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Acoustic architecture of glaciolacustrine sediments deformed during zonal stagnation of the Laurentide Ice Sheet; Mazinaw Lake, Ontario, Canada

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Abstract

In North America, the last (Laurentide) Ice Sheet retreated from much of the Canadian Shield by ‘zonal stagnation’. Masses of dead ice, severed from the main ice sheet by emerging bedrock highs, downwasted in situ within valleys and lake basins and were commonly buried by sediment. Consequently, the flat sediment floors of many valleys and lakes are now pitted by steep-sided, enclosed depressions (kettle basins) that record the melt of stagnant ice blocks and collapse of sediment. At Mazinaw Lake in eastern Ontario, Canada, high-resolution seismic reflection, magnetic and bathymetric surveys, integrated with onland outcrop and hammer seismic investigations, were conducted to identify the types of structural disturbance associated with the formation of kettle basins in glaciolacustrine sediments. Basins formed as a result of ice blocks being trapped within a regionally extensive proglacial lake (Glacial Lake Iroquois ~ 12,500 to 11,400 years BP) that flooded eastern Ontario during deglaciation. Kettles occur within a thick (>30 m) succession of parallel, high-frequency acoustic facies consisting of rhythmically laminated (varved?) Iroquois silty-clays. Iroquois strata underlying and surrounding kettle basins show large-scale normal faults, fractures, rotational failures and incoherent chaotically bedded sediment formed by slumping and collapse. Mazinaw Lake lies along part of the Ottawa Graben and while neotectonic earthquake activity cannot be entirely dismissed, deformation is most likely to have occurred as a result of the rapid melt of buried ice blocks. Seismic data do not fully penetrate the entire basin sediment fill but the structure and topography of bedrock can be inferred from magnetometer data. The location and shape of buried ice masses was closely controlled by the graben-like form of the underlying bedrock surface.

Keywords: Glaciolacustrine sediment; Laurentide Ice Sheet; Mazinaw Lake; Kettle basin

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1. Introduction

In Canada, the thickest covers of glacial sediment (up to 200 m) are restricted to the southernmost part of the country underlain by easily eroded Paleozoic and Mesozoic strata. Northwards, across the Canadian Shield which is composed of resistant Archean and Proterozoic rocks, the thicker glacial sediment fills are limited to fault-controlled valleys and lake basins (e.g., Kaszycki, 1987). Currently, there is much interest in the fills of shield lake basins because of the paleoenvironmental information recorded therein and also because strata may contain a record of postglacial neotectonic activity (e.g., Klassen and Shilts, 1982; Shilts and Clague, 1992; Doig, 1999; Aylsworth et al., 2000). Many lakes show enclosed depressions on their floors attributed to the melting of ice buried during deglaciation. This paper presents the results of geophysical surveys at one such lake (Mazinaw Lake in eastern Ontario) designed to further understanding of the origin of such basins and their sedimentology.

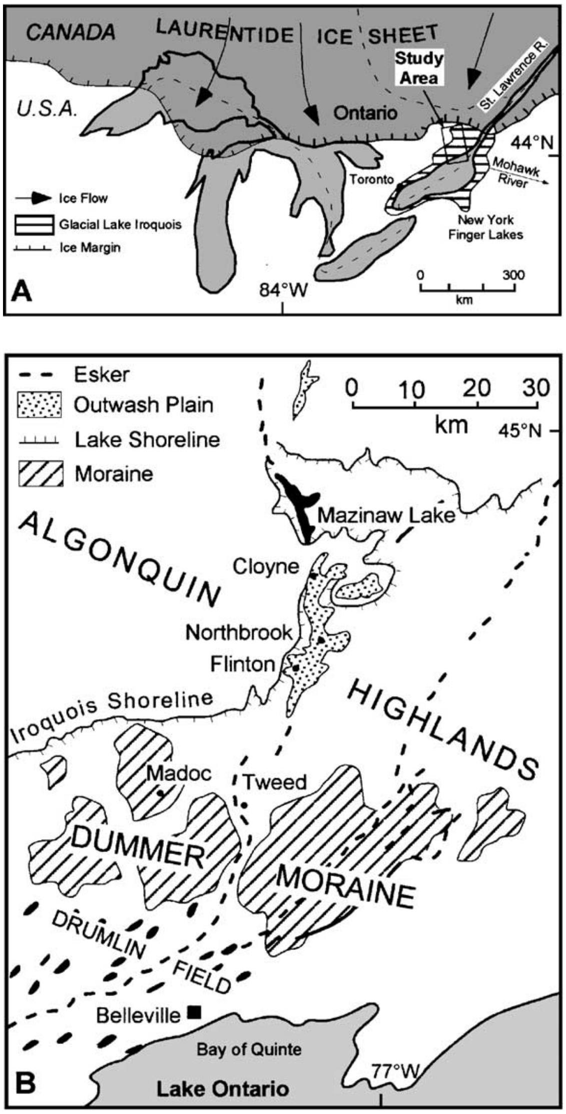

Fig. 1. (A) Study area in eastern Ontario, Canada depicted at the time (~ 12,500 years BP) of maximum extent of Glacial Lake Iroquois; (B) Mazinaw Lake district showing major glacial geomorphological features in the surrounding area.

2. Physical setting of Mazinaw Lake

Mazinaw Lake is a narrow 'finger lake' some 13 km long with an average width of 800 m cut into the Laurentian Highlands (Figs. 1–3) and is one of the deepest water bodies (>130 m) outside the Great Lakes. It occupies a fault-controlled glacially deepened basin within the Grenville Province of the Canadian Shield composed of mid-Proterozoic plutonic and metamorphic rocks belonging to the Grenville Orogeny (ca. 1300–1000 Ma; Easton, 1992). These show prominent west–east trending Grenville shear zones (Easton and Ford, 1991) reflected in the presence of broad embayments in Mazinaw Lake such as Campbell Bay, German Bay, Snyder Bay and Buck Bay (Figs. 2 and 3). The axis of Mazinaw Lake is eroded along the much younger Mazinaw Fault (Easton and Ford, 1991), which records the Late Jurassic opening of an early Atlantic Ocean when the Ottawa–Bonnechere Graben of eastern Ontario formed as a failed rift. The Mazinaw Fault defines the westernmost limit of the graben in eastern Ontario. Mazinaw Lake consists of 'upper' and 'lower' basins separated by a shallow (2 m) sill (the Narrows; Figs. 2 and 3) within Bon Echo Provincial Park. The linear low relief shoreline of the western lake margin contrasts with the embayed form of its eastern shore which shows steep rock walls more than 100 m high that drop precipitously into deep water (e.g., Mazinaw Rock; Fig. 4). The constriction between upper and

