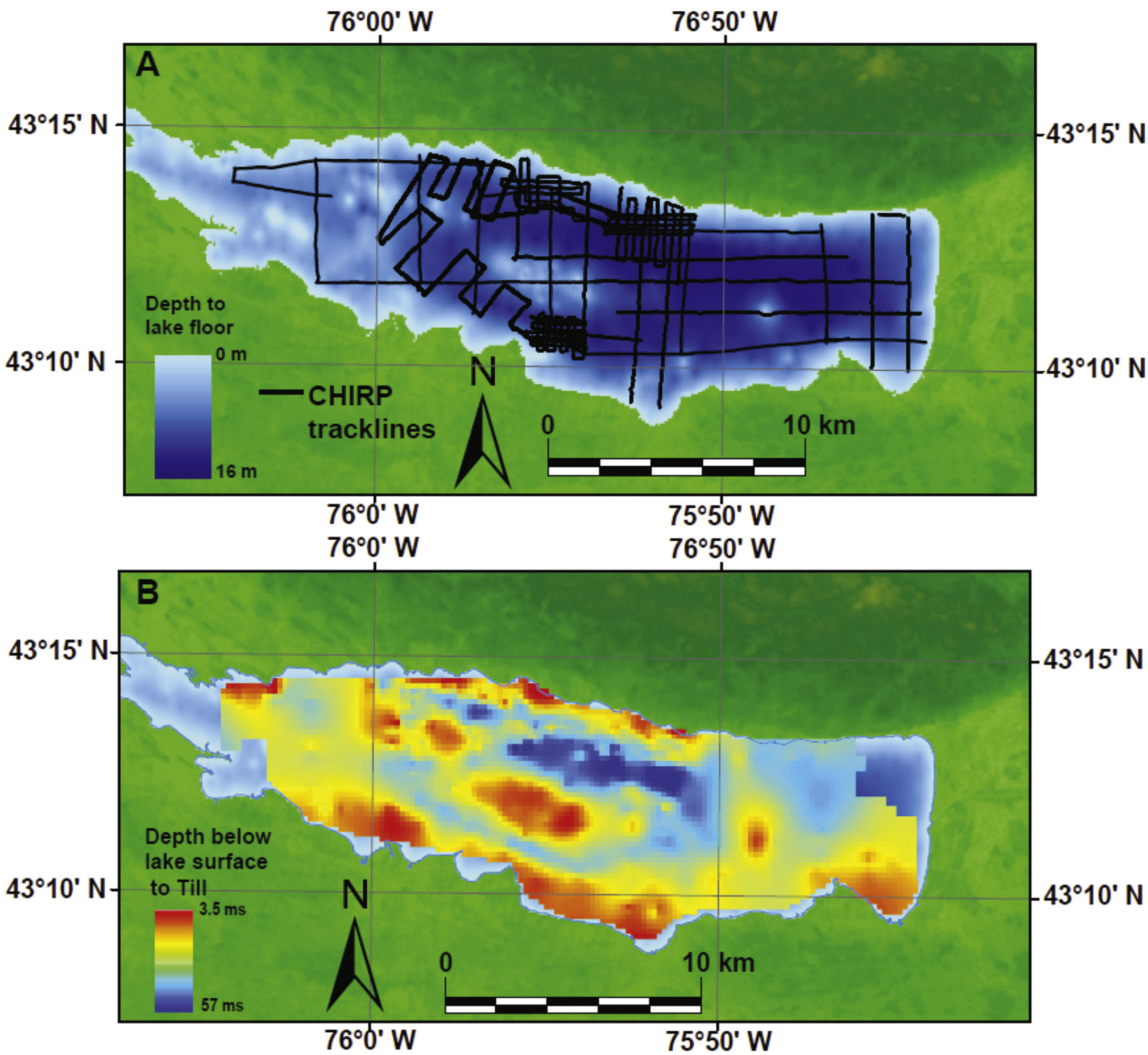

Fig. 2. 2A) Modern bathymetry of Oneida Lake referenced to NAD83 (NOAA) National Oceanic and Atmospheric administration and National Ocean Service Coast Survey, 2016. Tracklines of high-resolution CHIRP seismic reflection data collected for this study indicated by the black lines. 2B) Depth to top of till from the lake surface in two-way travel time. Note the location of the topographic high in the middle of the lake which forms the modern shoals observed in 2A.

seismic data is a moderate- to high-amplitude, continuous reflection. It is best imaged over the modern shoals of Oneida Lake where it is observed at the lake floor, before the reflection descends under the imaged sedimentary section (Figs. 2B, 3). It is imaged as deep as ~57 ms below the lake surface or ~ 45 ms below the lake floor. The apparent dip of the surface is as high as 5° in some locations. The acoustic basement is observed forming a WNW-ESE topographic high in the center of the basin, with two topographic lows on either side of the high (Fig. 2). Acoustic basement is imaged deepest in the northern part of the lake, whereas in the southern basin the reflection is imaged to 45 ms below lake surface. It is well imaged throughout the southern section of the basin, however in the northern section the signal is attenuated by the presence of gas in the stratigraphic column; accordingly, the maximum depth of Reflection 1 is unknown in the center of the lake. On topographic highs the acoustic basement is a high-amplitude, well imaged reflection, whereas in the topographic lows the seismic signal is attenuated by the overlying sedimentary column and the surface is less clearly delineated (Fig. 3).

4.2. Seismic Unit 1

Seismic Unit 1 overlies and drapes Reflection 1 (acoustic basement) (Fig. 3) and contains moderate- to high-frequency internal reflections with high- to moderate-amplitudes, that are highly continuous and parallel (Fig. 4). Unit 1 extends over broad reaches of the Oneida Basin (Fig. 4). The base of the unit (acoustic basement or Reflection 1) is imaged to a maximum of 57 ms below the lake surface datum (maximum of 45 ms below lake floor) and has a maximum thickness of ~28 ms. The top of this stratigraphic unit is imaged as shallow as 4 ms below the lake surface, and is commonly observed outcropping on the lake floor. Seismic Unit 1 is separated into two subunits, 1A and 1B, based upon differences in internal reflection amplitudes over the basin. The two subunits are generally conformable, or show no clear evidence of truncation over the majority of the lake basin. However, Unit 1A is truncated in a few locations (Figs. 3, 4, 5). Both subunits contain medium- to high-amplitude, high-frequency and highly continuous reflections, with Seismic Unit 1B containing markedly higher-amplitude reflections (Fig. 4). Reflection-free, lens-shaped, seismic facies are observed in topographic lows and separate Units 1A and 1B in several locations (Figs. 3, 5, 6). These reflection-free deposits both truncate and

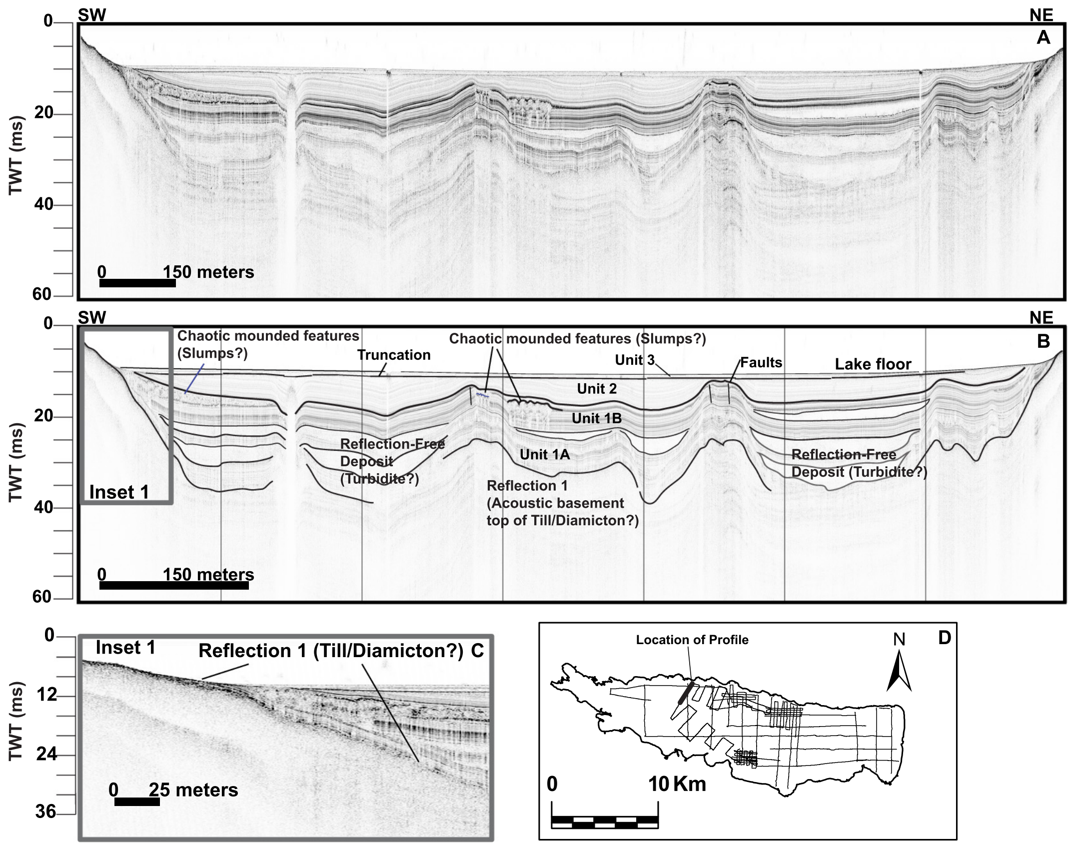

Fig. 3. Uninterpreted (A) and interpreted (B) seismic profile located in northwestern Oneida Lake. Note stacked reflection-free deposits that occupy the bathymetric lows are interpreted to be from a mass transport event such as a turbidity or hyperpycnal flow. Faults on the bathymetric highs and chaotic mounded features are interpreted to be slump deposits. Inset 1 (C) shows Reflection 1 (acoustic basement) interpreted as top of till. D) is trackline map with profile location.

are conformable with the underlying stratigraphy, and three stacked reflection-free deposits are observed in Unit 1B (Figs. 3, 5, 6). These reflection-free deposits vary in size, with the largest covering ~6 km^2 and ~3–5.25 m thick. Several smaller reflection-free deposits are also observed, measuring only 0.25–2 m thick and 10–100 m in apparent width (Fig. 7). These smaller deposits are observed on many profiles, but due to wide seismic profile spacing their geometry is poorly constrained. The larger, better-constrained reflection-free deposits are observed in structural lows, whereas the smaller deposits are broadly distributed across the lake and are even observed on topographic basement highs (Fig. 7). However, the small deposits have the same stratigraphic position, and therefore the same relative age as the larger reflection-free, deposits. Drape style deposition is commonly observed above the reflection-free deposits, however onlap is observed locally in a few instances.

