Quaternary Research (2017), **88**, 265–276.

doi:10.1017/qua.2017.40

Cosmogenic ^{10}Be dating of raised shorelines constrains the timing of lake levels in the eastern Lake Agassiz-Ojibway basin

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(Received October 28, 2016; Accepted April 12, 2017)

Abstract

Surface exposure dating was applied to erosional shorelines associated with the Angliers lake level that marks an important stage of Lake Ojibway. The distribution of 15 ^{10}Be ages from five sites shows a main group (10 samples) of coherent ^{10}Be ages yielding a mean age of 9.9 ± 0.7 ka that assigns the development of this lake level to the early part of the Lake Ojibway history. A smaller group (3 samples) is part of a more scattered distribution of older ^{10}Be ages (with 2 outliers) that points to an inheritance of cosmogenic isotopes from a previous exposure, revealing an apparent mean age of 15.8 ± 0.9 ka that is incompatible with the Ojibway inundation and the regional deglaciation. Our results provide the first direct ^{10}Be chronology on the sequence of lake levels in the Ojibway basin, which includes the lake stage presumably associated with the confluence and subsequent drainage of Lakes Agassiz and Ojibway. This study demonstrates the potential of this approach to date glacial lake shorelines and underlies the importance of obtaining additional chronological constraints on the Agassiz-Ojibway shoreline sequence to confidently assign a particular lake stage and/or lake-level drawdown to a specific time interval of the deglaciation.

Keywords: Glacial Lake Ojibway; Lake Agassiz-Ojibway; Meltwater volume; Last deglaciation; Laurentide Ice Sheet; Geochronology; Surface exposure dating

INTRODUCTION

The decay of the Laurentide Ice Sheet (LIS) during the last deglaciation led to large-scale releases of meltwater that accumulated over the isostatically-depressed terrain of the Canadian prairie in the west and the James Bay basin in the east, resulting in the formation of Lake Agassiz and Lake Ojibway, respectively (Fig. 1A; Teller, 1987). These ice-dammed lakes evolved independently until the final stages of deglaciation, when continued ice retreat presumably allowed their coalescence and gave rise to the so-called Lake Agassiz-Ojibway (Elson, 1967; Dyke and Prest, 1987; Leverington et al., 2002; Teller et al., 2002; Dyke, 2004). Interest in the final stages of Lake Agassiz-Ojibway comes from its abrupt drainage into a climatically key region of the North Atlantic Ocean where the sudden and massive injection of meltwater likely slowed the meridional overturning circulation and triggered a major short-lived cold pulse around 8.2 ka (Alley et al., 1997; Grafenstein et al., 1998; Barber et al., 1999; Kleiven et al., 2008). Assessing the impact of this freshwater forcing and the resulting feedbacks in the Earth's climate system requires reliable estimates of the meltwater volumes involved in the drainage, as well as geochronological constraints on this lake discharge. However, geomorphological (shoreline) records constraining the changes in areal extent and depth of Lake Agassiz and Lake Ojibway during their late stages – including their northward expansion and subsequent confluence – are relatively rare and remain inadequately documented. The timing (and number) of the inferred lake stages is also still largely unconstrained due to the physiographic setting of these basins that does not favour the use of radiocarbon (^{14}C) dating or other geochronological methods (e.g., Thorleifson, 1996; Dyke, 2004).

The history of these glacial lakes is documented from complex sequences of raised shorelines and associated geomorphic features that record fluctuations in lake levels, which occurred in association with changes in basin configuration