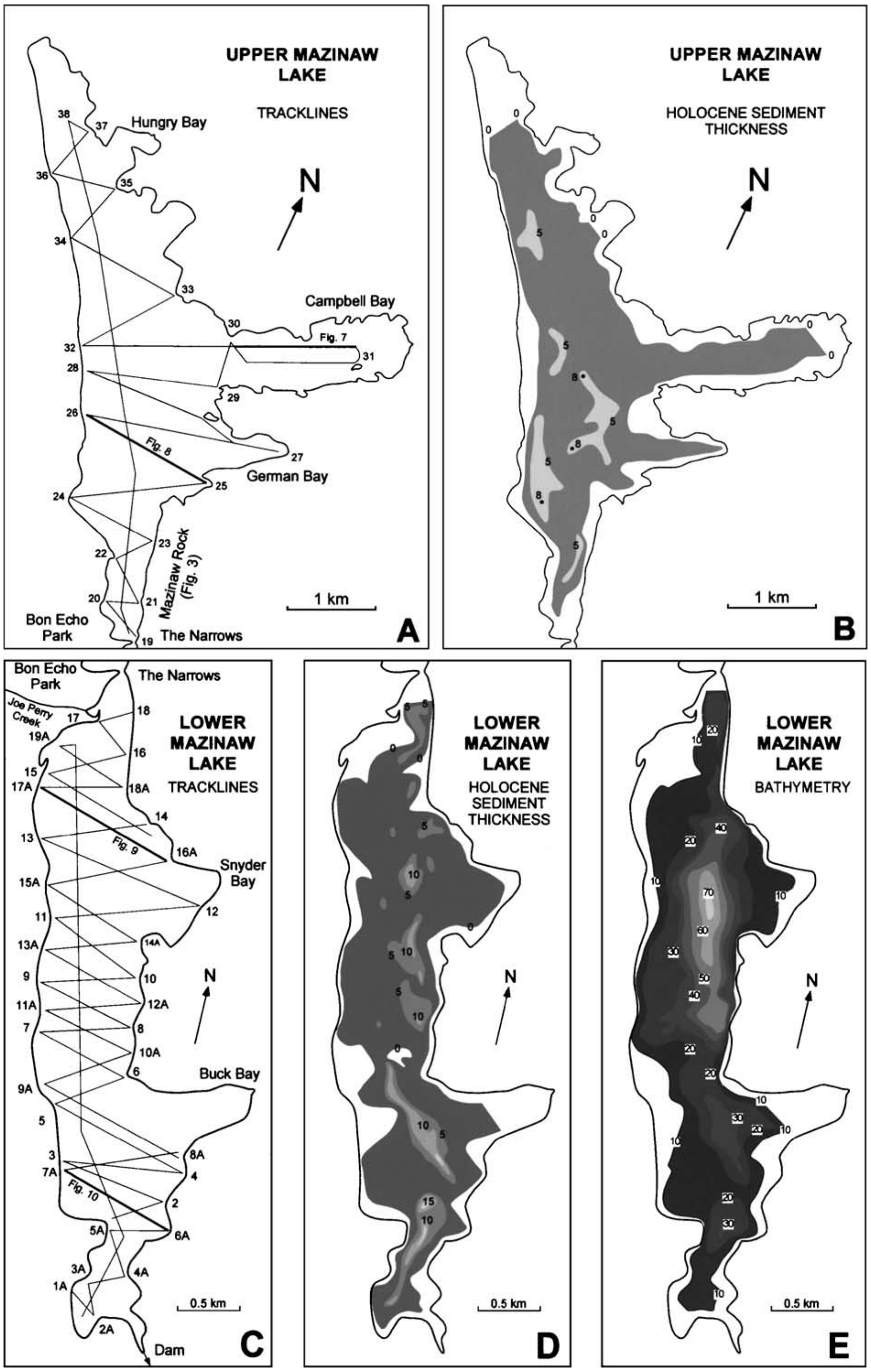

Fig. 2. Maps of Upper Mazinaw Lake illustrating seismic tracklines (A) and thickness of Holocene sediment (B). Bathymetry data are shown in Fig. 4. Seismic tracklines in Lower Mazinaw Lake are shown in (C) Holocene sediment thickness in (D) and bathymetry (E).

Fig. 3. Mazinaw Rock (~ 100 m high) composed of Proterozoic granite forming the linear cliffed shoreline of Mazinaw Lake just north of the Narrows (Fig. 2). The cliff demarcates the trace of the Mazinaw Lake Fault, which controls the axis of the lake basin (Fig. 5).

lower lakes is formed of rock debris derived from the cliffed eastern lakeshore together with a post-glacial fan-delta constructed at the mouth of Joe Perry Creek. Canada's Mississippi River enters the northern end of the basin and drains from the southern margin, ultimately discharging eastward into the Ottawa River.

3. Pleistocene geology of Mazinaw Lake basin

During the last glaciation (late Wisconsin ca. 20,000 years BP) the Laurentian Highlands were covered by the Laurentide Ice Sheet (Fig. 1). Mazinaw Lake is surrounded by typical 'glaciated shield terrain' consisting of glacially streamlined bedrock knobs and 'whalebacks' having a sparse cover of coarse-grained glacial sediment and numerous lakes, bogs and ponds confined to structurally controlled valleys (Henderson, 1973). Mazinaw Lake occurs at the northernmost limit of a regionally extensive glaciofluvial depositional system that can be traced as outwash plains and eskers ridges for more than 100 km to a prominent belt of hummocky topography (the Dummer Moraine; Fig. 1). Just south of Mazinaw Lake, between Cloyne and Flinton, the outwash plain is pitted by numerous kettle basins indicating the trapping of ice as the outwash plain aggraded (Henderson, 1973). Mazinaw Lake itself is a relict water body remaining from ice-dammed Glacial Lake Iroquois which flooded the study area about 12,500 years BP and drained to the Atlantic Ocean through the valley of the Mohawk River in New York State (Muller and Prest, 1985; Anderson and Lewis, 1985; Pair and Rodriguez, 1993) (Fig. 1). The lake floor displays deep enclosed kettle basins typical of many shield lakes (e.g., Klassen and Shilts, 1982; Kaszycki, 1987). By about 11,400 years BP, Iroquois water levels fell to more than 100 m below the modern level of Lake Ontario (Anderson and Lewis, 1985) resulting in isolation of Mazinaw Lake as a separate water body. The lake contains a relict lateglacial shrimp fauna (*Mysis relicta*) inherited from the former glacial lake (Dadswell, 1974).

4. Geophysical methods

4.1. Bathymetry

Hitherto, only generalized bathymetric data existed for Mazinaw Lake. Detailed bathymetric data were

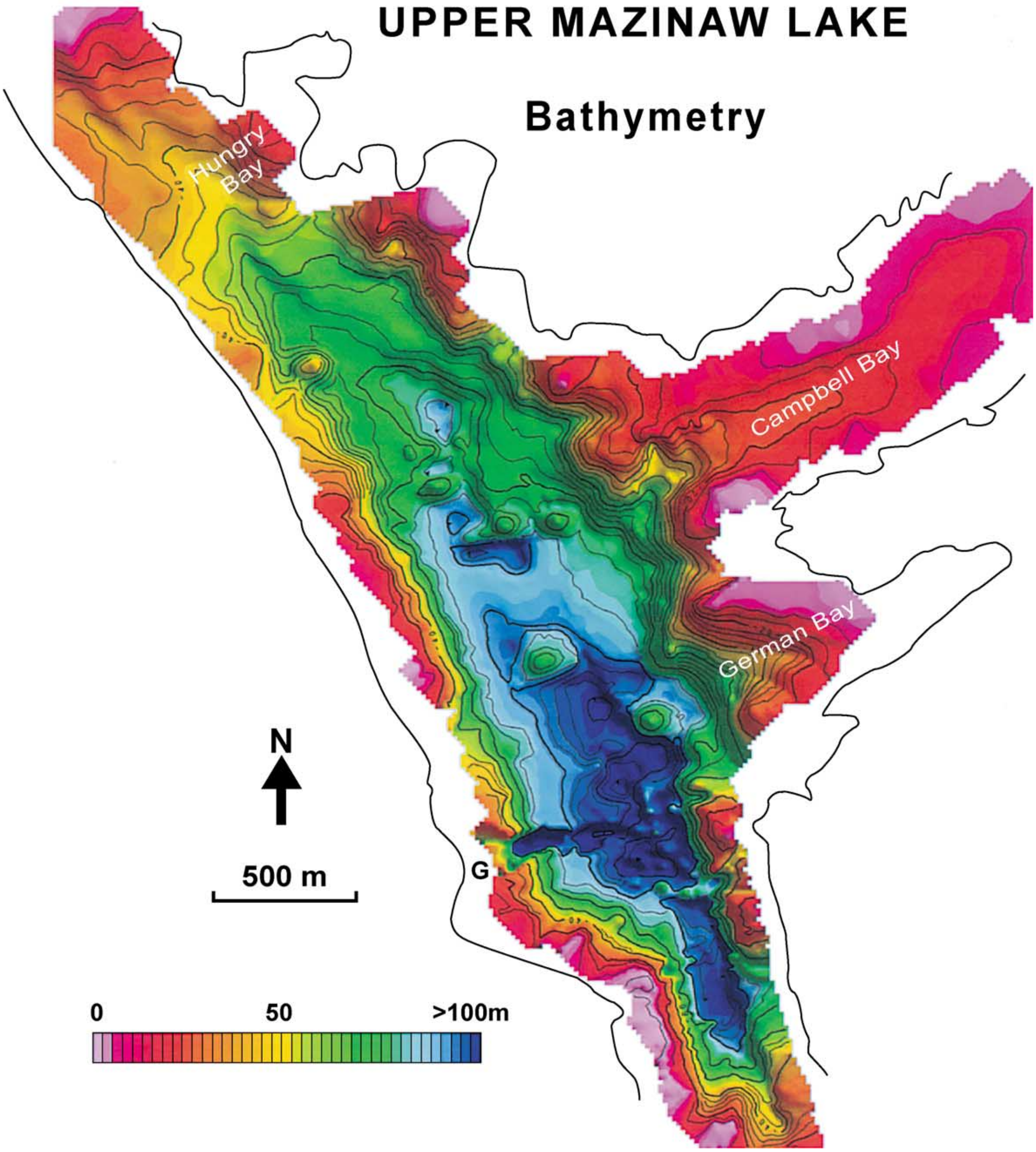

Fig. 4. Bathymetry of upper Mazinaw Lake showing several large enclosed kettle basins, where water depths exceed 100 m, and a prominent canyon-like gully (G) incised into the lake floor.