Chaotic reflections as well as transparent horizontal wedge-shaped features are imaged at the top of Seismic Unit 1 (Figs. 3, 5, 8). The chaotic reflections contain internal structures such as offset reflections, tilted reflections, soft sediment deformation and transparent vertical wedges that penetrate into the underlying stratigraphy (Figs. 3, 5). Horizontal transparent wedges are imaged directly below steep erosive surfaces that truncate Unit 1B (Fig. 8). These features are always observed toward the top of Seismic Unit 1B, and occur on slopes with apparent dips up to 3°. The upper part of the chaotic reflections is irregular, hummocky, high-amplitude surfaces with positive relief (Figs. 3, 5). These deposits range in thickness from 2 to 6 ms and are observed between 13 ms and 23 ms below the lake surface, with a length-scale along the profiles of ~80–330 m.

4.3. Seismic units 2 and 3

Seismic Unit 2 consists mainly of a parallel-stratified, reflective, low-amplitude seismic facies that in most localities conformably overlies Unit 1 (Figs. 3, 5, 6, 7, 8). Seismic Unit 2 internal reflections are highly continuous, and generally are high-frequency reflections, with amplitudes markedly lower than Seismic Unit 1. The base of Seismic Unit 2 reaches a maximum thickness of ~ 10 ms where the top of the unit is imaged ~30 ms below the lake surface. Unit 2 is not observed in water shallower than 5.2 ms or 3.9 m below lake surface (mbls).

Seismic Unit 3 is a thin, mainly acoustically transparent unit, generally ~1–3 ms thick with a maximum thickness of ~7 ms, that contains a few flat-lying horizontal internal reflections (Fig. 5). Seismic Unit 3 is not imaged in water depths shallower than 8.78 ms or 6.5 mbls where it onlaps onto Unit 2 or 1 (Fig. 7). The deepest it is imaged is within the northern basin where it is observed at a depth of ~15 ms or 11 mbls.

Several abrupt changes in slope are observed at the top of Seismic Unit 2, and these are subsequently buried by Unit 3 or occur on the lake floor (Fig. 7). These abrupt changes in the depth to the top of Unit 2 range in height from 0.7 to 1.4 ms, and are observed at a depths of 10–15 msbls (8.2 to 11 mbls) (Fig. 9). These features occur within or on the flanks of the NW-SE trending lows of Oneida Lake (Fig. 2).

Abrupt changes in bathymetry, with sigmoidal profiles, are observed on eight separate seismic lines near the modern lake shoreline. These sigmoidal features each resemble a classical clinothem and could be terraces or delta fronts (Fig. 10) (e.g. Anell and Midtkandal, 2017). The seismic signal is commonly attenuated at the sediment-water interface of the shallower horizontal surface or topset, and accordingly it is difficult to discern the seismic unit that underlies each of these features. On four of the observed sigmoidal features (out of eight observed), the seismic signal does not penetrate below the lake floor, and

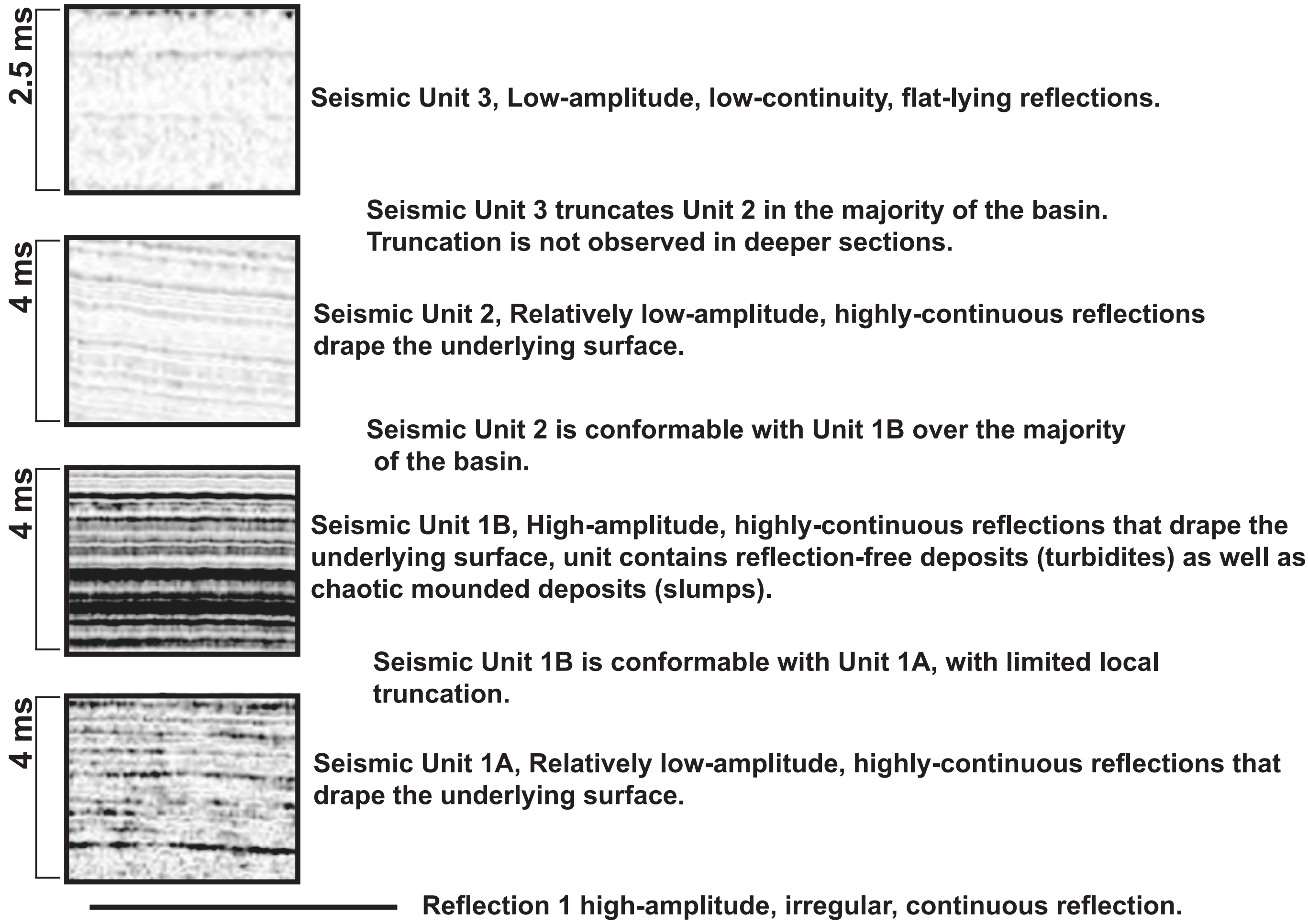

Fig. 4. Summary and description of seismic unit acoustic facies and relationship with overlying stratigraphic unit. Note the vertical scale for each seismic unit is included. All boxes represent 4 ms except for Unit 3.

no subsurface facies are imaged adjacent to these features (Fig. 10A). Seismic Unit 1 is imaged directly underneath and adjacent to two of these sigmoidal features, and Seismic Unit 2 is observed beneath one of them (Fig. 10B). Seismic Unit 1 is imaged directly adjacent to two of these features, but not directly underneath, as the seismic signal does not penetrate below the lake surface at these locations (Fig. 10A). The westernmost sigmoidal feature does not reveal any underlying information, although Seismic Units 1, 2 and 3 are imaged directly adjacent to it (Fig. 10A). The bases of these features are imaged in a range of depths from 3 to 7 msbls. The shallowest sigmoidal features are imaged from 2 to 5.5 msbls (Fig. 9) and extend along 25 km of lake margin. Only one of these features is imaged near the south shoreline of the lake (Figs. 9, 10).

5. Interpretations

5.1. Reflection 1

The acoustic basement (Reflection 1) is interpreted to be composed of glacial till or diamicton, by analogy to other seismic reflection data sets recovered from the region (Mullins et al., 1996; Wellner et al., 1996; Lyons et al., 2005). Because of the high central frequency of the EDGETECH CHIRP system, it is not capable of penetrating through compacted coarse-grained materials, including tills or diamicton, even when it is exposed directly on the lake floor. The topographic high formed by the acoustic basement material is an elongate feature oriented WNW-ESE, similar to the orientation of drumlins and mega scale glacial lineations (MSGL) to the north of Oneida Lake aligned in the direction of paleo-ice sheet flow (Kerr and Eyles, 2007; Briner, 2007; Benn and Evans, 2010; Margold et al., 2015; Sookhan et al., 2018; Margold et al., 2018). Accordingly, the topographic high is likely a glacially streamlined feature or remnant of one; however, it has relief of 40 m with a maximum dip of ~ 5°, a length of ~5 km, and a width of ~1.5 km with an elongation ratio of ~3.3. The feature is too large with too shallow a dip to be a drumlin. MSGL are defined as having elongation ratios higher than 1:10 (Benn and Evans, 2010; Sookhan et al., 2016), much higher than the feature imaged in this study. Given the geologic setting and orientation of the antecedent highs and lows, Reflection 1 likely images the surface of a glacially streamlined landform that was possibly reworked by meltwater drainage during recession of the ice sheet. However, Reflection 1 could also be the surface of multiple drumlins that are not delineated by the widely spaced CHIRP track lines. Similar to other high-resolution seismic records in the region, the basal surface observed (Reflection 1) is interpreted as glacial till or diamict (Todd et al., 2008) (Figs. 3, 4). The late Pleistocene and Holocene sedimentary fill of the Oneida Basin is controlled by the shape of this interpreted till surface (Fig. 2).