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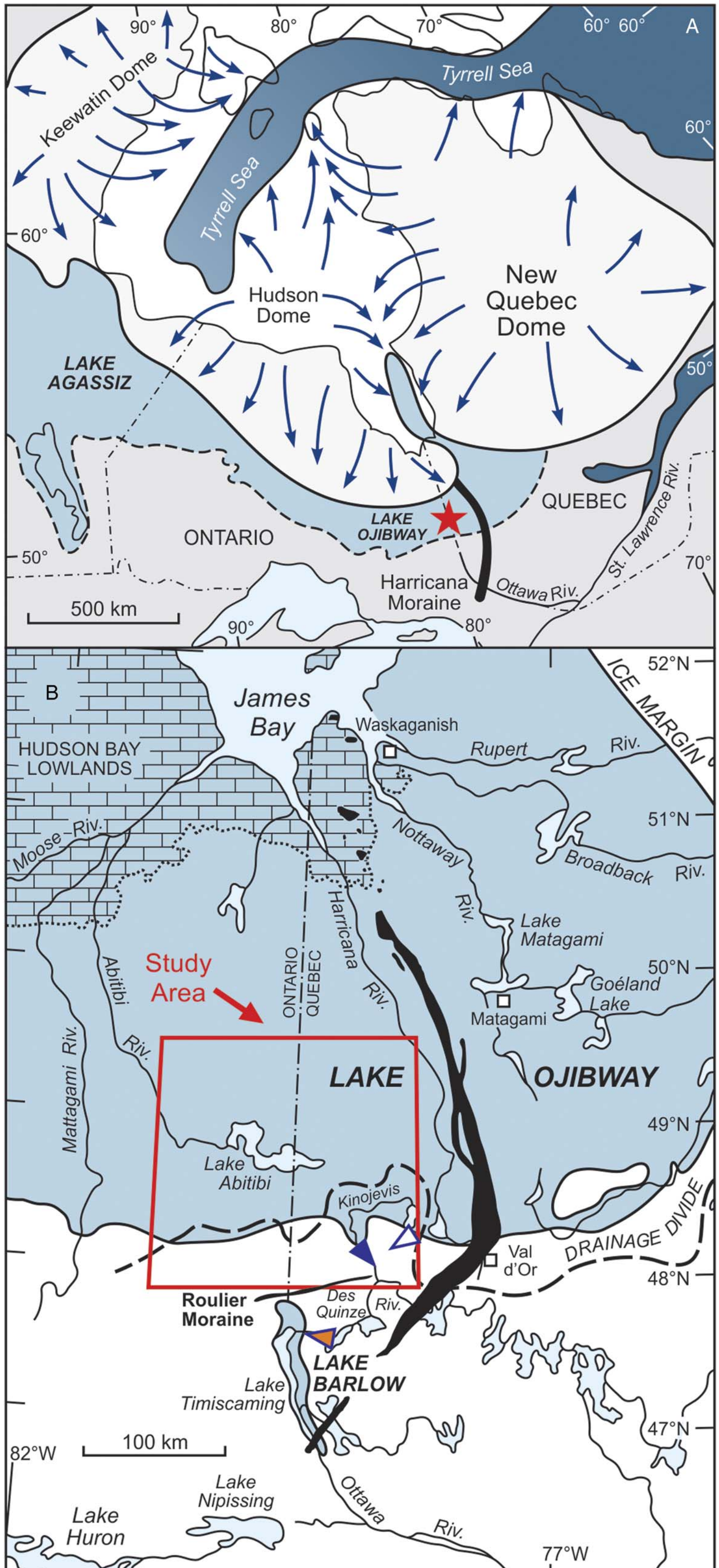

Figure 1. (A) Schematic extent of Lake Agassiz and Lake Ojibway in the context of the Laurentide Ice Sheet at ~8.5 cal yr BP (Dyke et al., 2003; Dyke, 2004); location of the study area (red star). (B) Study area and main physiographic features of the Ojibway basin in Ontario and Quebec. Note that the red box covers the area shown in Fig. 3. Triangles show the location of the outlet system related to the main stages of Lake Ojibway (orange, Angliers; blue, early Kinojévis; white, late Kinojévis; after Vincent and Hardy, 1979). (For interpretations of the references to color in this figure legend, the reader is referred to the web version of this article.)

https://doi.org/10.1017/qua.2017.40 Published online by Cambridge University Press

that were largely controlled by the position and dynamics of the retreating ice margin (Upham, 1895; Johnston, 1946; Elson, 1967; Vincent and Hardy, 1979; Teller and Thorleifson, 1983; Smith and Fisher, 1993; Breckenridge, 2015; Veillette, 1994; Thorleifson, 1996; Teller and Leverington, 2004; Lewis et al., 2005; Fisher et al., 2009). Reconstructions of Lake Agassiz regroup the different lake levels reported into five main phases, the last of which comprises the coalescence and drainage of Lake Agassiz and Lake Ojibway (e.g., Thorleifson, 1996; Teller and Leverington, 2004). This last phase (named Ojibway), however, involves correlation of lake levels that are separated by several hundreds of kilometres and that are based on shoreline records that are, for the most part, still inadequately constrained due to their sporadic occurrence and scattered distribution across remote and forested northern regions.