acquired using a Garmin 200 kHz echo sounder and a single channel seismic 'chirp' profiling system (described below). Echo sounder data were collected in upper Mazinaw Lake to resolve the detailed form of bottom topographic features identified in bathymetric maps produced from seismic track lines (Figs. 2 and 4). Water depths were calculated from echo sounder and seismic data using an assumed water velocity of 1550

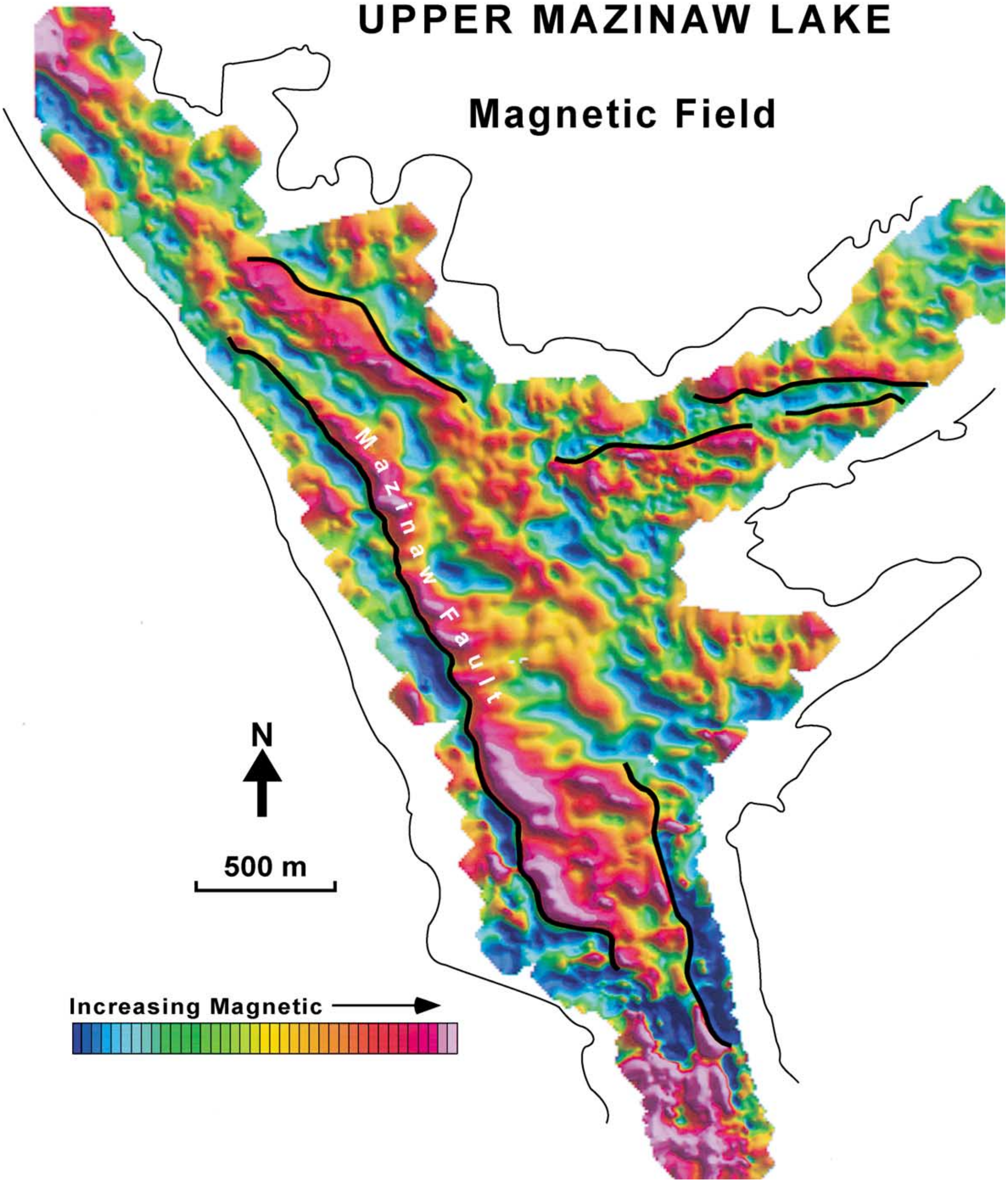

Fig. 5. Magnetic residual map of upper Mazinaw Lake showing northwest–southeast striking magnetic anomalies identifying strands of the Mazinaw Lake Fault (in black lines) defining a graben-like structure along the axis of the lake basin. West–east anomalies identify shear zones in Grenville rocks. Note clear association between the graben-like structure and the shape and location of kettle basins on the lake floor (Fig. 4) indicating the trapping of ice in structurally-controlled lows in the bedrock floor of Mazinaw Lake.