5.1.1. Unit 1

Seismic Unit 1 is characterized by highly continuous strata, which drapes onto the underlying surface. Furthermore, these data acquired with the EDGETECH CHIRP system penetrate through thick sections of this unit (> 20 m in some locations), suggesting it likely consists entirely of fine-grained sediments, as the CHIRP 4–24 kHz signals are

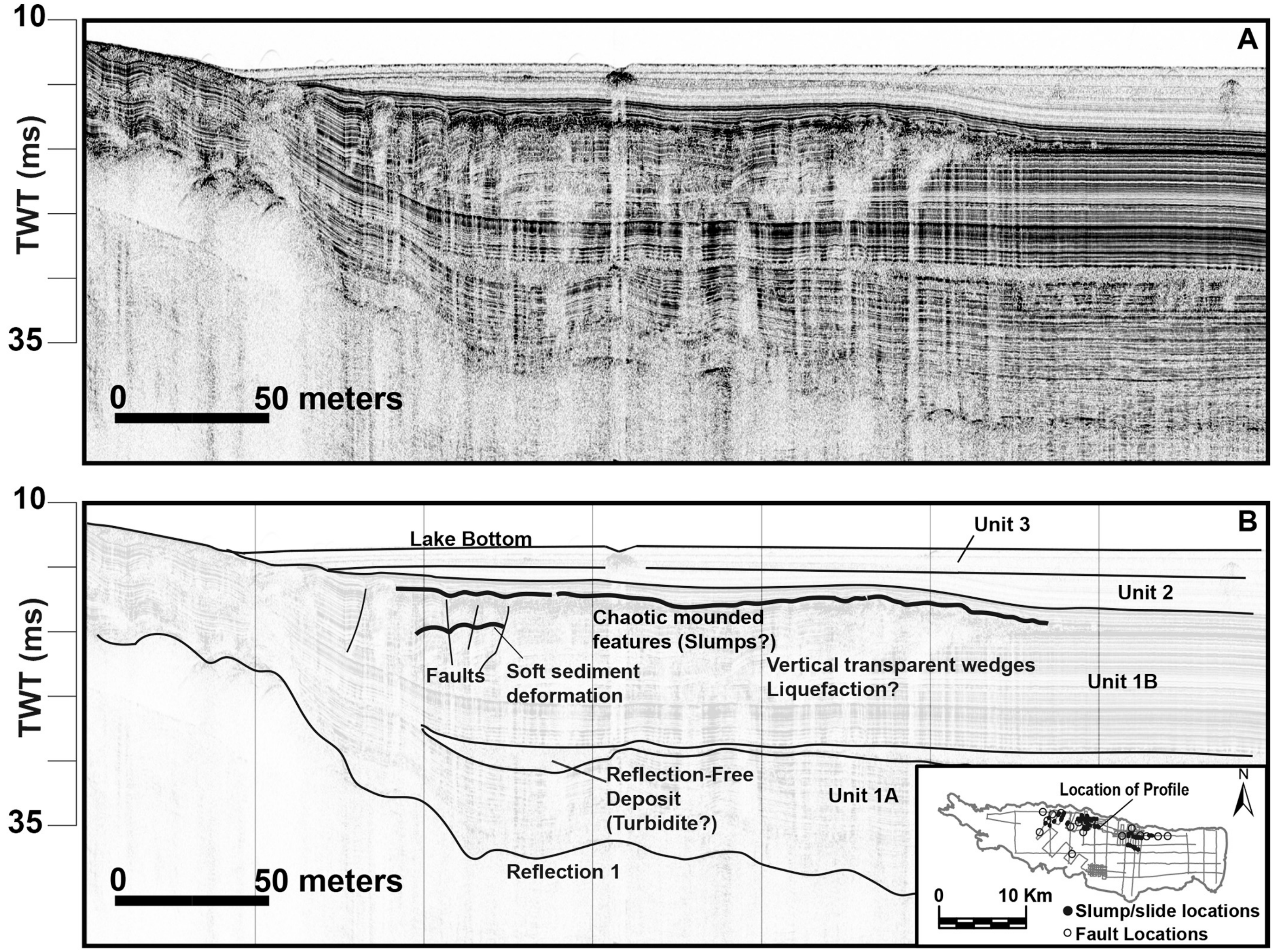

Fig. 5. Uninterpreted (A) and interpreted (B) seismic profile located in the North-Central Oneida Lake. Profile images one of the chaotic mounded features interpreted to be slide/slump deposits as well faults, soft sediment deformation and transparent wedges sections interpreted as formed from liquefaction. The inset map indicates the location of other slide/slump deposits in the seismic data as well as the location of small faults.

generally attenuated in the presence of coarse-grained or sandy deposits. In a few locations ice scour or ice keel marks are observed similar to what is described in other studies (Fig. 6) (Eyles et al., 2005). These observations suggest that Unit 1 was deposited in a deep-water setting. Based upon analogy to many high-resolution seismic reflection profiles observed in northern North America (Lyons et al., 2005; Eyles et al., 2005; Hofmann et al., 2006) this unit is interpreted to be Glacial Lake Iroquois deposits. The change in character between Units 1A and 1B likely represents a change in the depositional conditions in the lake, as Unit 1B's reflections are higher in amplitude. Our working interpretation is an increase in grain-size variability during deposition of Unit 1B compared to 1A, producing the observed increase in reflectivity; this requires confirmation through further sediment groundtruth studies. Seismic Unit 1A is interpreted as deposited from underflows fed by glacial fan deltas (Fig. 4), whereas during deposition of Unit 1B, additional processes were likely operative such as mass transport events, or glacial outburst floods. Furthermore, the presence of the reflection-free deposits within Unit 1B, suggests mass transport events during this interval (Figs. 3, 5, 6, 7), that did not occur during deposition of Unit 1A.

The maximum possible age of Unit 1 can be temporally constrained to the initial retreat of the Ontario Lobe north of the Oneida Basin. Previous work constrained the Rome Readvance of the Ontario Lobe over the Oneida Basin to ~14.8 cal kyr BP, which provides a maximum age estimate for the proglacial lake deposits that drape Reflection 1 (Ridge et al., 1990; Ridge et al., 1991; Ridge, 2004; Franzi et al., 2016). Rosenheim et al. (2016) reported two preliminary radiocarbon age estimates from Unit 1B indicating older ages of 15,344–14,855 cal yr BP and 15,737–15,197 cal yr BP, suggesting that Unit 1A is significantly older than 14.8 cal kyr BP (Rosenheim et al., 2016). However, these age estimates are preliminary and based on samples with very low organic carbon content; accordingly it is possible that Unit 1 contains reworked organic matter that contributes to age estimates older than the time of deposition.

The minimum age of Seismic Unit 1 is estimated by evaluating the subsurface acoustic records, in the context of temporal constraints provided by previous work (Ridge et al., 1990; Ridge, 2004; Franzi et al., 2016). A rapid change in lake level would have altered the depositional environment of the Oneida Basin, which is likely represented by the change in the seismic facies observed in Units 1 and 2. Accordingly, we tentatively interpret the change from Unit 1 to Unit 2 to have occurred at ~13 cal kyr BP, when Glacial Lake Iroquois drained into the Champlain Valley (Rayburn et al., 2011) (Fig. 1). The drawdown in lake level would have been rapid, and isolation of the Oneida Basin from Glacial Lake Iroquois would have occurred at most within centuries (Rayburn et al., 2011). Previous work has dated an early Lake Ontario shoreline to ~12.9 cal kyr BP, when this shoreline was located entirely within the modern shoreline of Lake Ontario (Dyke, 2004). This

