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High-resolution seismic sub-bottom reflection record of low hypsithermal lake levels in Ontario lakes

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ABSTRACT

Recently published work in mid-continent North America based on coring of Lake Huron sediments and paleo-environmental analysis of their included pollen and microorganisms has revealed low water levels during the warmth of the mid-Holocene hypsithermal, suggesting the Great Lakes were largely disconnected from each other sometime shortly before 8000 years ago. We have supported this hypothesis by interpreting a large database of high-resolution seismic reflection track lines (~2000 km) from sixteen lakes in Ontario found principally on the Canadian Shield and within the limits of former glacial Lake Algonquin. Geophysical data show a common seismo-stratigraphy of late and postglacial sediment sequences bounded by distinct erosion surfaces that are regionally correlative. These can be correlated with published data on cored and dated seismic sequence boundaries from the French River area of Georgian Bay in northeastern Lake Huron together with other subsurface data from the central basin of Lake Huron. A consistent regional paleo-environmental picture emerges of lowered water levels when glacial Lake Algonquin drained approximately 11,000 ybp, fluctuating lake levels thereafter (the Mattawa–Stanley phase) accompanied by the cutting of a distinct erosion surface subaerially or in shallow water across older lacustrine sediments between approximately 9,000 and 8,000 ybp that identifies a regional lacustrine response to a much dryer mid-continent hypsithermal climate. Younger postglacial sediments deposited as lake levels recovered during more humid Neoglacial climates are spatially discontinuous across lake floors occurring as mounds and sheets similar to marine contourite deposits ("drifts") reflecting modern sediment-starved conditions and strong wind-driven bottom currents.

Introduction

Central Canada is the most heavily populated area in the country with significant pressures on surface water resources especially that of the Great Lakes, but the longer-term geological history of such water bodies following the retreat of the Laurentide Ice Sheet is still yet to be fully understood. This lack of information is surprising given that lakes cover 21% of the total area of Ontario, and their bottom sediments and included microfauna and pollen yield significant information regarding late glacial and postglacial paleo-environments and climates (e.g., McCarthy et al., 2012). Ongoing geophysical work by the authors has to date generated more than ~2000 line km of high-resolution sub-bottom seismic reflection "chirp" track line data from many lakes (Figs. 1–3). This is part of a concerted effort over the last several decades to collect data from the floors of lakes in central Canada to identify those areas that have experienced ground shaking and sediment disturbance by mid-continent intraplate earthquakes and, if so, to better understand their spatial relationship to deep-seated Precambrian basement structures (e.g., Doughty et al., 2010, 2013, in press; Shilts and Clague, 1992; Thomas et al., 1993; Wallach et al., 1998). During the course of this investigation, it has been noted that a consistent bi-partite seismo-stratigraphy is preserved below their floors recording a common geologic history. This stratigraphy consists of lowermost thick (~tens of meters) rhythmically laminated ("varved") late glacial sediments which commonly rest on bedrock, and which began to accumulate in ice-dammed "precursor" lakes such as glacial Lake Algonquin after 12,000 ybp (years before present; calibrated ^{14}C ages ybp are used to support all dates) when the Laurentide Ice Sheet (LIS) was retreating northwards but still blocking outlet drainage from the Great Lakes basin. Such deposits commonly account for the bulk of the sediment volume (~90–95%) preserved in most lake basins. Younger postglacial sediments (<c. 11,000 ybp) that underlie modern lake floors are in contrast largely seismically transparent and reflection-free, thinner, organic-rich, and often markedly discontinuous in extent. The contrast in thickness and character between late and postglacial sediments is widely developed across Canada (e.g., Gilbert and Desloges, 2005, 2012; Shilts and Clague, 1992), which in Ontario lake basins essentially reflects the availability of large volumes of glacially derived sediment and meltwater during deglaciation and LIS retreat, and a lack of clastic sediment thereafter from forested watersheds underlain by resistant Precambrian crystalline rocks.

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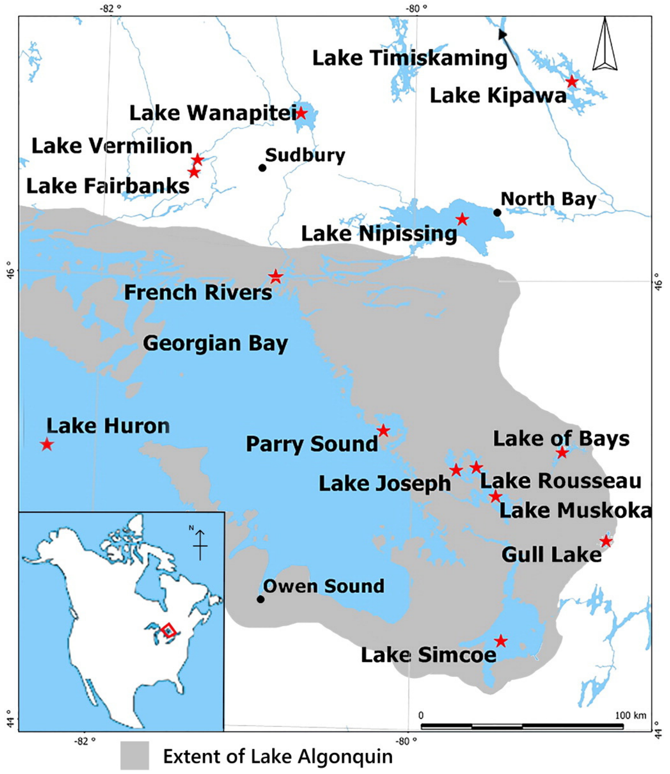

Fig. 1. Location of study area in central Ontario with lake basins referred to in text. Approximate outline of glacial Lake Algonquin from Jackson et al. (2000).