Our current comprehension of the final stages of Lakes Agassiz and Ojibway comes from the eastern (Ojibway) basin (Fig. 1B), where raised shorelines were used to define three lake stages (Fig. 2; Hughes, 1955; Vincent and Hardy, 1979; Veillette, 1983; 1988; 1994). The Angliers lake stage represents the highest and best-defined lake level documented (Veillette, 1994), while the lower elevation early and late Kinojévis lake stages were defined by a lesser number of shorelines (Vincent and Hardy, 1979), which introduces substantial uncertainties on the configuration (elevation, extent) of the associated water planes and regional isobases. Nevertheless, in the absence of a better-defined lake-level record, reconstructions have associated the lowest lake level – the late Kinojévis lake stage – with the time interval preceding the final drainage of the coalesced Lake Agassiz-Ojibway (c.f., at ~8.2 ka) (e.g., Leverington et al., 2002; Teller et al., 2002; Teller and Leverington, 2004). However, the recent recognition of well-defined shorelines standing below the late Kinojévis lake level raises new questions about the timing of lake-level changes in the Ojibway basin (Roy et al., 2015). The newly documented lake levels indicate the occurrence of additional (late) stages that point to a lake configuration characterized by a lower surface-elevation and restricted areal extent, which, in turn, has important implications for the reconstructions of the volumes of meltwater discharges of the late deglacial interval. Overall, these different lake-level reconstructions emphasize the importance of having reliable geochronological constraints on the sequence of shorelines in order to properly place the associated lake levels and their attendant meltwater volumes into the chronological framework of the last deglaciation.