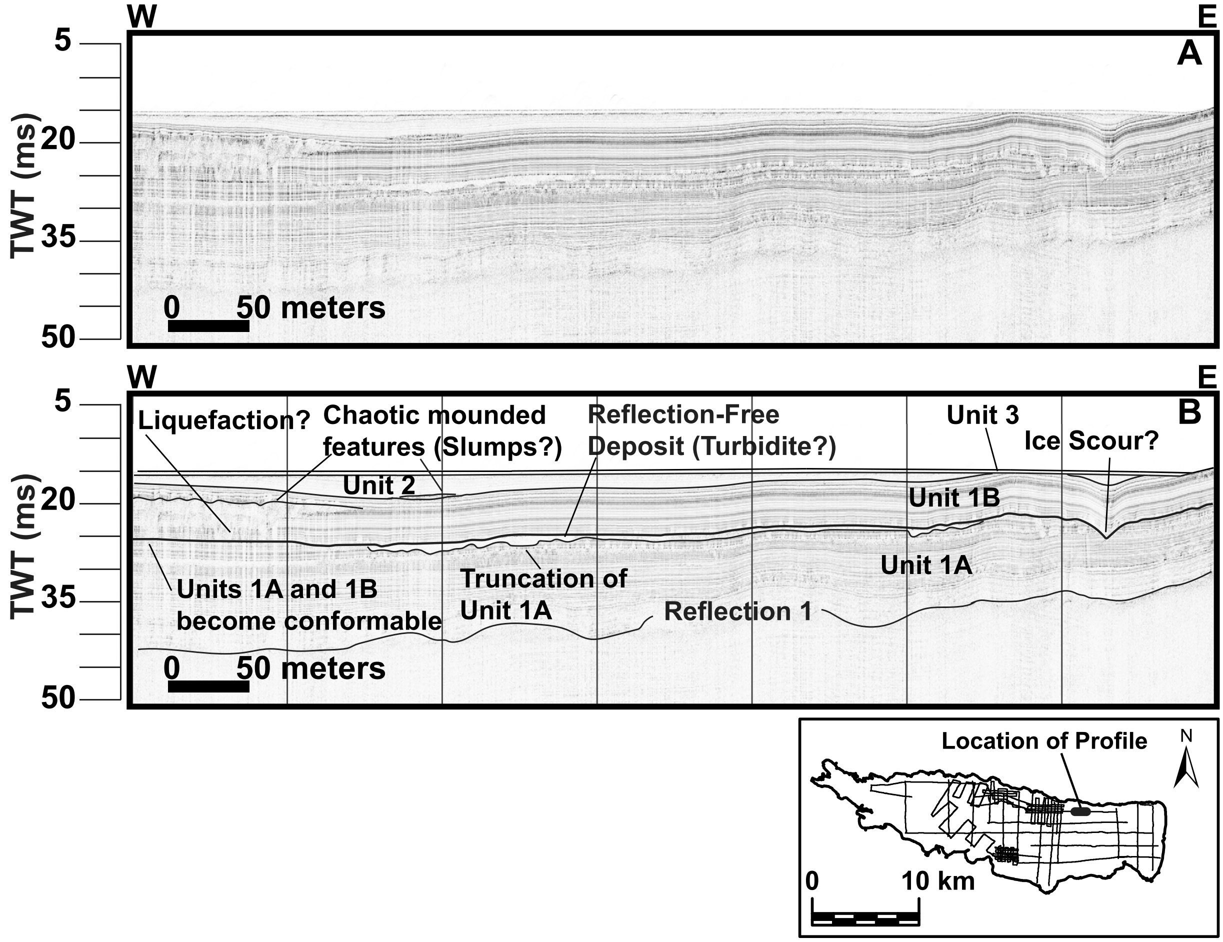

Fig. 6. Uninterpreted (A) and interpreted (B) seismic profile images the reflection-free deposits interpreted to be a mass flow deposit such as a turbidite or hyperpycnal flow, as well as truncation of Unit 1A. Note the interpreted ice scour or ice keel mark on the east side of the profile.

suggests that the Oneida Basin separated from Glacial Lake Iroquois ca. 13 cal kyr BP.

5.1.2. Unit 1; reflection-free deposits

The reflection-free deposits observed within Unit 1B represent very rapid sedimentation within the lake (Figs. 3, 5, 7). These features commonly incise into the underlying seismic Unit 1A or 1B, and a regional unconformity between Units 1A and 1B can be correlated to the reflection-free deposits (Fig. 6). This indicates that the process responsible for the reflection-free, lens-shaped features also created bottom currents sufficiently strong to locally truncate underlying deposits. However, the bases of the reflection-free deposits as well as the transition between 1A and 1B are commonly conformable. The conformable as well as erosive nature of these features suggests that either 1) the depositional processes originated distally, and local bathymetric variations enhanced the localized erosive bottom currents or 2) the process was very proximal to the basin and local topography slowed or reduced flows so that the entrained material was deposited conformably. An example of the former is either a turbidite triggered by seismic activity possibly as a result of isostatic rebound or a cold, sediment-laden body of water derived from the glacial front, driven by an increase in meltwater producing a hyperpycnal flow. When this flow reached the Oneida Basin it was no longer erosive except where it encountered steep bathymetric gradients. An example of a proximal mechanism would be mass transport of sediment such as a debris flow or turbidite triggered by seismic activity from isostatic rebound and sourced from higher terrain to the north; as the gravity flow encountered changes in bathymetric gradients it slowed to the point where it was no longer erosive. The impact of the reflection-free deposits on subsequent deposition is also spatially variable. Reflections that underlie and overlie the reflection-free, lens-shaped features exhibit drape style geometries. This suggests that before and after deposition of the reflection-free deposits, sedimentation processes were unchanged, indicating that the processes responsible for the reflection-free deposits were temporally short and punctuated (e.g. Figs. 5, 7). However, in a few locations the stratal geometry above the reflection-free features exhibit onlap. This suggests a long-lived change in depositional processes following deposition of the reflection-free deposits, and diminishing of the processes responsible for the reflection-free deposits. Future sediment ground-truth analysis is required to fully constrain the characteristics of Unit 1A, 1B, and the reflection-free deposits within the Oneida Basin. Reflection-free acoustic facies that fill topographic lows within the proglacial packages are interpreted as instantaneous catastrophic discharges, either of mass flows possibly triggered by seismic activity, or ice sheet meltwater discharges.

Previous studies in the Finger Lakes observed reflection-free, lens-shaped features similar to those presented in this study (Fig. 1), and were interpreted as slide deposits (e.g. Lyons et al., 2005). The slide deposits found in the Finger Lakes were interpreted to have possibly been triggered by multiple mechanisms, including changes in lake level, seismicity and sediment loading (Halfman and Herrick, 1998; Mullins and Halfman, 2001; Lyons et al., 2005). The reflection-free deposits in Oneida Lake could be slide deposits caused by a similar mechanism, but it is unlikely considering the relief around Oneida Lake is substantially less than around the Finger Lakes (Fig. 1). It is more likely that these reflection-free deposits in Oneida Lake are turbidites, possibly triggered

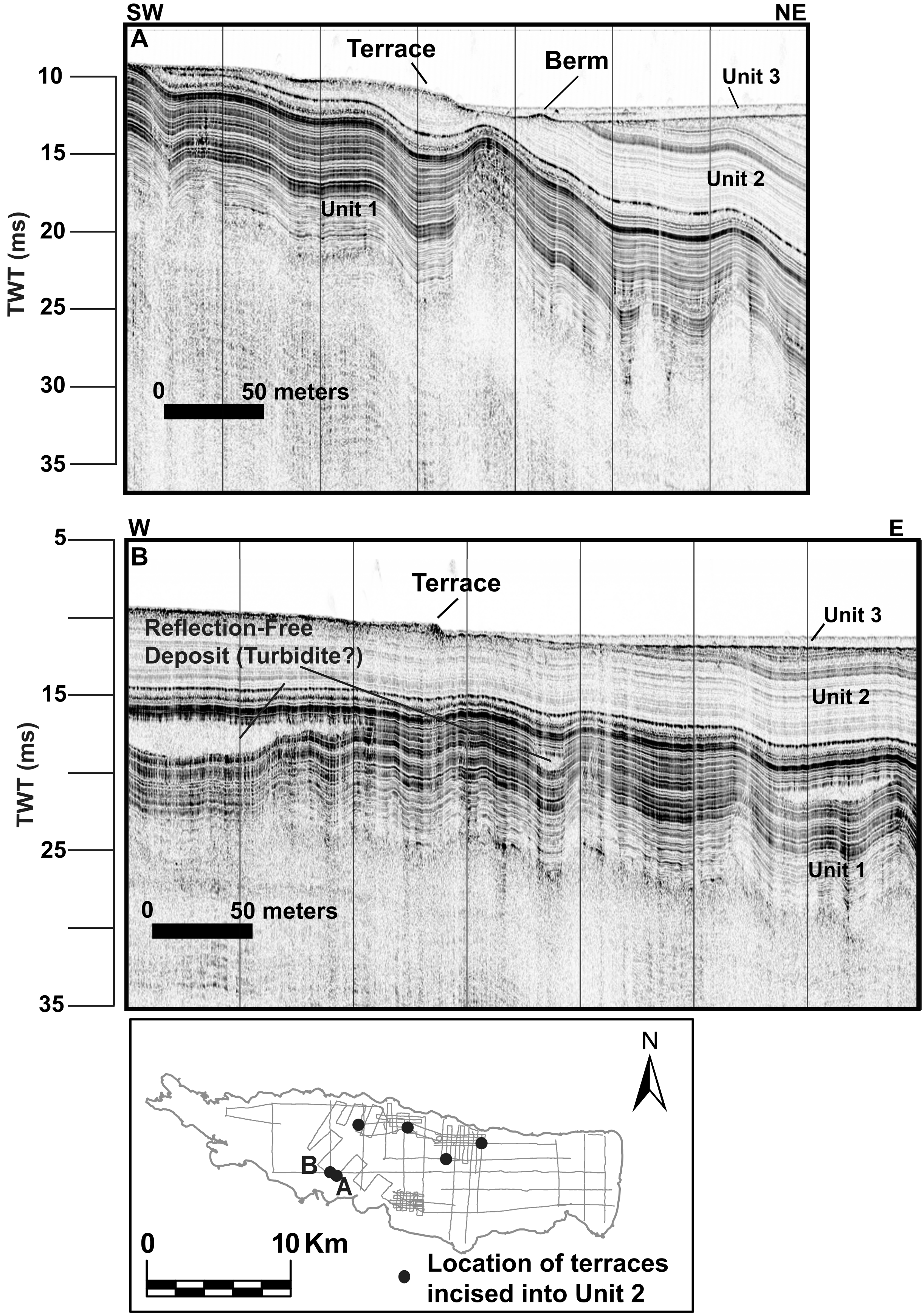

Fig. 7. Two seismic profiles image wave-cut terraces or paleoshorelines. These features as well as truncation of Unit 2 indicate that lake level was substantially lower than modern lake level before deposition of Unit 3.