The most complete sub-lacustrine stratigraphic work completed to date in the Lake Huron basin is that by Moore et al. (1994), Rea et al. (1994), Dobson et al. (1995), and most recently by Brooks and Medioli (2012). These workers identified and dated distinct boundaries separating sequences of acoustic facies in lake floor sediments in the main Huron Basin and in various sub-basins along the French River outlet of Lake Nipissing (Figs. 4 and 5). These data provide important ground truth for interpreting ~<2000 km of seismic data sets recently collected from many other lakes in Ontario in the course of the present study, which is primarily related to understanding earthquake risk. A full analysis of such a large geophysical data set and its paleo-environmental significance is in hand and will be reported in due course; our purpose here is to simply report the presence of a consistent seismo-stratigraphy in these lake basins and, in particular, highlight the significance of a sequence boundaries consistent with hypsithermal closed basin conditions and much lowered lake levels.

First, we describe the field methods and computational methodology used in collecting and interpreting seismic data and then outline the paleo-environmental significance of such data for understanding Holocene water level history in the Great Lakes basins.

Study area and methodology

The study area extends from Georgian Bay in the west to Lake Timiskaming along the Ontario/Quebec border in the east, north to the Sudbury area and to Toronto in the south. It includes sixteen lake basins the largest of which are lakes Huron, Nipissing, and Timiskaming (Fig. 1). Most of the basins lie within the former limits of glacial Lake Algonquin and thus have a common late and postglacial history. Seismic data from some of these lakes principally lakes Timiskaming and Kipawa have been presented previously in the context of understanding earthquake risk (Doughty et al., 2010, 2013, in press). The underlying bedrock geology of these lakes consists dominantly of Precambrian crystalline rocks of the Canadian Shield with the single exception of Lake Simcoe which is formed in Paleozoic limestones.

Sub-bottom geophysical data were gathered from lake floors within the study area using an EdgeTech High Resolution X-Star or 3200-XS digital sub-bottom profiler with an SB-216S tow vehicle (referred to as a “fish”; for full details see Doughty et al., 2013). The tow vehicle utilizes a “chirp pulse,” which is an FM pulse that linearly sweeps over a frequency range of 2–12 kHz for 20 ms (Edgetech, 1998). Using a tow cable the “fish” is connected to the onboard system which amplifies and records the incoming signal in either X-Star SEGY (EdgeTech High Resolution X-Star sub-bottom profiler) or JSF format (3200-XS digital sub-bottom profiler) (Edgetech, 1998, 2010). Boat speed is normally ~10 km per h^{-1} and the depth of the “fish” ranges (approximately) between 1 and 3 m. Wave action and any increased output from the boat's motor increases background noise, which is continuously corrected by adjustment of the running depth of the “fish.” Geographic co-ordinates are routinely recorded using an onboard Garmin-GPS (Doughty et al., 2013). The “chirp” seismic method has proven capable of imaging to depths of ~60 m below lake floors depending on sediment type and thickness and allows decimetric-scale resolution of beds within the sediment fill. Bedrock is easily resolved by the presence of gently undulating prominent reflectors typical of glacially scoured basin floors with deeper sub-basins and abrupt bedrock highs that commonly emerge through the sediment fill as islands (e.g., Lazorek et al., 2006; Mullins and Eyles, 1996).

The recorded sub-bottom data are manipulated subsequently using a batch process creating appropriately scaled cross-sectional (sub-bottom) images and plan-view track lines for all lakes. An envelope was calculated for the X-Star SEGY file's signal, reducing noise and improving the image quality (Edgetech, 1998). Resultant files were then converted into standard SEGY format (Barry et al., 1975). The conversion process ensured the higher precision of the X-Star SEGY coordinates, in minutes-of-arc, were preserved. The SEGY files were then split into separate files as determined by the field-assigned line numbers (stored/indicated in the file headers; usually based on the timing of collection). A series of latitude/longitude coordinates were derived, projected to UTM, and interpolated (an imposed correction to remove duplicate GPS coordinates across succeeding traces). Outlying (i.e., invalid) coordinates were then identified and removed from the data by screening for points outside a specified range. For correction purposes, a new coordinate is interpolated between the point previous to the erroneous coordinate and the next valid point; this itself is checked by specifying a maximum search distance so as to not introduce widely spaced points. The corrected coordinates are subsequently reassigned to the original trace within the standard SEGY file. With the coordinates computed, the data can then be manipulated to create both a (spatial) line object (in DXF format allowing direct import into a Geographic Information System) and a cross-sectional (sub-bottom) image. The standard SEGY traces were manipulated in order to be equivalent in depth across all traces (dependent on the number of samples and any imposed signal-record delay). This step reduced the scale with increasing depth, consequently magnifying near-surface seismic facies and features. The standard SEGY file was parsed in order to generate information concerning the coordinate range, trace depth, and track length data and used to generate a file in Seismic Unix format (Cohen and Stockwell, 2012). From the Seismic Unix file, an image file was generated assuming a constant velocity of 1450 m/s and variable vertical exaggeration, which maximizes the size of the image to the output document (Doughty et al., 2013; Eyles and Mullins, 1997). The seismic sub-bottom data collected most recently (2013) in Lake Nipissing were written to a JSF file format during the surveying process (Edgetech, 2010). Similar to the X-Star SEGY files (above), the JSF data files were converted into standard SEGY and underwent similar batch processing to create DXF files of the track lines. However, the cross-sectional images for the JSF files were derived directly using the recently available 3200-XS Discover Sub-Bottom

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