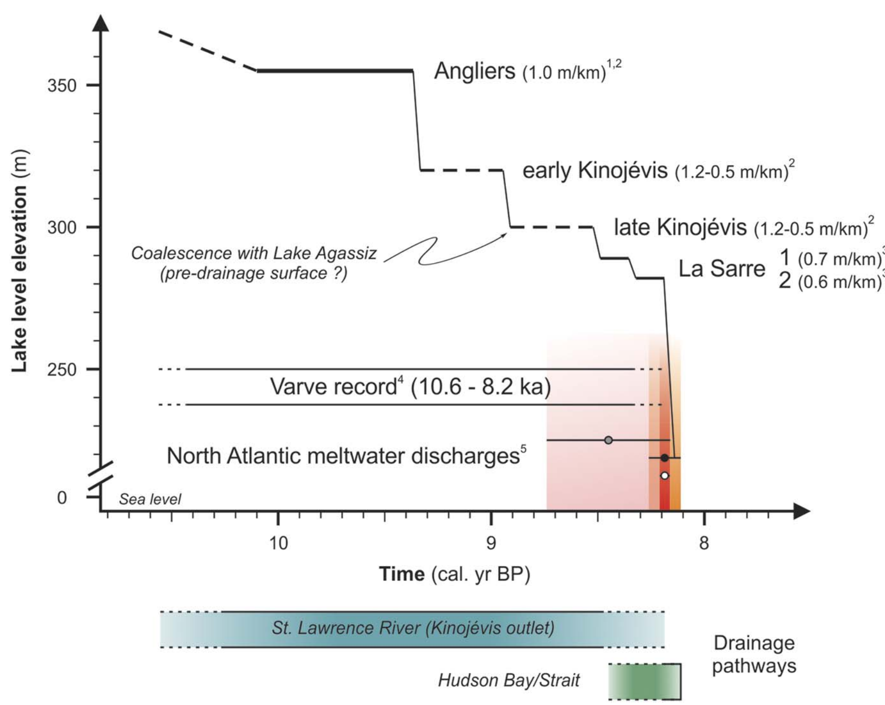

Figure 2. Schematic representation of the main lake levels reported in the Lake Ojibway basin, with the corresponding uplift gradients (data sources: 1-Veillette, 1994; 2-Vincent and Hardy, 1979; 3-Roy et al., 2011). Full and dotted horizontal lines represent well- and poorly-defined lake levels, respectively. The timing and duration of each lake level is unknown; elevations are approximate and based on a crude projection of these lake levels in the southern Lake Abitibi region. Time span for the lake comes from a varve chronology (4-Antevs, 1955; Breckenridge et al., 2012), while its termination is given by the chronology of meltwater discharges associated with the final lake drainage (5-Jennings et al., 2015). Shaded areas correspond to calibrated ages reported for the lake drainage (with 1-sigma error bars); pink is from marine sediment cores (Barber et al., 1999); orange is from continental sediment sequences (Roy et al., 2011). Red bar corresponds to the 8.2 ka event documented in the Greenland ice-core records (Rasmussen et al., 2006). The lower rectangles show proposed drainage pathways for meltwater overflow/discharges for the lake. (For interpretations of the references to color in this figure legend, the reader is referred to the web version of this article.)

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Here we apply ^{10}Be surface exposure dating to erosional shorelines associated with the Angliers lake stage in the Ojibway basin in order to evaluate whether this method can be used to date former lake levels and gain insights on the timing of the main stages of Lake Ojibway during the late deglaciation. The novel approach developed here has the potential to bring new (and direct) geochronological constraints on the complex sequences of raised shorelines forming glacial lake reconstructions and their attendant estimates of meltwater volumes, a set of constraints that is critically needed to assess the role of meltwater discharges in the late deglacial climate interval.

HISTORY OF LAKE OJIBWAY STAGES

Lake Ojibway developed due to the accumulation of meltwater between the height of land formed by the Hudson Bay-St. Lawrence River drainage divide to the south and the ice margin to the north (Coleman, 1909); progressive retreat caused the lake to expand and form a large meltwater reservoir (Fig. 1A; Leverington et al., 2002; Dyke, 2004). Lake Ojibway was initially connected for a brief interval with glacial Lake Barlow, which had previously invaded the upper Ottawa River valley to the south of the divide (Vincent and Hardy, 1979; Veillette, 1994). Temporal reconstructions of the Ojibway submergence, and the attendant positions of the retreating ice-margin, are mainly based on minimum-limiting ^{14}C ages obtained from the first organic matter accumulated in small lakes present on high ground that rose above the former lake limit. Such sites are relatively scattered and not abundant, in addition to being located for the most part at the periphery (south) of the basin (Veillette, 1988; Richard et al., 1989). Sedimentary archives relating directly to Lake Ojibway are largely deprived of organic matter suitable for ^{14}C dating, and if present, the material is often prone to contamination by old carbon sources (Veillette, 1988; Stroup et al., 2013; Daubois et al., 2014). The time span of Lake Ojibway is currently constrained by a varve chronology (Antevs, 1925; Hughes, 1965; Hardy, 1976; Breckenridge et al., 2012) and ^{14}C ages from continental sediment sequences and marine and lake sediment cores (Veillette, 1988; Lewis and Anderson, 1989; Richard et al., 1989; Barber et al., 1999; Ellison et al., 2006; Hillaire-Marcel et al., 2007; Kleiven et al., 2008). Together, these studies indicate that the glaciolacustrine episode lasted for about 2100 years (varve record), being bracketed between 10,570 and 8200–8150 cal yr BP, where the timing of the lake termination may vary depending on the chronology used for the meltwater outburst(s) associated with the final drainage of Lake Agassiz-Ojibway into Hudson Bay (Fig. 2) (e.g., Jennings et al., 2015).