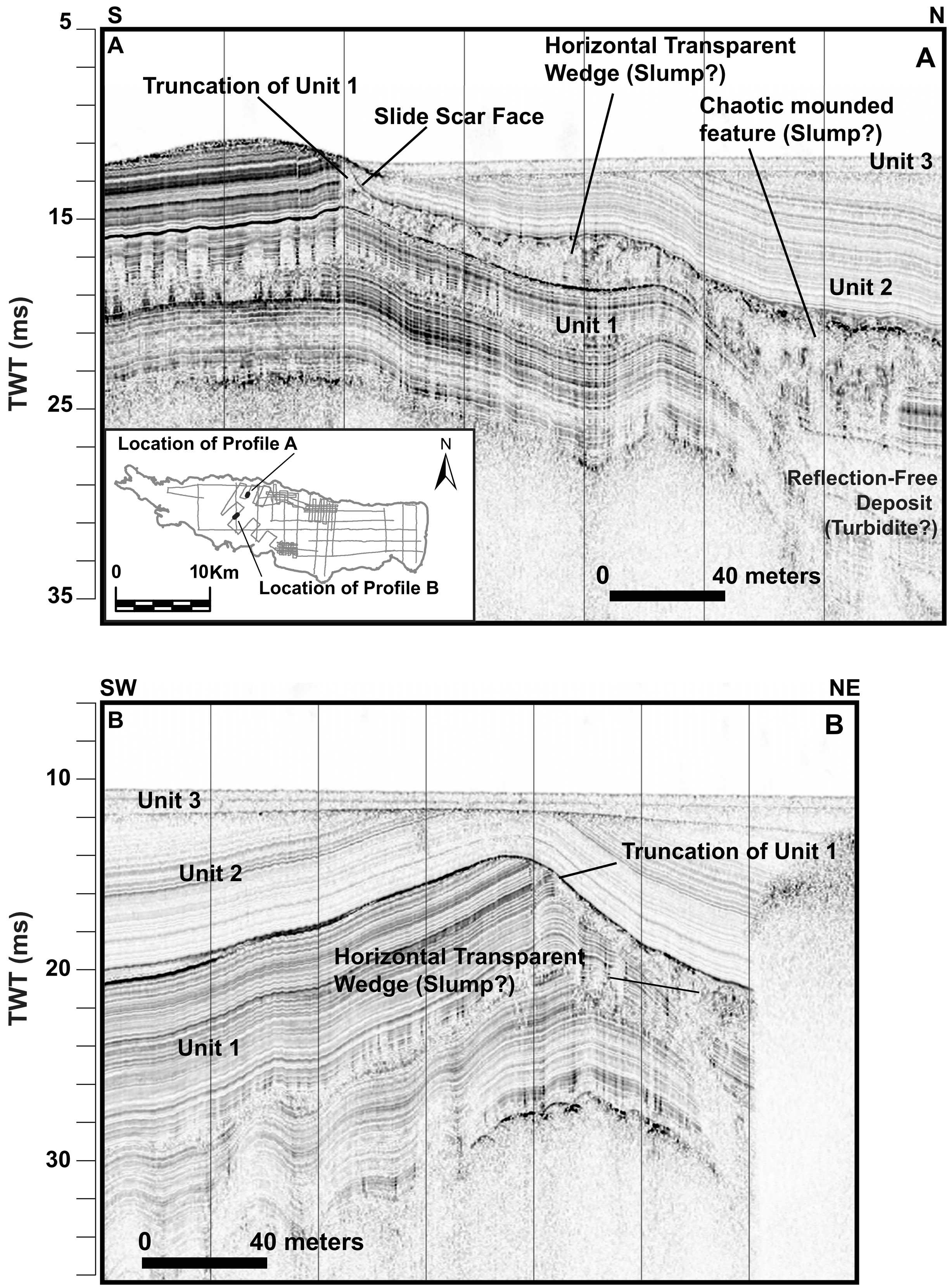

Fig. 8. Two seismic profiles that image transparent wedge-shaped features interpreted to be proximal slide/slump deposits. Directly above the transparent wedges is the interpreted slide scar face where Unit 1 has been truncated.

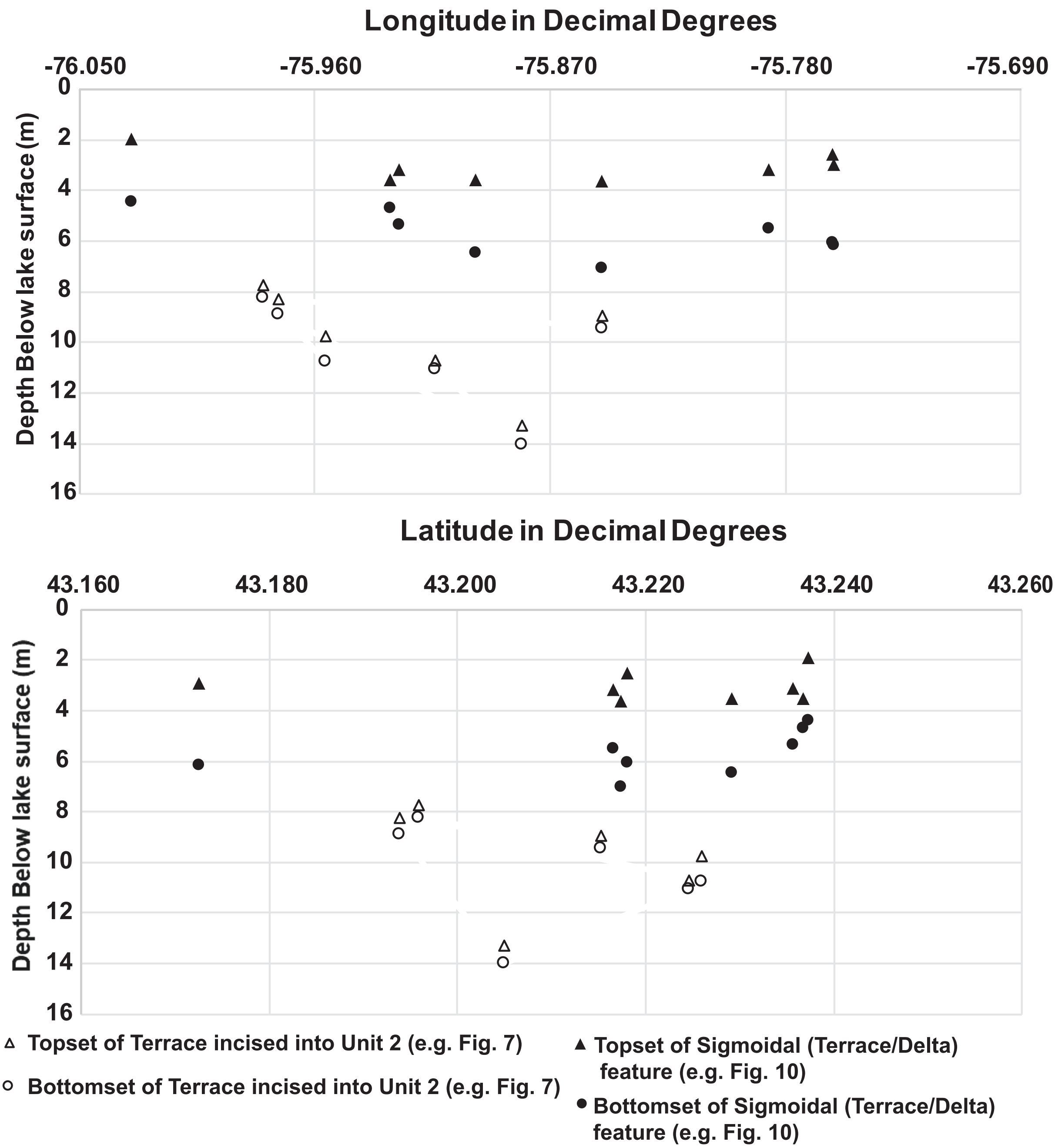

Fig. 9. Depth vs. latitude and longitude for observed terraces and sigmoidal features in Oneida Lake. Open white triangles and circles represent the terraces incised into Unit 2. The black circles and triangles represent the larger sigmoidal shaped features that could be interpreted to be delta/terrace features located near the lakeshore.

by seismic activity, or hyperpycnal flows. Either turbidites triggered by seismic activity or hyperpycnal flows could have been sourced from large meltwater pulses from the Laurentide Ice Sheet. The faults observed in seismic Unit 1B offset younger deposits, so they cannot be interpreted as the trigger mechanism for mass gravity flows depositing the reflection-free deposits (Figs. 3, 5).

An alternative interpretation for the deposition of the reflection-free deposits is a large release of glacial meltwater from the Black River Valley into Glacial Lake Iroquois. The Laurentide Ice Sheet could have acted as an ice dam at the northern end of the Black River Valley forming a tributary proglacial lake to Glacial Lake Iroquois (Fig. 1). If lake levels were higher in the Black River Valley tributary proglacial lake than lake levels in Glacial Lake Iroquois, then retreat of the Laurentide Ice Sheet northward could have released large volumes of water into the Oneida Basin. Such an event could have been responsible for producing the large reflection-free deposits. However, based on the number of these events and their spacing in the stratigraphic record, it is unlikely that this mechanism can explain all of these deposits. The origin of the large reflection-free deposits remains speculative; however, these features make up a substantial part of the late Pleistocene stratigraphy of the Oneida Basin, influencing the stratigraphic architecture by infilling topographic lows.