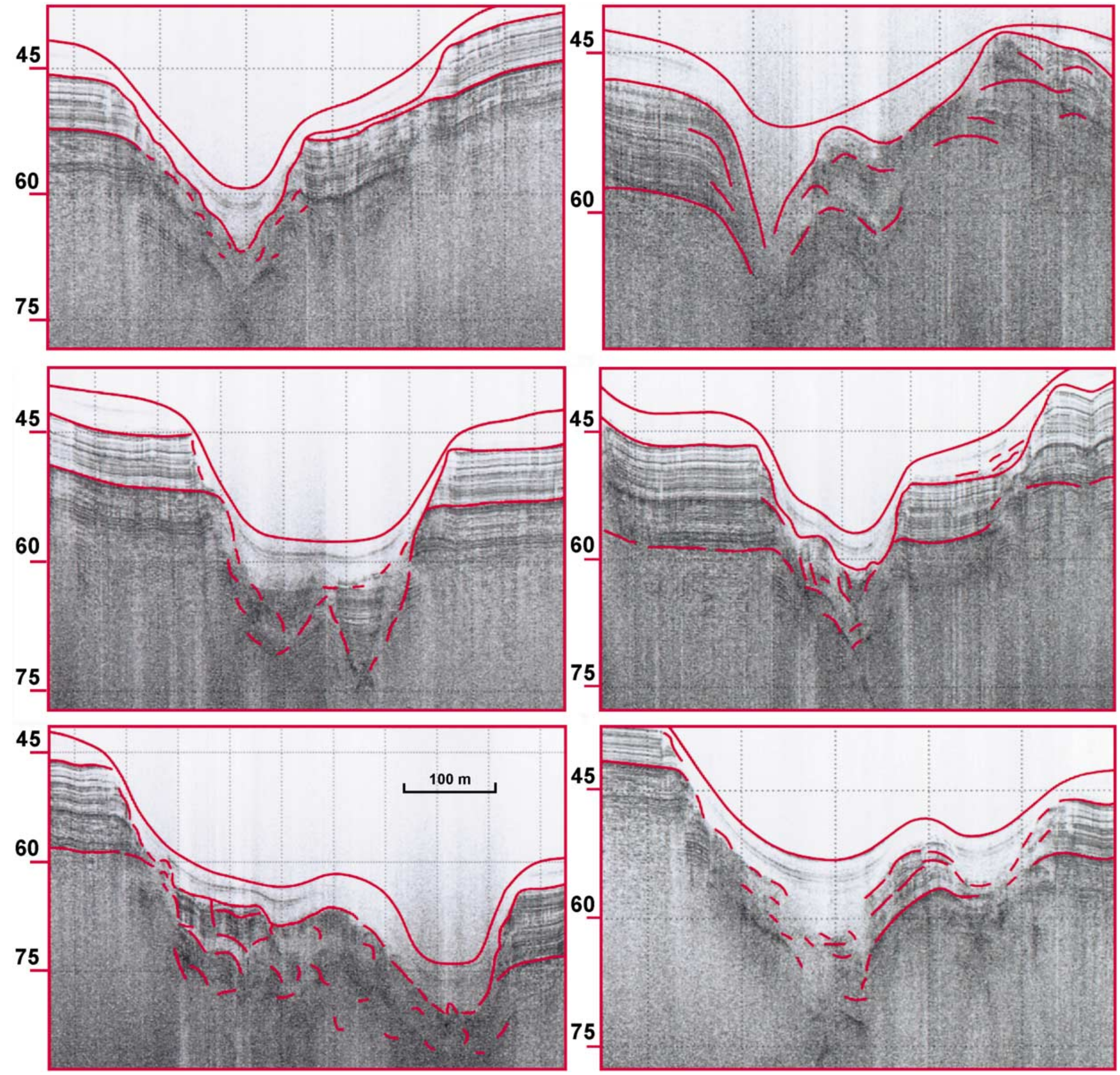

Fig. 6. Single-channel seismic reflection profiles across a single kettle hole basin in upper Mazinaw Lake (G; see Figs. 2 and 4) formed by the melt of buried ice. The basin is underlain and flanked by collapsed Iroquois sediment shown by dashed lines and draped by largely transparent Holocene sediments that are ponded in the deeper parts of the basin.

m/s. Echo sounder data were collected simultaneously with a lake-based magnetometer with track line spacings of 25–75 m. Survey navigation and positional data were acquired using an onboard differential GPS with a horizontal positioning error of <3 m. Post-cruise processing of echo sounder data involved corrections for spherical divergence of the sonar pulse and interpolation of track line data to a detailed bathymetric map (Fig. 4) using a minimum curvature gridding.

4.2. Lake-based magnetics

A lake-based magnetic survey was conducted in upper Mazinaw lake with the object of identifying

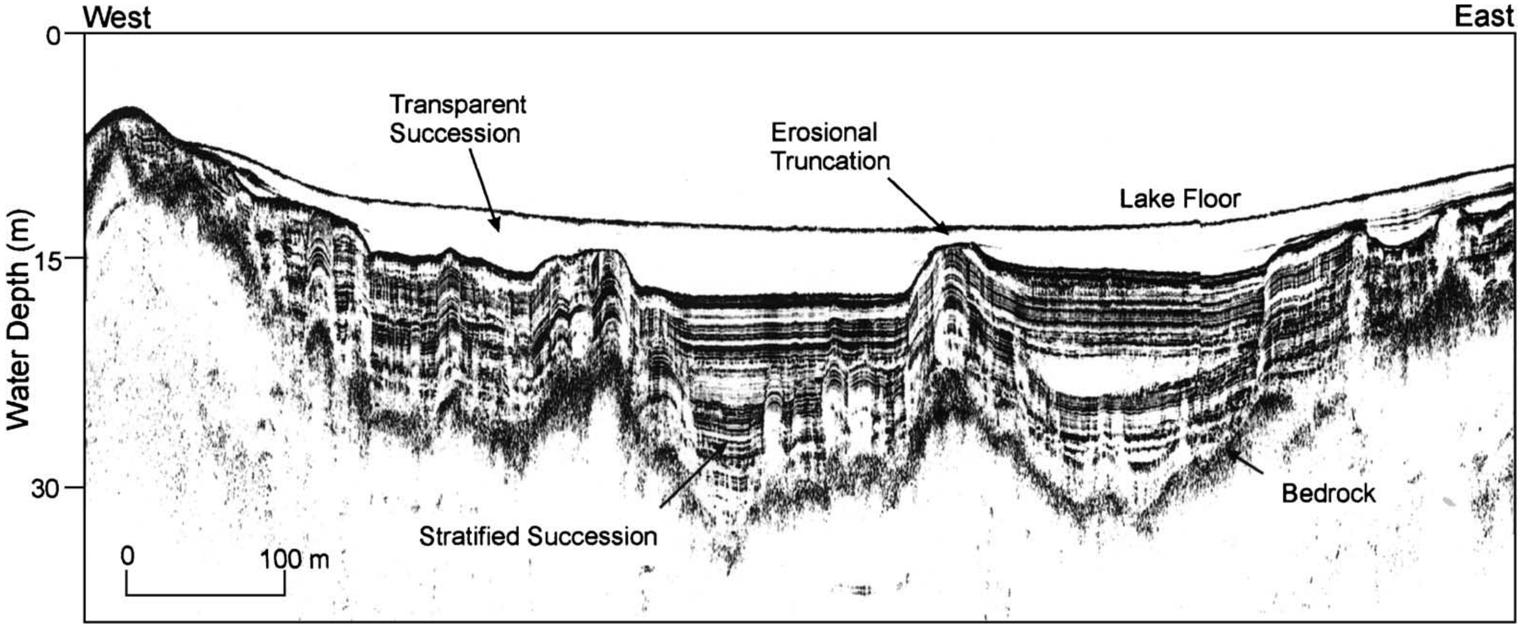

Fig. 7. Eastern portion of single-channel seismic reflection profile 31–32 from Campbell Bay in upper Mazinaw Lake across low relief lake floor between kettle basins (see Figs. 2 and 4). Profile shows basal reflector (bedrock), stratified proglacial lake (Iroquois) deposits and transparent Holocene deposits. Note the presence of lens-like massive facies within the stratified succession and interpreted as debris flow. The undulatory deformation of strata largely mimics the form of the bedrock surface below and results from the draping and ponding of sediment on the undulatory topography below and emphasized by differential compaction.