For most of Lake Ojibway's existence, including its confluence with Lake Agassiz, meltwater overflow was controlled by a single outlet system located in the southern Ojibway basin (Fig. 1B). The elevation and position of a rocky sill forming this outlet varied through time due to the on-going glacial isostatic adjustment of the land, and complex changes in outlet configuration apparently played a strong role in the development of lake levels in the Ojibway basin (Vincent and Hardy, 1979). The Ojibway lake-level history has long been articulated around three lake stages that are attributed to periods of maximum submergence (Fig. 2; Vincent and Hardy, 1979; Veillette, 1994). The Angliers stage, presumably the oldest, was controlled by an outlet standing at 260 m near the Des Quinze River, while the early and late Kinojévis stages are associated with the Kinojévis River outlet standing at 275 m and 300 m, respectively (Fig. 1B). The Kinojévis stages, however, are based on the correlation of relatively few shorelines that are spread across a large area and were primarily defined to outline the trend of shoreline development within the basin (Vincent and Hardy, 1979, p.14).

In spite of these uncertainties, regional isobases originally defined in the southern Lake Agassiz basin were subsequently modified and tentatively expanded at the scale of the entire Agassiz-Ojibway basin in paleogeographic reconstructions (Thorleifson, 1996). This approach led to the correlation of the Ponton lake level in the west with the late Kinojévis lake level in the east (Vincent and Hardy, 1979), thereby giving rise to the confluence of Lake Agassiz and Lake Ojibway (Thorleifson, 1996). This connection, although probable, is not supported by firm geomorphological data, but rather inferred by paleoecological data (Stewart and Lindsey, 1983), an early varve chronology (Satterly, 1937; Elson, 1967), and by ice margin histories that are broadly constrained for the time interval involved (c.f., Dyke, 2004). Nevertheless, extensive mapping in the Ojibway basin outlined several geological considerations and predictable relationships arguing for the existence of a stable water plane before the demise of the ice dam in Hudson Bay, which implied a pre-drainage lake surface controlled by an outlet standing at an elevation of ~300 m (Veillette, 1994), thus comparable to the one ascribed to the late Kinojévis stage in an earlier lake-level reconstruction (Vincent and Hardy, 1979).

However, the recent documentation in the lowest parts of the Ojibway basin of post-late Kinojévis shorelines (Roy et al., 2015) provides evidence for significant changes in the configuration of the lake before its final drainage. These late-stage shorelines form two closely related lake levels projecting below the elevation of the main (Kinojévis) outlet (Fig. 2). These lake levels may be equivalent to similar low-elevation shorelines in the Agassiz basin (the Fidler beaches) that also lie below the Kinojévis outlet (Dredge, 1983; Klassen, 1983). The Fidler lake level is poorly understood and has been interpreted as evidence for a two-step drainage of Lake Agassiz-Ojibway involving separate (but closely spaced) discharges from the eastern (Ojibway) and western (Agassiz) basins (Thorleifson, 1996; Leverington et al., 2002; Teller et al., 2002). An alternative interpretation associates the low-elevation strandlines with subglacial drainage(s) across the ice dam in Hudson Bay (Klassen, 1983; Shoemaker, 1992), a mechanism that is now supported by glaciological modeling (Clarke et al., 2004) and geological data (Roy et al., 2011). Regardless of their origin, the presence of the newly defined (low-elevation) shorelines in the Ojibway basin implies substantial changes in the areal extent and depth of the lake across the entire Agassiz-Ojibway basin near the end of the deglaciation, with water planes potentially lying up to 10 to 17 m below the late Kinojévis lake level. Unlike previous models articulated around a single drawdown from a fairly elevated lake surface, these results argue for multi-step lake drainage involving lower lake levels (and thus smaller meltwater volumes). Although these results point to a complex history that is more compatible with marine records showing several outbursts of meltwater during the late deglacial interval (e.g., Jennings et al., 2015), the lack of geochronological constraints on the shoreline sequence defining these lake levels prevent the assignment of the associated lake stages with specific intervals of the late deglaciation.