5.1.3. *Unit 1; chaotic mounded deposits*

The chaotic mounded deposits and transparent horizontal wedges are interpreted to be slide or slump deposits (Figs. 3, 5, 8), by analogy to features observed in high-resolution seismic data observed in other paleolake basins (Hofmann et al., 2006; Eyles et al., 2015). This is

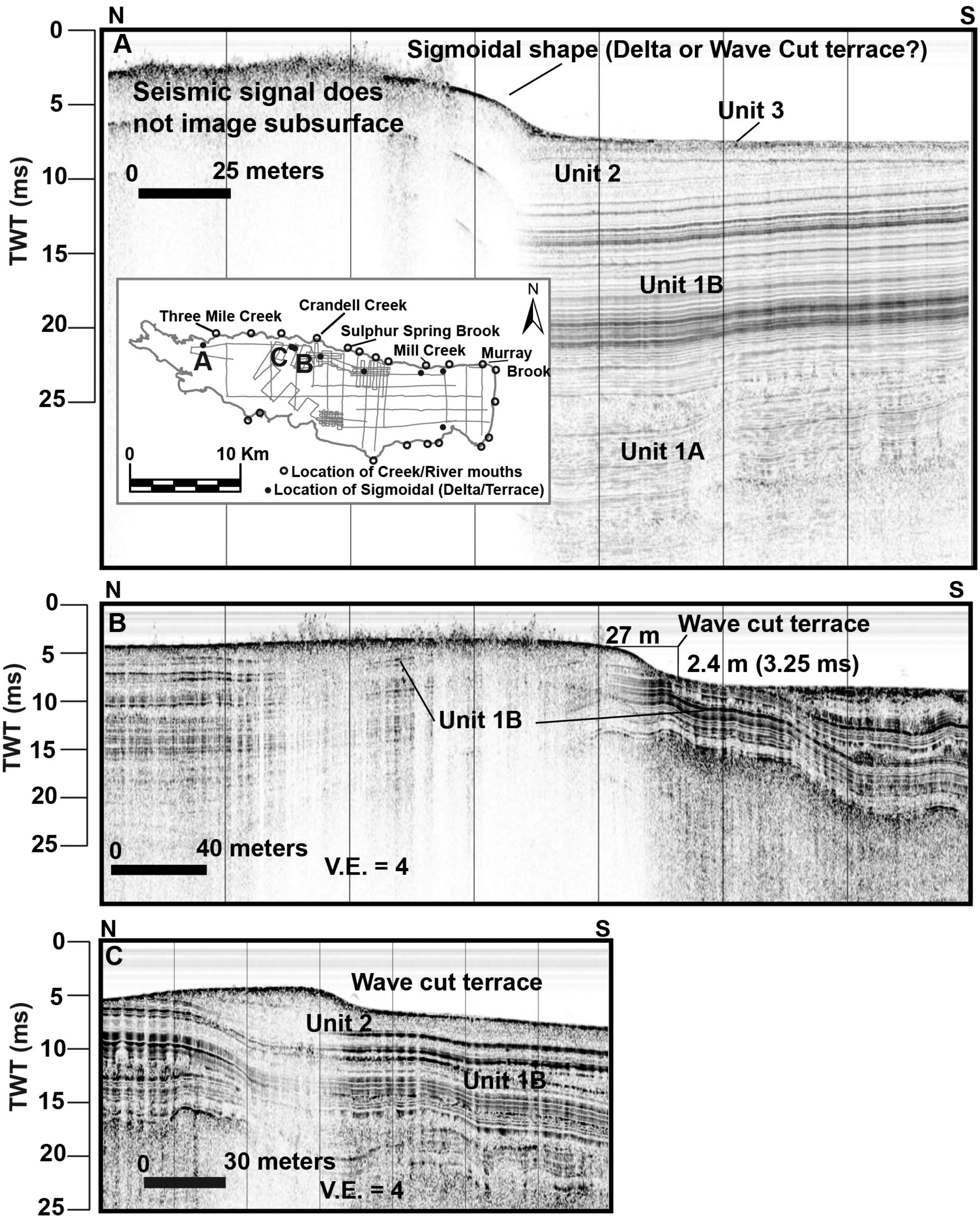

Fig. 10. A) Seismic profile imaging the sigmoidal-shaped feature interpreted to be either a terrace or delta with seismic units 1, 2 and 3 imaged directly adjacent to it. Seismic signal is attenuated likely by coarse-grained deposits or aquatic vegetation. No information is available directly below the feature to indicate if it is a terrace or a delta. B) Wave cut terrace incised into Unit 1. Coarse-grained deposits on top of the terrace attenuate the seismic signal. C) Wave cut terrace composed of Units 1 and 2 constrain the age of formation of the terrace to sometime after deposition of Unit 2. Note the boundary between Unit 1 and 2 is apparent where the seismic profile is viewed farther to the south.

suggested by the location of these features positioned primarily on steep topographic inclines with apparent dips up to 3.5°. Faults with throws of ~ 0.6 ms are observed upslope of the slide deposits as well as within the features (Fig. 5). Transparent vertical wedge-shaped features (Fig. 5) are imaged that penetrate down into high-continuity reflections of Unit 1. These vertical wedge-shaped features are interpreted to be caused by liquefaction of the underlying stratigraphic unit (Hofmann et al., 2006) and could be the result of seismic activity Doughty et al., 2010. The transparent horizontal wedge-shaped features are observed directly below steep erosive surfaces interpreted to be slide scar faces from mass wasting events (Fig. 8). The locations of the horizontal wedge-shaped features and the interpreted slide scar faces indicate that these slide/slump deposits originated within the basin, and the material that composes the horizontal wedges or chaotic mounded deposits traveled a few hundred meters. All of the interpreted slumps were deposited at approximately the same time based on their relative stratigraphic position. While seismic activity is suggested by the small faults and transparent vertical wedges within the basin, and explains the occurrence of the mass wasting events described above, it cannot explain the transition to Seismic Unit 2 (Figs. 3, 5, 8). Seismic Unit 2 drapes the positive topography of the slide/slump deposits, and along with the change in seismic facies indicates a change in the depositional environment of the lake directly following the basin-wide mass wasting event (Figs. 5, 8). This sequence of events can be explained by a drop in lake level, which either allowed wave energy to interact with the lake floor or modified pore pressure conditions within the fine-grained deposits, which destabilized the overlying strata and allowed the slide/slump to progress. This rapid change in lake level would have altered the depositional environment of the basin, indicated by the change to Seismic Unit 2. Furthermore, rapid drainage of the lake could have affected the rate of isostatic rebound generating small earthquakes, and inducing deformation and faulting within the basin. Seismicity could induce soft sediment deformation, faulting and liquefaction of fine-grained material, creating the vertical transparent wedges (Fig. 5). Drainage of Glacial Lake Iroquois could explain the occurrence of the slide/slump deposits, the formation of small-scale faults, and the change in seismic stratigraphy from Unit 1 to Unit 2. Depositional processes within the basin would have been substantially different after a lake level drop, considering ice sheet processes would no longer be present in the Oneida Basin. The separation of the Oneida Basin from Glacial Lake Iroquois is manifested in the stratigraphic record quite differently, than what is observed in other remnant proglacial lake deposits (Hougardy and Colman, 2018). Separation of Lake of the Woods from Lake Agassiz is represented by a widespread unconformity, a result of isostatic tilting of the basin (Hougardy and Colman, 2018). Comparison of the two basins seismic data sets provides insight into how various processes are manifested in proglacial lake stratigraphy.

5.1.4. Unit 2 and 3

The drape-like geometry of Seismic Unit 2 suggests deposition in a deep-water setting. However, unit 2 is observed primarily within the deeper bathymetric lows, suggesting that Unit 2 was deposited in a shallower lake with a lower base level than Unit 1. Internal reflections within Unit 2 are lower in amplitude than the reflections imaged in Unit 1, suggesting that the sediments within Unit 1 contain a larger range of densities or acoustic impedance contrasts. This change in the seismic facies is likely the result of a change in the depositional processes operating in the basin, perhaps reducing or obstructing sediment input sourced from glacially fed underflows or deltas, and implying a change in catchment conditions. Therefore, sedimentation within the basin during deposition of Unit 2 may have been sourced entirely from local runoff.

5.1.5. Low stand and Unit 2 incision

Seismic Units 2 and 3 are separated by a surface interpreted as caused by a lake level low stand. The abrupt changes in depth to the top of Unit 2 (Fig. 7) are interpreted as wave cut terraces demarking prior low stands of the lake. Furthermore, Unit 3 truncates Unit 2 in many locations suggesting a drop in lake level before deposition of Unit 3 (Fig. 7). The wave cut terraces incised into Unit 2 are relatively small, with relief of ~0.5–1 m, calculated assuming a sediment P-wave velocity of 1500 m/s. During formation of the terraces the lake was likely substantially reduced in size compared to the modern lake, resulting in fetch-limited bodies of water constrained to the antecedent lows in the northern and southern sections of the basin. Reduced wave height in these fetch-limited bodies of water may explain why the terraces are low relief and are sparse in the stratigraphic record. The bases of the terraces occur 8.2 to 11 m below the modern lake surface. No pattern between terrace height and latitude or longitude is observed (Fig. 9) therefore, the various depths of the terraces cannot be explained as a result of regional isostatic rebound since initial formation. However, the terraces provide estimates of paleolake surface elevations during the Holocene. Based on the location of the terraces we interpret that much of the basin was subaerial during the low lake phase however, there is no evidence of fluvial incision within the basin. Furthermore, in order to preserve the terraces, lake level must have risen rapidly, especially since these features are comparatively small and likely incised into fine-grained material susceptible to erosion.

5.1.6. Sigmoidal shaped features; terraces or deltas?

The 1–3.5 m sigmoidal features found near the modern lake shoreline can be interpreted as either wave cut terraces or stranded delta deposits (Fig. 10). Two of the features are interpreted as wave cut terraces since seismic data indicate that they are composed of seismic Units 1 (Fig. 10B) and Unit 2 (Fig. 10C). These provide another indication of lower lake levels in Oneida Lake. These wave cut terraces provide few temporal constraints on the timing of the lower lake level only that it occurred sometime after the deposition of Unit 2. The other sigmoidal features could either be delta deposits or wave cut terraces, as there is no subsurface information below them. Several small creeks, including Murray Brook and Mead Creek enter the Oneida Basin close to these features (Fig. 10). Of particular interest is the delta/wave cut terrace adjacent to where seismic Units 3, 2, and 1 are imaged (Fig. 10A). This relationship provides temporal constraint on the formation of the terrace or delta in the Holocene (Fig. 10). This feature is located only 1.3 km to the SE of Three Mile Creek; therefore, it is likely a delta formed during slightly lower lake levels. Future work including ground-truth sediment coring or acquisition of additional subsurface seismic data is required to further assess its genesis.

6. Discussion

The relatively thick stratigraphic units observed in the Oneida Basin document a high-resolution record of deglaciation and ice sheet retreat, and the lake's location at the edge of the Mohawk Valley suggests the system was a primary valve for meltwater release into the Hudson Valley during periods of deglaciation. The regional late Pleistocene history is well described from studies in the Laurentian Great Lakes (e.g. Hutchinson et al., 1979; Lewis and Anderson, 1989; Anderson and Lewis, 2012), the lakes of the southern Canadian Shield and southern Ontario (e.g. Lewis and Anderson, 2012; Eyles et al., 2015), and New York's Finger Lakes (e.g. Mullins and Hinchey, 1989; Mullins et al., 1996; Lyons et al., 2005); however those lakes are relatively deep, have limited sedimentary sections, or are located farther to the north. Oneida Lake provides a unique opportunity to image Glacial Lake Iroquois deposits to better understand the evolution of the lake and the various processes that impacted deposition.