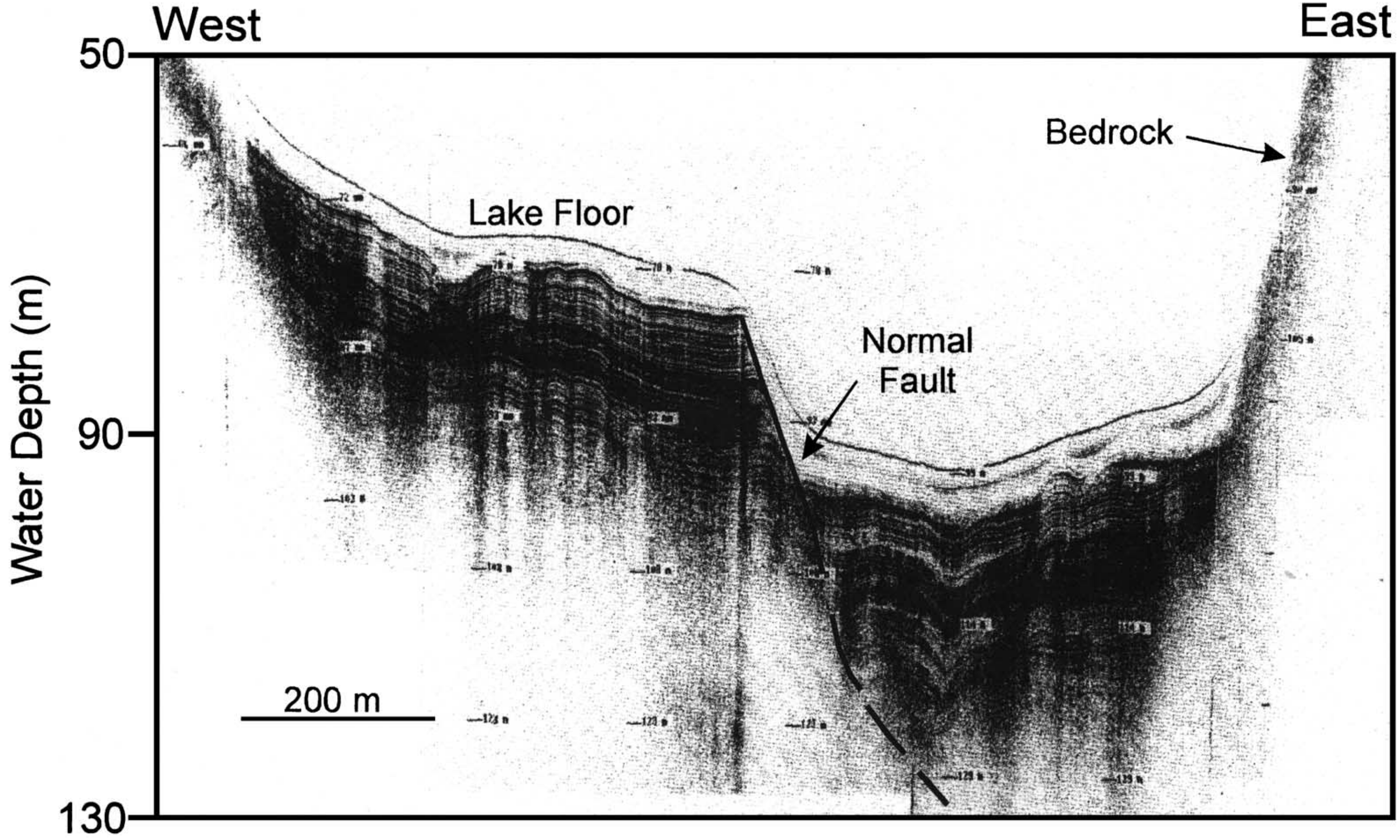

Fig. 8. Single-channel seismic reflection profile 25–26 across a prominent kettle basin in upper Mazinaw Lake (see Fig. 5 for location). The basin results from large-scale faulting accompanying the melt of a buried ice block and the downward movement of sediment that rested on the block. Note that the dip of fault is exaggerated.

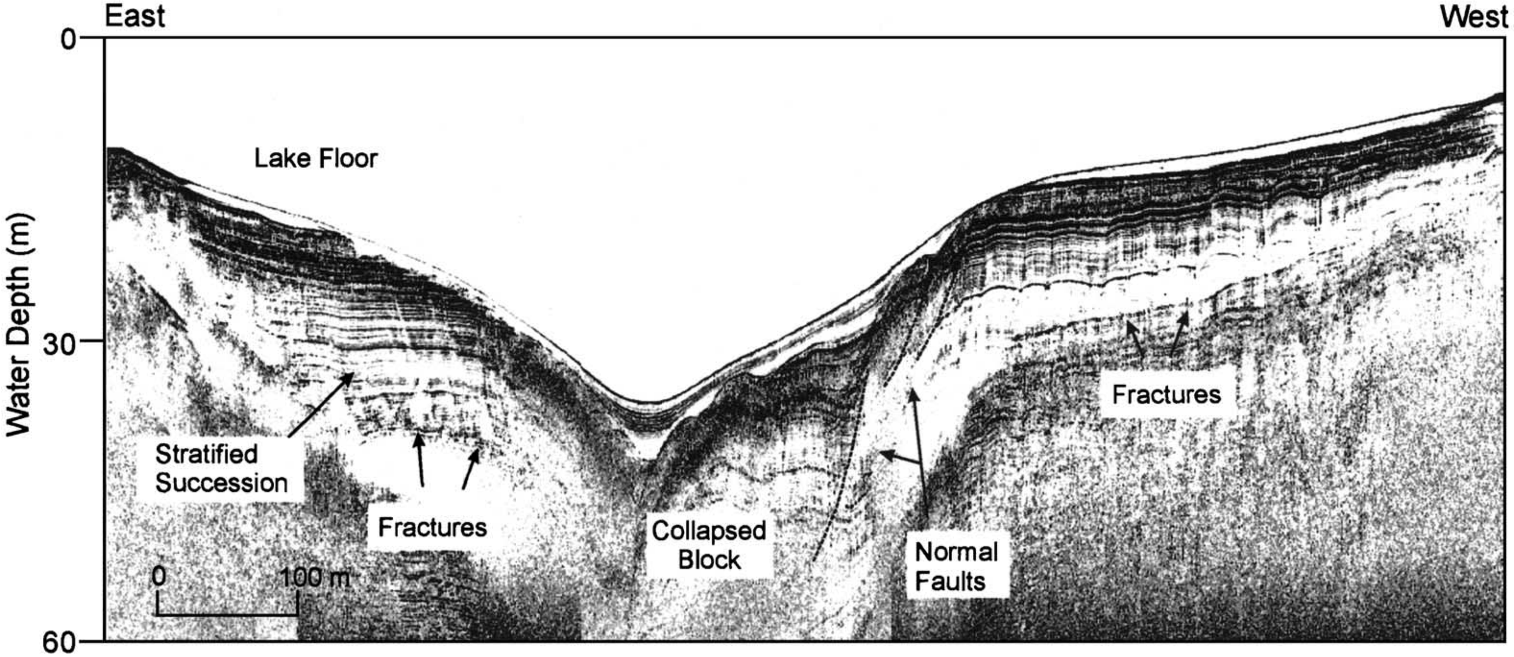

Fig. 9. Single-channel seismic reflection profile 16A–17A from lower Mazinaw Lake (see Fig. 3) illustrating large collapsed block of stratified proglacial succession bounded by normal faults and fractures. Strata record deposition of stratified sediment over ice block and subsequent melt and collapse.

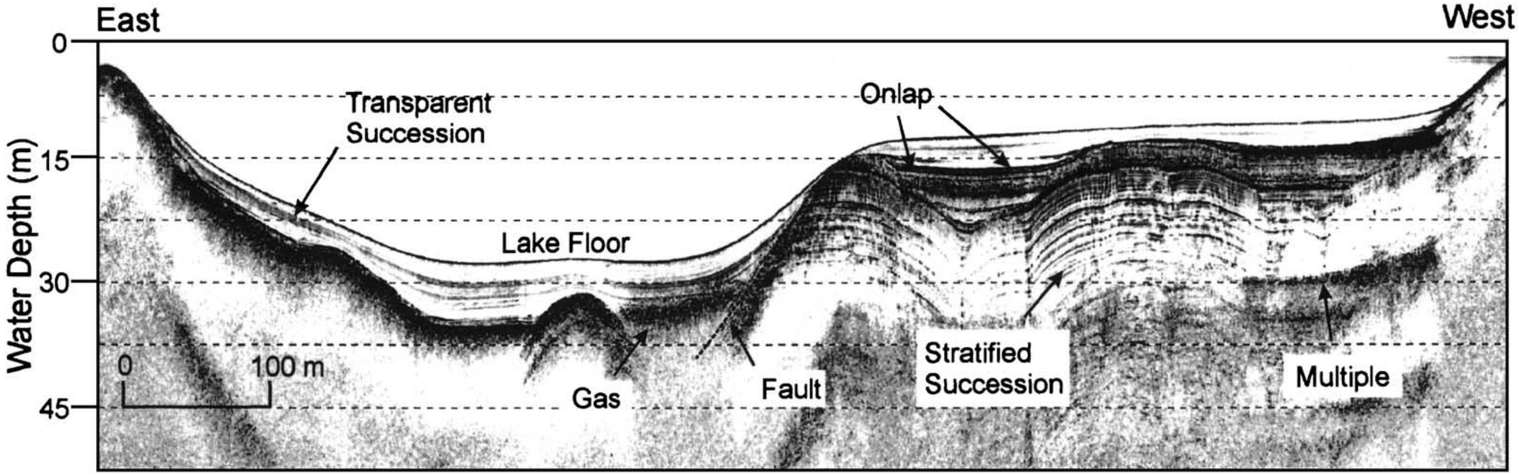

Fig. 10. Single-channel seismic reflection profile 6A – 7A from lower Mazinaw Lake across a lake floor kettle basin (Fig. 2 for location). The steep faulted western margin of the kettle basin records the presence of an ice block on the eastern half of the profile which likely prevented deposition of the stratified succession. The profile also shows the warping of the stratified Iroquois succession due to melt of buried ice during deposition of Iroquois sediments. The resulting structural depression has been filled by a sub-sequence that onlaps within Iroquois strata.