GEOMORPHIC SETTING OF OJIBWAY SHORELINES

Reconstruction of Ojibway lake stages is complicated by the physiography of this basin, which forms a large clay plain averaging 310–320 m in elevation (e.g., Roy et al., 2015). This terrain is broken in places by topographic rises that lie, for the most part, below the maximum reported lake level (i.e., 460 m near Goéland Lake, ~250 km northeast from the study area) (Fig. 1B; Veillette, 1994), thus leaving very few bedrock-core hills to record the development of high- and intermediate-elevation lake levels. For this reason, Ojibway lake stages were identified using the elevation of dispersed shorelines throughout the basin, in addition to ice-front reconstructions providing insights on the northern limit of the lake (e.g., Veillette, 1994).

All shorelines targeted in this study come from the Angliers lake level (Figs. 2, 3A), which was primarily documented from distinct erosional shorelines that are

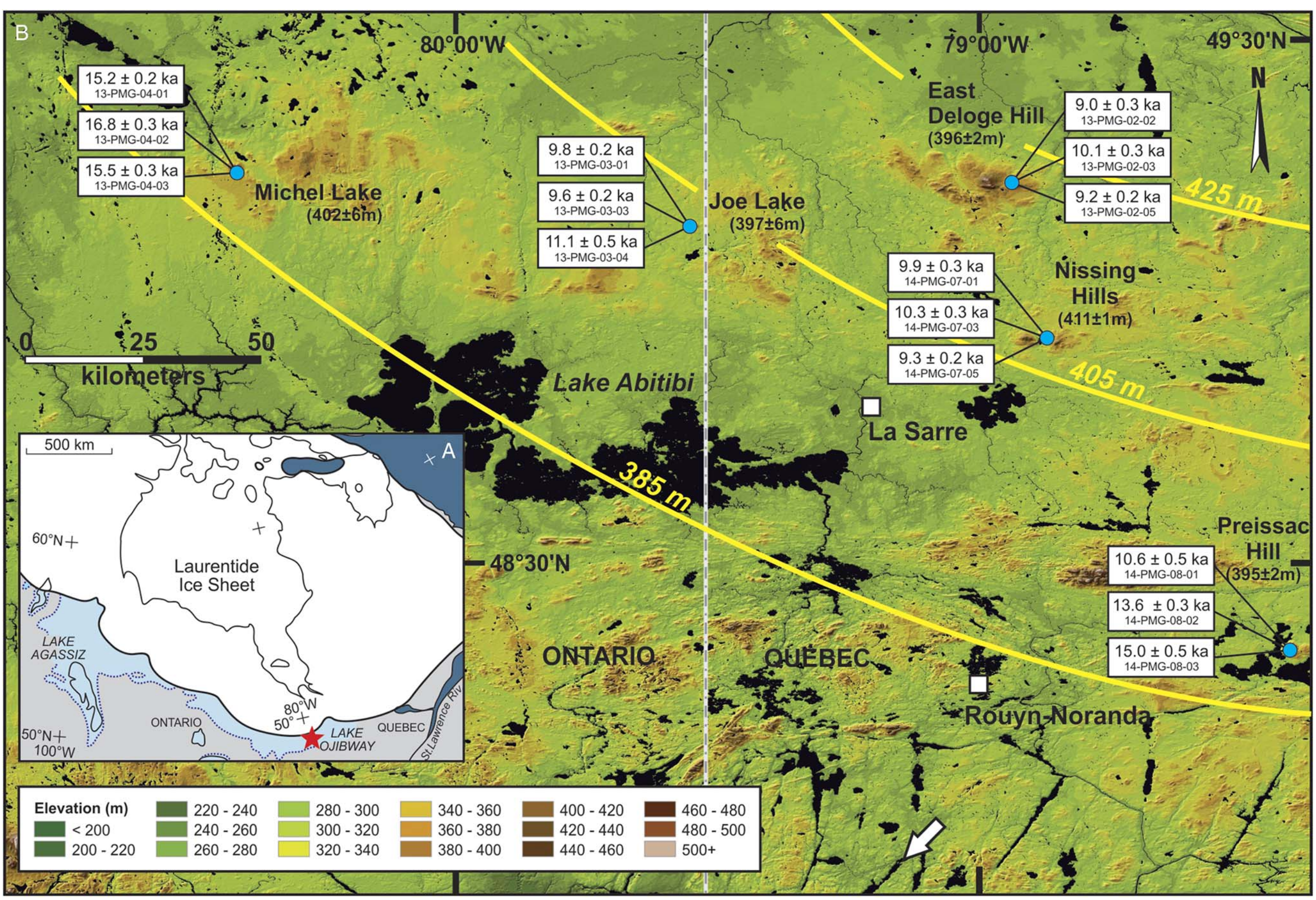

Figure 3. (A) Location of the study area (red star) with respect to Lakes Agassiz and Ojibway and the Laurentide Ice Sheet margin at ~9.5 cal ka BP (Dyke et al., 2003; Dyke, 2004). (B) Digital elevation model showing the physiography of the study area. The low-lying areas (green colors) correspond to the flat-lying Ojibway clay plain, which is broken in places by hills (brown colors) where raised erosional shorelines of the Angliers lake level developed. Yellow lines show the isobases associated with the inclined water plane formed by the Angliers lake level (Veillette, 1994). White boxes show ^{10}Be ages and sample numbers (see Fig. 5, Table 1, and Supplementary Table 1 for details). The high-rise terrains to the south of Lake Abitibi mark the continental drainage divide that encompasses the Kinojévis River outlet system. The outlet at the time of the Angliers lake stage was located ~40 km to the south of the river identified by the white arrow (see Fig. 1 for location). (For interpretations of the references to color in this figure legend, the reader is referred to the web version of this article.)

commonly present on bedrock knobs (hills) standing above the clay plain (Fig. 3B; Veillette, 1994). During the lake inundation, these hills stood out as isolated islands where the littoral (wave) erosion caused the removal of the glacial sediment cover from the hill flanks, leaving narrow and sub-horizontal rims of bare bedrock that mark the former stable lake surface (Fig. 4, Supplementary Fig. 1). Extensive