Using previous work described in the interpretation section as temporal constraints the time span of deposition of Seismic Unit 1 is estimated at a maximum of ~1800 years. Assuming a sound velocity of 1500 m/s, Unit 1 has a maximum thickness of ~21 m. Accordingly, the sedimentation rate for the thickest section of Seismic Unit 1 imaged within Oneida Lake averaged ~1.1 cm/year. While this estimate provides an average rate, it is likely that deposition rates were highly variable and affected by proximity of the Oneida Basin to Laurentide Ice Sheet processes including ice sheet retreat and advance as well as periods of increased melt water production (Leonard, 1997). Such high rates of deposition indicate that the Oneida Basin contains a high-resolution record of ice sheet processes that span the interval ~14.8–13.0 cal kyr BP. The abrupt climatic fluctuations that occurred during this time period include the Older Dryas (14.3–14.0 cal kyr BP) as well as the Intra-Allerod cold period which was possibly triggered by drainage of Glacial Lake Iroquois (Donnelly et al., 2005) described from Greenland ice cores (Stuiver et al., 1995; Rasmussen et al., 2006)

(~13.35–13.0 cal kyr BP).

Unit 2 is interpreted to have been deposited after a decrease in lake level. Unit 2's base is conformable with Unit 1, whereas the top of Unit 2 is truncated with wave cut terraces or berm incision which is commonly buried by Unit 3. Within Lake Huron and surrounding lakes, an unconformity has been interpreted as caused by a drop in lake level at ~9 cal kyr BP (Eyles et al., 2015). Similar low lake levels were detected in Lake Ontario between ~9.5 and ~12.5 cal kyr BP (Anderson and Lewis, 2012). These regional drops in lake levels are interpreted to coincide with the Holocene Hypsithermal, a period of drier conditions within the mid-continent of North America (Lewis et al., 2008a, Lewis et al., 2008b; McCarthy et al., 2010; McCarthy and McAndrews, 2010). In the Finger Lakes, pollen assemblages suggest drier conditions at the same time that decreases in lake levels were detected, and are constrained to ~9.2 cal kyr BP. (Webb, 1987; Wellner and Dwyer, 1996).

This low stand observed in Oneida Lake was likely the result of drier conditions during the Holocene Hypsithermal. If this correlation is correct it provides an estimate of the age of Unit 2 and constrains it to ~13–9 cal kyr BP. A radiocarbon age estimate derived from bulk organic material in the middle of Unit 2 (Domack, 2016; Rosenheim et al., 2016) provides a calibrated age estimate of 12,689–12,420 cal yr BP, in agreement with our estimates for deposition of Unit 2, however slightly older than expected based on the stratigraphic position of the age estimate. This sample has very low amounts of organic carbon (Rosenheim et al., 2016) and it is likely the sample contains reworked organic carbon producing an age older than the actual age of deposition. Based on a maximum thickness of ~ 7.4 m (10 ms, assuming a velocity of 1480 m/s), sedimentation rates in Unit 2 were ~2.5 mm/yr in the deepest part of the basin. Such a rapid decrease in sedimentation rate from Unit 1 to Unit 2 indicates a drastic and rapid change in the depositional environment, which is also indicated by the change in seismic facies between the two units. The absence of fluvial incision further supports the interpretation that lake level was impacted by drier climate conditions. This low stand identified in Oneida Lake extends the known geographic extent of the effect of the Holocene Hypsithermal to the Oneida Basin.

The preservation of unmodified wave cut terraces suggests that lake level rose very rapidly. The Nipissing transgression detected in Lake Huron is described as a rise in lake level, a result of differential isostatic rebound and wetter conditions/increased precipitation in the mid-continent (Jackson et al., 2000; Brooks and Medioli, 2012; Anderson and Lewis, 2012; Eyles et al., 2015). This event occurred between ~8500 and ~6000 ca BP, where lake level rose ~100 m within the Huron-Georgian basins (Brooks and Medioli, 2012). Evidence of a rapid rise in lake level within Oneida Lake suggests that the changes in climate that affected lake levels in the Great Lakes influenced climate as far south as the Oneida Lake catchment, which was isolated at that time with its own overflow sill, inlets and outlet. Therefore, if the transgression in Oneida Lake occurred at the same time as the Nipissing transgression then this reinforces the conclusions of previous work that the Nipissing transgression was in part a result of changes in climate as well as differential isostatic rebound (Lewis and Anderson, 1989; Anderson and Lewis, 2012; Brooks and Medioli, 2012).

Multiple terraces or deltas (sigmoidal features) are observed in shallow water near the modern shoreline (Fig. 10). These terraces or deltas are much larger and occur in shallower water than the low stand wave cut terraces discussed in the previous paragraph (Fig. 7). These sigmoidal-shaped wave cut terraces provide evidence for another paleo-lake level sometime after deposition of Unit 2 (Fig. 10C). In addition, seismic data images Unit 3 (Fig. 10A) adjacent to one of the sigmoidal features suggesting it was formed during the Holocene. However, we cannot be certain if it is a wave cut terrace or delta (Fig. 10A). Whether a deltaic deposit or a wave cut terrace, in either case the sigmoidal features indicate a lower than modern lake level. These features likely formed at the same time as the wave cut terraces in Fig. 10B and C during a lake level still stand before the rise to modern lake level.

7. Conclusions

High-resolution seismic reflection data reveal a high-fidelity acoustic stratigraphy that provides a stratigraphic framework for the retreat of the Laurentide Ice Sheet, the transition to Glacial Lake Iroquois, and the subsequent change to modern Oneida Lake. Glacial Lake Iroquois deposits are ~21 m thick in some localities with no basin wide unconformities observed. During the latter stages of Glacial Lake Iroquois, turbidity or hyperpycnal flows were operative, suggested by reflection-free facies that infill topographic lows. The exact mechanisms that caused these mass transport events are unknown, but seismic activity resulting from isostatic rebound or glacial melt water floods are possible triggers. Other important geological features recognized in the seismic reflection data include small scale normal faults, slide scars and liquefaction features which are interpreted as local slump deposits formed by either seismic activity or a rapid lowering of lake level, likely the drawdown of Glacial Lake Iroquois. Holocene wave cut terraces provide evidence of a low stand we link to the Holocene Hypsithermal expanding upon the known geographic extent and effects of this climate interval. Preservation of the wave cut terraces suggests lake level rose rapidly and that climate forcing in part responsible for the Nipissing transgression impacted the hydroclimate of the Oneida catchment. Terraces and possible stranded delta fronts imaged near the modern shoreline suggest another Holocene lake level that developed before the lake rose to its current level. These data provide the high-resolution stratigraphic framework of southeastern Glacial Lake Iroquois, an area that modulated the release of large amounts of glacial meltwater to the Atlantic Ocean during the last deglacial period.

Data availability

High-resolution CHIRP seismic reflection data collected in 2018 was funded through National Science Foundation-EAR (P2C2 program) and will be released to the public 2 years from data acquisition (2020).

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Declaration of Competing Interests

The authors have no competing interests to declare.

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References

Anderson, T.W., Lewis, C.F.M., 2012. A new water-level history for Lake Ontario basin: evidence for a climate-driven Early Holocene low stand. J. Paleolimnol. 47, 513–530.
Anell, I., Midtkandal, I., 2017. The quantifiable clinothem – types, shapes and geometric relationships in the Plio-Pleistocene Giant Foresets Formation, Taranaki Basin, New