bedrock structure. Total field surveys were acquired with a Marine Magnetics Overhauser proton magnetometer towed at a depth of 5 m and a speed of 5 knots. A total of 85 line kilometers of magnetic data were collected along a series of west–east tracklines crossing the projected strike of the mapped fault zones;

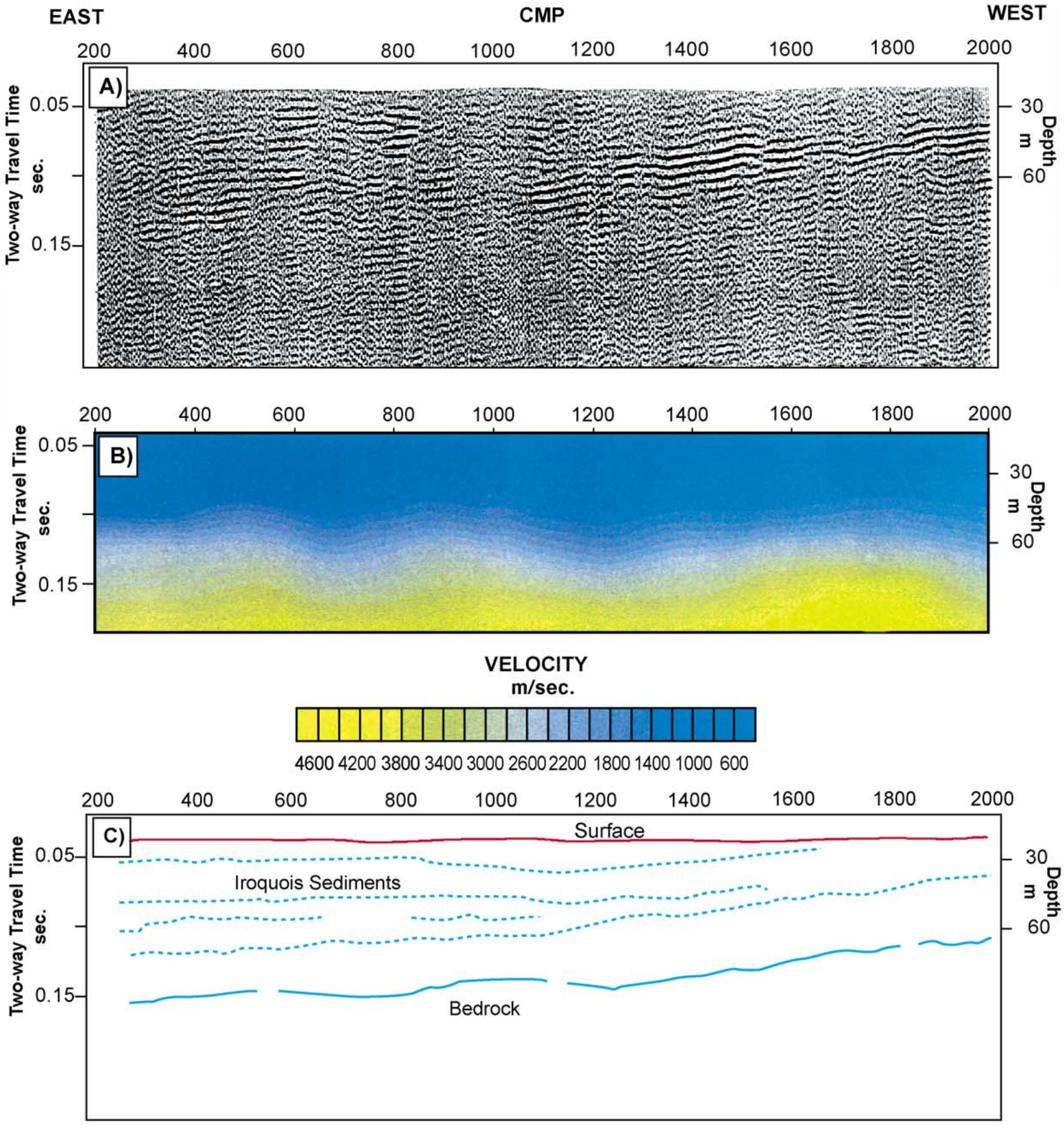

Fig. 11. Land-based multichannel seismic reflection profile (A) collected from Bon Echo Provincial Park with calculated velocity structure (B) and interpretation (C). The prominent basal reflector forms acoustic basement below the sediment infill of Mazinaw Lake (Fig. 7) and is interpreted as bedrock.

several north–south axial lines were also recorded to permit later tie-line levelling of magnetic data. The magnetometer was cycled at 4 Hz, providing in-line sample intervals of about 2 m. A second base station magnetometer was deployed onshore to record diurnal magnetic field variations throughout the survey period. Positional data from onboard DGPS were encoded with magnetic data during survey operations. Post-cruise processing of magnetic data involved corrections for diurnal variations, tie-line levelling, upward continuation (to 100 m) and regional residual separation. Other corrections involved application of continuation algorithms to remove magnetic variations (up to 40 nT) associated with changes in water depth. The final processed magnetic residual field map identifies several northwest and west–east striking linear magnetic anomalies (Fig. 5).

4.3. Seismic reflection

A seismic reflection survey was completed to determine the thickness, stratigraphy and origin of sediments below the lake floor (Figs. 6–10). We employed an EdgeTech high-resolution X-STAR digital sub-bottom profiling system utilizing chirp technology with a SB-216S tow vehicle and magnetic tape data storage. The system transmits a pulse that is linearly swept over a full frequency range of 2–12 kHz for 20 ms (a 'chirp' pulse). The acoustic return received by two sets of hydrophones is matched filtered with the outgoing pulse in order to increase the signal to noise ratio. Data were plotted on a GSP-1086 EPC graphic recorder with a time-varying gain that increased linearly (0.5 dB/m) below the lake floor; no additional post-cruise processing was performed. The acoustic package was towed approximately 0.5 m below the lake surface at a speed of 1.5 m/s (3 knots). Navigational fixes by GPS were recorded on magnetic tape with each trace of the seismic data and were confirmed by dead reckoning using compass headings between prominent points along the shoreline.

The X-STAR FM seismic system typically resolves reflections within the upper 20–30 m of the sediment column at a 20–30-cm scale resolution. Sediment and water depths discussed below, and displayed on the figures, assume a constant water column velocity of 1550 km/s and average sub-bottom velocity of 1650 m/s (e.g., Mullins and Eyles, 1996; Eyles and Mullins, 1997; Eyles et al., 2000).

A land-based seismic reflection survey (Fig. 11) was also completed along a 350 m transect in Bon Echo Provincial Park using a 24-channel EG&G seismograph with a 10 lb hammer and 100 Hz geophones. Data acquisition employed a 3 m receiver and source separation with end-on geometry. Data acquisition and processing steps involved two-dimensional filtering to remove background noise and surface waves, normal move-out correction and common mid-point stacking (see Boyce et al., 1995; Boyce and Koseoglu, 1997; Buker et al., 2000). Geophysical data were groundtruthed by on-land field surveys of sediment outcrops exposed along Joe Perry Creek together with a 4-m-long piston core recovered from Mazinaw Lake in winter through the ice cover.

5. Results

5.1. Bathymetric data

Lake bathymetry was reconstructed by interpolation of water depths from seismic track lines but because of the relatively broad line spacing this gives only a generalized picture of lake floor topography (e.g., Fig. 2E). Large enclosed basins exist in both upper and lower parts of the basin and these are surrounded by areas of flat lake floor which were called 'terraces' by Kaszycki (1987) when describing the floors of shield lakes in Ontario. Results of the much more detailed echo sounder survey in upper Mazinaw Lake provide a clear picture of the configuration of the kettle basins, particularly their steep sidewalls, and also more closely defines areas of hummocky topography such as at the mouth of Campbell Bay (Fig. 4). Echo sounder data also identify a deep erosional gully cut into the sidewalls of the large depression at the southern end of upper Mazinaw lake, (G; Fig. 4). This feature provides important evidence for erosion of the lake fill during a period of lowered lake levels after the drainage of Lake Iroquois (see below).

5.2. Lake-based magnetics

The magnetometer survey of upper Mazinaw Lake basin shows two prominent northwest-trending subparallel magnetic lineaments that cross-cut more subtle west–east lineaments (Fig. 5). Northwest-trending structures define the late Jurassic Mazinaw Lake Fault as mapped by Easton and Ford (1991). A single fault plane was mapped by these workers who were constrained by a lack of subsurface data below the lake. Magnetic mapping clearly shows that the fault is not simple but consists of two subparallel structures, which we suggest defines a graben along the deepest part of the bedrock basin. The presence of a graben below Mazinaw Lake agrees with what is known of the regional Late Jurassic structural evolution of eastern Ontario, which saw regional crustal extension and formation of the Ottawa-Bonnechere Graben. The west–east magnetic trends within upper Mazinaw identify older Grenville shear zones that strike across the basin (Easton and Ford, 1991). In general, it can be noted that there is an excellent spatial correlation between lineaments on magnetic data (Fig. 5) and the location and dimensions of enclosed basins on the floor of upper Mazinaw Lake (Fig. 4). The significance of this relationship is discussed below.

5.3. Seismic reflection data

Seismic profiles from Mazinaw Lake (Figs. 6–10) allow identification (from bottom to top) of: (1) a basal high-amplitude reflector of moderate to high relief; (2) an acoustically stratified succession, characterized by even, parallel and high-frequency reflections that locally show extensive structural disturbance below kettle basins; and, (3) an uppermost transparent acoustic succession that underlies the modern lake floor. Each of these is briefly described and interpreted below.

5.3.1. Basal reflector

The basal reflector where recognized in Mazinaw Lake shows marked, high-amplitude diffractions and a distinct hummocky form. In shallow-water areas, acoustic basement rises toward the basin margins to outcrop above lake level as glacially scoured bedrock devoid of sediment cover. In shallow embayments, such as Campbell Bay (Fig. 7), the basal reflector has the same hummocky surface typical of glacially streamlined 'whalebacks' of the surrounding shield surface. Land-based seismic data also identifies the same prominent reflector horizon (Fig. 11B, C). As a result, acoustic basement in Mazinaw Lake is identified as bedrock. Along the axis of the basin, the high-frequency sound source was unable to fully penetrate the deeper portions of the basin fill (e.g., Figs. 8–10) and it is in these locations that older glacial sediment might be preserved.

5.3.2. Acoustically stratified succession

This succession has a maximum thickness of at least 30 m, consisting of even, parallel, high-frequency reflections that thin and increase in frequency upwards toward the lake floor. Prominent reflectors within the succession appear to define the tops and bottoms of sub-sequences that can be traced laterally for hundreds of metres but not throughout the entire lake basin (e.g., Figs. 7 and 8). In addition, massive, acoustically transparent facies with a lens-like architecture occur within the stratified succession in topographic lows (Fig. 7).

The acoustically stratified succession is exposed above lake level along the sidewalls of Joe Perry Creek near the narrows that separate upper and lower Mazinaw Lake basins. Outcrops show rhythmically laminated (varved?) glaciolacustrine silty-clays of Glacial Lake Iroquois. These lithofacies are classically deposited by underflows derived from glacier-fed fan deltas (Ashley, 1975) and a similar origin is proposed here for the high frequency acoustically stratified succession present below lake level in Mazinaw Lake. The presence of prominent internal reflections and apparent sub-sequences on seismic records suggests variation in depositional conditions created by changes either in water depth, meltstream discharge or location of sediment sources consistent with a dynamic proglacial lacustrine environment. Massive facies within Iroquois sediments are interpreted as homogenous silts, most likely deposited as single beds by sediment gravity flow. These could be the result of enhanced discharges of meltwater into the lake or downslope collapse of sediment elsewhere in the basin.

5.3.3. Upper acoustically transparent succession

This succession is acoustically transparent with no significant density and/or velocity contrasts and only a few very low-amplitude and poorly defined reflections. It rests directly on Iroquois sediments with the contact marked by a prominent high-amplitude reflector. This upper acoustically transparent succession is thin (< 2 m) or absent across much of the shallow-water regions around the perimeter of Mazinaw Lake. In deeper offshore areas, this succession is draped across bathymetric highs and ponded within depressions (Figs. 6 and 10). Maximum thickness (up to 15 m) occur in depressions along the axis of the lake (Fig. 2) indicating preferential deposition in the deeper portions of the lake (e.g., Davis and Ford, 1982).

Uppermost acoustically transparent sediments are identified as Holocene in age, which is in keeping with the bipartite seismic stratigraphy reported from other shield lakes (e.g., Klassen and Shilts, 1982). A 4-m-long sediment core taken through the upper acoustically transparent unit at the southern end of lower Mazinaw Lake recovered loosely consolidated, poorly laminated organic-rich mud. The drape-like geometry of these facies over bathymetric highs on the lake floor suggests deposition by fall-out from suspended fine sediment moving through the lake basin as either interflows or overflows. Given the sparseness of sediment on the surrounding shield and the near absence of suspended sediment in area rivers, much of this sediment may have originated within the Mazinaw Lake basin by erosion and resuspension of older Iroquois sediment. Another source may be autocthonous biological processes given the prevalence of Holocene gyttja deposits in shield lakes of Ontario (e.g., Kaszycki, 1987).

6. Kettle basins and associated deformation structures

The floors of both upper and lower Mazinaw Lake basins are not flat but display deep, very steep-sided enclosed basins where water depths are greater than 100 m (Figs. 2 and 4). Seismic profiling shows that flat-lying strata of Iroquois age (acoustically stratified succession) have been been downfaulted and deformed on the margins and below the base of enclosed basins (Fig. 6). Deformation structures include normal faults that progressively step down into the basins, large rotational slides and closely spaced fractures (Figs. 8–10). Faulted Iroquois sediments pass downslope into chaotic acoustic seismic facies where pre-existing seismic stratigraphy has been destroyed by downslope slumping and slope failure from the adjacent basin margins. Seismic data from areas of hummocky lake floor show that this topography is underlain by gently warped Iroquois sediments (Fig. 7).

6.1. Origin of basins and associated deformation structures

Deformation of strata in glaciated terrains can result from many processes. These include glaciotectonic thrusting below or at the margins of ice sheets, by the melt of buried glacier ice or permafrost, and by the reactivation and upward propagation of pre-existing bedrock structures during late or postglacial neotectonic activity. Of these, the melting of buried ice appears to be the most likely explanation for the deformed fill of Mazinaw Lake. No overlying till resting on Iroquois sediments can be recognized on seismic profiles nor has been identified from mapping around the lake basin. Data indicate that ice had evacuated the area prior to flooding by proglacial Lake Iroquois (Henderson, 1973). Consequently, a glaciotectonic origin involving subglacial deformation is not considered further. The effect of permafrost is also ruled out given the entirely subaqueous origin of Iroquois sediments below Mazinaw Lake and the lack of any record of extensive ground freezing during deglaciation elsewhere in Southern Ontario. The extensive, large-scale structural disturbance in Mazinaw Lake and the presence of deep enclosed basins in the lake floor is also not consistent with the known record of earthquake activity and neotectonic deformation in the region (e.g., Wallach et al., 1998). Nonetheless, it has to be said that the history of neotectonic activity in Ontario is not well known as relatively few detailed investigations have been conducted. Mazinaw Lake is unusual in that it lies directly above faults associated with the Ottawa Graben (Fig. 5). It is very noticeable that collapse and deformation of the lake fill appears to have taken place more or less at the same time and coincides with the abrupt drainage of Lake Iroquois. For example, Iroquois sediments are extensively deformed while those of the Holocene are not implying an abrupt deformation event. Rapid lake level lowering (by as much as 100 m) may have resulted in an increase in bottom water temperature but this is unlikely to have created a rapid response at depth within the sediment fill. Given the very large regional extent of Lake Iroquois, however, abrupt drainage would have given rise to a rapid decrease in crustal loading at a time of rapid glacio-isostatic rebound. It is possible that this could have triggered reactivation of faults along the Ottawa Graben and given rise to earthquake activity and sediment collapse. We note in this regard that large magnitude Holocene earthquakes are recorded along the Ottawa Valley, within 100 km of Mazinaw Lake, by massive landsliding of lateglacial marine clays (Aylsworth et al., 2000). Other earthquake-related mass flow events are recorded in the fill of Lake Temiscaming (Doig, 1999) which is a northwesterly extension of the Ottawa Graben along the Ontario–Quebec border. A key feature of the Mazinaw deformation is that it is associated with large enclosed depressions on the lake floor and these are difficult to explain as a result of earthquake shaking. The sites of structural disturbance below the lake floor are restricted to locations under and along the margins of enclosed basins (e.g., Fig. 6). The formation of such basins by the melt of buried ice is in keeping with descriptions of other enclosed depressions from shield lakes (Klassen and Shilts, 1982). It is a reasonable conclusion that deformation results from the collapse of sediment that had been deposited over glacier ice trapped at depth.