Zealand. Basin Res. 29, 277–297. https://doi.org/10.1111/bre.12149.
Benn, D.I., Evans, D.J.A., 2010. Glaciers and Glaciation. Hodder Education, pp. 802.
Bird, B., Kozlowski, A., 2016. Late Quaternary reconstruction of Lake Iroquois in the Ontario Basin of New York. New York State Museum Map & Chart 80.
Briner, J.P., 2007. Supporting evidence from the New York drumlin field that elongate subglacial bedforms indicate fast ice flow. BOREAS 36, 143–147.
Brooks, G.R., Medioli, B.E., 2012. Sub-bottom profiling and coring of sub-basins along the lower French River, Ontario: insights into depositional environments within the North Bay outlet. J. Paleolimnol. 47, 447–467.
Dean, W.E., Moore, W.S., Nealson, K.H., 1981. Manganese cycles and the origin of manganese nodules, Oneida Lake, NY, USA. Chem. Geol. 34, 53–64.
Domack, E.W., 2016. Summary of Oneida Lake acoustic stratigraphy. In Oneida Basin, Glacial Lake Iroquois, and archaeologic contexts. Northeast friends of the Pleistocene, 79th annual field Excursion, June 3-5.
Donnelly, J.P., Driscoll, N.W., Uchupi, E., Keigwin, L.D., Schwab, W.C., Thieler, R., Swift, S.A., 2005. Catastrophic meltwater discharge down the Hudson Valley: a potential trigger for the Intra-Allerød cold period. Geology 33, 89–92.
Doughty, M., Eyles, N., Daurio, L., 2010. Earthquake-triggered slumps (1935 Timiskaming M6.2) in Lake Kipawa, Western Quebec Seismic Zone, Canada. Sediment. Geol. 228, 113–118.
Dyke, A.S., 2004. An outline of North American Deglaciation with emphasis on central and northern Canada. Dev. Quat. Sci. 2, 373–424.
Eyles, N., Eyles, C.H., Woodworth-Lynas, C., Randall, T., 2005. The sedimentary record of drifting ice (early Wisconsin Sunnybrook deposit) in an ancestral ice-dammed Lake Ontario. Quat. Res. 63, 171–181.
Eyles, N., Zajch, A., Doughty, M., 2015. High-resolution seismic sub-bottom reflection record of low Hypsithermal levels in Ontario lakes. J. Great Lakes Res. 41, 41–55.
Fairchild, H.L., 1909. Glacial Waters in Central New York. New York State Museum Bulletin. (no. 442).
Franzi, D.A., Ridge, J.C., Pair, D.L., Desimone, D., Rayburn, J.A., Barclay, D.J., 2016. Post-valley heads deglaciation of the Adirondack Mountains and adjacent lowlands. Adirondack J. Environ. Stud. 21, 119–146.
Halfman, J.D., Herrick, D.T., 1998. Mass Movement and reworking of late Glacial and Postglacial sediments in northern Seneca lake, New York. Northeast. Geol. Environ. Sci. 20, 227–241.
Hofmann, M.H., Hendrix, M.S., Moore, J.N., Sperazza, M., 2006. Late Pleistocene and Holocene depositional history of sediments in Flathead Lake, Montana: evidence from high-resolution seismic reflection interpretation. Sediment. Geol. 184, 111–131.
Hougardy, D. D. & Colman, S. M., 2018. Sedimentary architecture of the southern basin of Lake of the Woods, Minnesota and its relation to Lake Agassiz history and Holocene environmental change. Quat. Res. 90, 96–109. doi:https://doi.org/10.1017/qua.2018.16.
Hutchinson, D.R., Pomeroy, P.W., Wold, R.J., Halls, H.C., 1979. A geophysical investigation concerning the continuation of the Clarendon-Linden fault across Lake Ontario. Geology 7, 206–210.
Jackson, L.J., Ellis, C., Morgan, A.V., McAndrews, J.H., 2000. Glacial lake levels and Eastern Great Lakes Palaeo-Indians. Geoarchaeology 15, 415–440.
Kerr, M., Eyles, N., 2007. Origin of drumlins on the floor of Lake Ontario and in upper New York State. Sediment. Geol. 193, 7–20.
Leonard, E.M., 1997. The relationship between glacial activity and sediment production: evidence from a 4450-year varve record of neoglacial sedimentation in Hector Lake, Alberta Canada. J. Paleolimnol. 17, 319–330.
Lewis, C.F.M., Anderson, T.W., 1989. Oscillations of levels and cool phases of the Laurentide Great Lakes caused by inflows from glacial Lakes Agassiz and Barlow-Ojibway. J. Paleolimnol. 2, 99–146.
Lewis, C.F.M., Anderson, T.W., 2012. The sedimentary and palynological records of Serpent River Bog, and revised early Holocene lake-level changes in the Lake Huron and Georgian Bay region. J. Paleolimnol. 47, 391–410.
Lewis, C.F.M., King, J.W., Blasco, S.M., Brooks, G.R., Coakley, J.P., Croley II, T.E., Dettman, D.L., Edwards, T.W.D., Heil Jr, C.W., Hubeny, B., Laird, K.R., McAndrews, J.H., McCarthy, F.M.G., Medioli, B.E., Moore Jr, T.C., Rea, D.K., Smith, A.J., 2008a. Dry climate disconnected the Laurentian Great Lakes. EOS 89, 541–542.
Lewis, C.F.M., Karrow, P.F., Blasco, S.M., McCarthy, F.M.G., King, J.W., Moore Jr., T.C., Rea, D.K., 2008b. Evolution of lakes in the Huron basin: deglaciation to present. J. Aquat. Ecosyst. Health Manag. 11, 127–136.
Lothrop, J., Beardsley, M., Clymer, M., Winchell-Sweeney, S., Younge, M., 2016. Current archaeological research on Paleoindian sites in central New York. In: Oneida Basin, Glacial Lake Iroquois, and archaeologic contexts. Northeast friends of the Pleistocene, 79th annual field Excursion, June 3–5.
Lyons, R.P., Scholz, C.A., Mullins, H.T., 2005. Seismic stratigraphy of Skaneateles Lake: a high-resolution history of lake level, paleoclimate, and natural hazards in central New York. Northeast. Geol. Environ. Sci. 27, 302–315.
Margold, M., Stokes, C.R., Clark, C.D., 2015. Ice streams in the Laurentide Ice Sheet: identification, characteristics and comparison to modern ice sheets. Earth Science Rev. 143, 117–146.
Margold, M., Stokes, C.R., Clark, C.D., 2018. Reconciling records of ice streaming and ice margin retreat to produce a palaeogeographic reconstruction of the deglaciation of the Laurentide Ice Sheet. Quat. Sci. Rev. 189, 1–30.
Marsh, B., 2017. Meltwater channel scars and the extent of Mid-Pleistocene glaciation in central Pennsylvania. Geomorphology 295, 354–363.
McCarthy, F., McAndrews, J., 2010. Early Holocene drought in the Laurentian Great Lakes basin caused hydrologic closure of Georgian Bay. J. Paleolimnol. 47, 411–428.
McCarthy, et al., 2010. Early Holocene brackish closed basin conditions in Georgian Bay. Ontario, Canada: microfossil (thecamoebian and pollen) evidence. J. Paleolimnol. 47, 429–445.
Muller, E.H., Calkin, P.E., 1993. Timing of Pleistocene glacial events in New York State. Can. J. Earth Sci. 30, 1829–1845.
Muller, E.H., Prest, V.K., 1985. Glacial Lakes in the Ontario basin. In: Karrow, P.F., Calkin, P.E. (Eds.), Quaternary Evolution of the Great Lakes. Geological Association of Canada Special Paper 30. pp. 213–229.
Mullins, H.T., Halfman, J.D., 2001. High-resolution seismic reflection evidence for Middle Holocene environmental change, Owasco Lake, New York. Quat. Res. 331, 322–331.
Mullins, H.T., Hinchey, E.J., 1989. Erosion and infill of New York Finger Lakes. Implications for Laurentide ice sheet deglaciation. Geology 17, 622–625.
Mullins, H.T., Hinchey, E.J., Wellner, R.W., Anderson, W.T., Dwyer, T.R., Hine, A.C., 1996. Seismic stratigraphy of the Finger Lakes: a continental record of Heinrich event H-1 and Laurentide Ice Sheet instability. GSA Special Paper 311, 1–35.
National Oceanic and Atmospheric administration, National Ocean Service Coast Survey, 2016. Oneida Lake. United States New York Channel System. United States Commerce (Chart 14788).
Rasmussen, S.O., et al., 2006. A new Greenland ice core chronology for the last glacial termination. J. Geophys. Res. 111, 1–16. https://doi.org/10.1029/2005JD006079.
Rasmussen, S.O., et al., 2014. A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: refining and extending the INTIMATE event stratigraphy. Quat. Sci. Rev. 106, 14–28. https://doi.org/10.1016/j.quascirev.2014.09.007.
Rayburn, J.A., Knuepfer, P.L.K., Franzi, D.A., 2005. A series of large, Late Wisconsinan meltwater floods through the Champlain and Hudson Valleys, New York State, USA. Quat. Sci. Rev. 24, 2410–2419.
Rayburn, J.A., et al., 2011. Timing and duration of North American glacial lake discharges and the Younger Dryas climate reversal. Quat. Res. 75, 541–551.
Ridge, J.C., 2004. The quaternary glaciation of western New England with correlations to surrounding areas. In: Quaternary Glaciations — Extent and Chronology. Part II: North America. 212–231.
Ridge, J.C., Brennan, W.J., Muller, E.H., 1990. The use of paleomagnetic declination to test correlations of late Wisconsinan glaciolacustrine sediments in central New York. GSA Bull. 102, 26–44.
Ridge, J.C., Franzi, D.A., Muller, E.H., 1991. Late Wisconsinan, pre-valley heads glaciation in the western Mohawk Valley, central New York, and its regional implications. GSA Bull. 103, 1032–1048. https://doi.org/10.1130/0016-7606(1991)103<1032:LWPVHG>2.3.CO;2.
Ridge, J.C., et al., 2012. The new north American varve chronology: a precise record of southeastern Laurentide ice sheet correlations with Greenland ice core records. Am. J. Sci. 312, 685–722.
Rosenheim, B.E., Venturelli, R.A., Domack, E.W., 2016. Ramped PyrOX^{14}C ages from Oneida Lake sediment cores. In: Oneida basin, Glacial Lake Iroquois, and archaeological contexts. Northeast friends of the Pleistocene, 79th annual field Excursion, June 3–5.
Sookhan, S., Eyles, N., Putkinen, N., 2016. LIDAR-based volume assessment of the origin of the Wadena drumlin field, Minnesota, USA. Sediment. Geol. 33, 72–83.
Sookhan, S., Eyles, N., Putkinen, N., 2018. LiDAR-based mapping of paleo-ice streams in the eastern Great Lakes sector of the Laurentide Ice Sheet and a model for the evolution of drumlins and MSGLs. GFF 140, 202–228.
Stuiver, M., Grootes, P.M., Braziunas, T.F., 1995. The GISP2 δ^{18}O climate Record of the past 16,500 years and the Role of the Sun, Ocean, and Volcanoes. Quat. Res. 44, 341–354. ISSN 0033-5894. https://doi.org/10.1006/qres.1995.1079.
Todd, B.J., Lewis, C.F.M., Anderson, T.W., 2008. Quaternary features beneath Lake Simcoe, Ontario, Canada: drumlins, tunnel channels, and records of proglacial to postglacial closed and overflowing lakes. J. Paleolimnol. 39, 361–380.
Webb, T., 1987. The appearance and disappearance of major vegetational assemblages: long-term vegetational dynamics in eastern North America. Plant Ecol. 69, 177–187.
Wellner, R.W., Dwyer, T.R., 1996. Late Pleistocene-Holocene lake level fluctuations and paleoclimates at Canandaigua Lake, New York. In: GSA Special Paper 311.
Wellner, R.W., Petruccione, J.L., Sheridan, R.E., 1996. Correlation of drill-core and geophysical results from Canandaigua Lake valley, New York: evidence for rapid late glacial sediment infill. Geol. Soc. Am. Spec. Pap. 311, 37–50.