6.2. Formation of kettle basins in Glacial Lake Iroquois

Stranding of dead ice in proglacial lakes has been observed at modern glacial lakes (e.g., Gustavson, 1975) and inferred from the deposits of Pleistocene glacial lakes (Eyles et al., 1987). Apparently, it was a very common process during Late Wisconsin deglaciation on the Canadian Shield. Enclosed depressions resulting from the melt of ice buried below sediment are widespread on the floors of shield lakes (e.g., Klassen and Shilts, 1982; Larocque, 1985; Kaszycki, 1987). These have variably been described as ice block depressions, kettle basins, dead ice sinks and ice block casts and moats. Kaszycki (1987) presented a glacial depositional model for the shield, stressing the importance of zonal stagnation in areas of moderate bedrock relief (up to 100 m). As the ice thinned during overall regional retreat, bedrock highs emerged through the ice and isolated remnant blocks from the main ice sheet in bedrock valleys (e.g., Rich, 1943; Fleisher, 1986; Wingfield, 1990; Eyles and Clague, 1991; Chikita et al., 2001). Typically, ice blocks were trapped in the deepest parts of bedrock basins (see Kaszycki, 1987) and this appears to be the case at Mazinaw Lake, as can be inferred from the very clear relationship between faults as identified by magnetometer data (Fig. 5) and those locations where ice blocks became trapped and now recorded by elongate kettle basins (Fig. 4). It can be noted that the largest kettle basins in upper Mazinaw Lake form a linear trough on the lake floor located between the two strongly defined magnetic lineaments defining the Mazinaw Lake fault (compare Figs. 4 and 5). As related above, these lineaments very likely define a narrow graben structure and it is not unlikely that the deepest part of the bedrock basin occurs there. If such inferences are correct, magnetometer data provide a first-order approximation of the bedrock topography below the sediment infill of Mazinaw Lake. It can be suggested that a large tongue-like mass of ice appears to have been trapped within the narrow graben below upper Mazinaw Lake (Fig. 4). It is likely that initial trapping occurred subaerially and ice was subsequently covered by waters of Lake Iroquois. In order to anchor dead ice below the waters of Glacial Lake Iroquois, ice must have been freighted with sediment sufficient to overcome buoyancy as the area became progressively flooded. These sediments may have been deposited subaerially or in shallow water but no record survives.

Normal faulting and the creation of graben-like kettle basins, has left large foot-wall blocks below the surrounding lake floor (Figs. 8–10). Simple correlation of reflector packages across basins indicates maximum throws of about 20 m suggesting a similar thickness for buried ice blocks. Acoustically chaotic facies in the kettle basins (Figs. 6, 8, and 9) are typical of sediments that have been destratified and homogenized by downslope collapse (Mulder and Cochonat, 1996; Mullins and Eyles, 1996; Halfman and Herrick, 1998). A very similar style of structural disturbance caused by the melt of buried ice blocks is reported by Todd and Lewis (1993) from Lake Simcoe some 100 km to the west of Mazinaw Lake.

Elsewhere in Mazinaw Lake, acoustic data from those areas of hummocky lake floor (Fig. 7), indicate that this topography is the result of a combination of sediment ponding and infilling around bedrock highs accentuated by the differential compaction of saturated fine-grained sediment (e.g., Williams, 1987). Prominent beds of acoustically transparent facies within the Iroquois deposits (Fig. 7) are interpreted as sediment gravity flows (see above).

6.3. Timing of ice melt and water level changes

Glacial Lake Iroquois formed when the Laurentide Ice Sheet margin had retreated from the Ontario basin sometime after 12,500 years BP (Anderson and Lewis, 1985). Because ice-melt related deformation structures affect the *entire* thickness of Iroquois sediment in Mazinaw Lake, it can safely be inferred that subsidence and collapse postdates the drainage of Lake Iroquois at 11,400 years BP. This suggests that buried ice blocks survived for no more than about 1000 years on the floor of Glacial Lake Iroquois. Nowhere in Mazinaw Lake is there any evidence suggesting that ice survived for any length of time into the Holocene. Transparent Holocene sediments drape the kettled floor of the lake and appear to be unaffected by collapse.

Our preferred explanation for the deformation seen in Mazinaw Lake is that of collapse over buried ice but because of its location over faults of the Ottawa Graben and the abrupt nature of deformation, we do not fully exclude neotectonic activity and lateglacial reactivation of bedrock faults as a contributor to deformation. Clearly, further surveys of the many shield lakes in and along the graben is required in order to identify any possible earthquake-related deformations. Locally, late glacial deformation structures terminate upwards intraformationally within Iroquois sediments and are overlain by undeformed Iroquois sediment (e.g., western half of Fig. 10). This relationship indicates that the final melt of buried ice blocks was diachronous. It is clear from the overlapping, infilling geometry of later Iroquois sediment seen in Fig. 10 that bathymetric lows created by ice melt during sedimentation controlled the routes taken by subsequent density underflows.

Seismic reflection profiles collected from the shallow-water (< 20 m) areas of Mazinaw Lake display evidence for erosional truncation of Iroquois sediment due to a phase of low lake level some 12 m below modern lake level. It is interesting to note that in upper Mazinaw Lake, a major erosional gully has been incised into the terrace surrounding the large kettle basin and is directly analogous to a submarine canyon (G; Fig. 4). This likely records lake lowering after the drainage of Glacial Lake Iroquois after 11,400 years BP. A small subaqueous fan deposit likely occurs on the floor of the kettle basin.

As a final comment, the data and interpretations presented here suggest a solution to a problem frequently encountered in geophysical imaging of thick lake basin fills in glaciated terrains. This is the inability to fully resolve the nature of the bedrock surface at depth given the considerable thickness of sediment fill. Typically, high-resolution subsurface seismic data can only be collected at relatively shallow depths and deeper penetration must be traded off against resolution. Work at Mazinaw Lake shows that valuable information regarding bedrock structure, and the likely relief of the bedrock surface, can be inferred from magnetic surveys.

7. Conclusions

Thinning of the Laurentide Ice Sheet in eastern Ontario, Canada at the end of the last glaciation allowed bedrock highs to emerge through the ice sheet. These acted as barriers and prevented any further ice flow to downstream parts of its margin, leaving blocks of dead ice stranded in topographic depressions, a process termed ‘zonal stagnation’. Trapping of dead ice blocks and their subsequent burial by sediment and the rising waters of Glacial Lake Iroquois (~ 12,500 to 11,400 years BP) is recorded across the Canadian Shield by pitted glaciofluvial outwash deposits and lake floors pockmarked by enclosed kettle basins. Seismic reflection data collected from kettle basins on the floor of Mazinaw Lake show that deformed glaciolacustrine sediments underlie and surround such basins. The style of deformation is consistent with gravitational collapse accompanying the melt of buried ice. No clear evidence can be found of postglacial neotectonic activity, but given the location of the lake basin directly above faults of the Ottawa Graben, the possibility of earthquake-related deformation cannot be entirely dismissed and should be investigated further.

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