photogrammetric measurements of these so-called washing limits yielded a statistically significant large set of elevation data points that outlined a slightly tilted water plane, thereby constraining broad regional isobases (Veillette, 1994). This setting allows the sampling of this lake level with a high degree of confidence, while the bedrock forming these erosional shorelines is ideally suited for the application of ^{10}Be surface exposure dating.

METHODS

We applied cosmogenic ^{10}Be dating to raised erosional shorelines belonging to the Angliers lake stage. The premise behind our approach is that, once the sediment has been removed by lakeshore erosion and the lake surface has dropped in response to a partial or complete drawdown, the newly uncovered (wave-washed) bedrock surface becomes exposed to cosmic rays, starting the cosmogenic ^{10}Be accumulation clock. As shown in Figure 4A, boulder beaches may be present in places in the basin, but these are primarily composed of small rounded boulders (25–40 cm in diameter) forming unstable surfaces, thereby precluding their use for ^{10}Be surface exposure dating. The erosional shorelines were sampled at 5 sites along the 405 m isobase to ensure the dating of the same (Angliers) lake surface. This particular isobase has the advantage to intersect several prominent hills within a reasonably restricted area (Fig. 3B). The sites were chosen by means of aerial photographs and satellite imagery (Google Earth and ArcGIS 10.3) to favor settings characterized by sparse vegetation and a good exposure to the elements (wind). These sites were underlain by granitic or tonalitic lithologies rich in quartz, with slightly inclined and largely unweathered bedrock surfaces (Supplementary Fig. 2–6). Most rock surfaces exhibited a well-preserved glacial polish, with striations and grooves still present, thereby indicating negligible erosion of the bedrock surfaces by the lakeshore processes. Lakeshore erosion was apparently limited to the removal of the sediment cover and did not affect the underlying bedrock.

Specifically, three samples of surface rock averaging 500 g were collected at each site; the samples being separated by 10 to 15 m from each other along a given contour line (i.e., within the same elevation range). The samples were processed following standard procedures developed at the Lamont-Doherty Earth Observatory Cosmogenic Dating Laboratory (c.f., Schaefer et al., 2009) and ^{10}Be/^{9}Be ratios were determined at Lawrence Livermore National

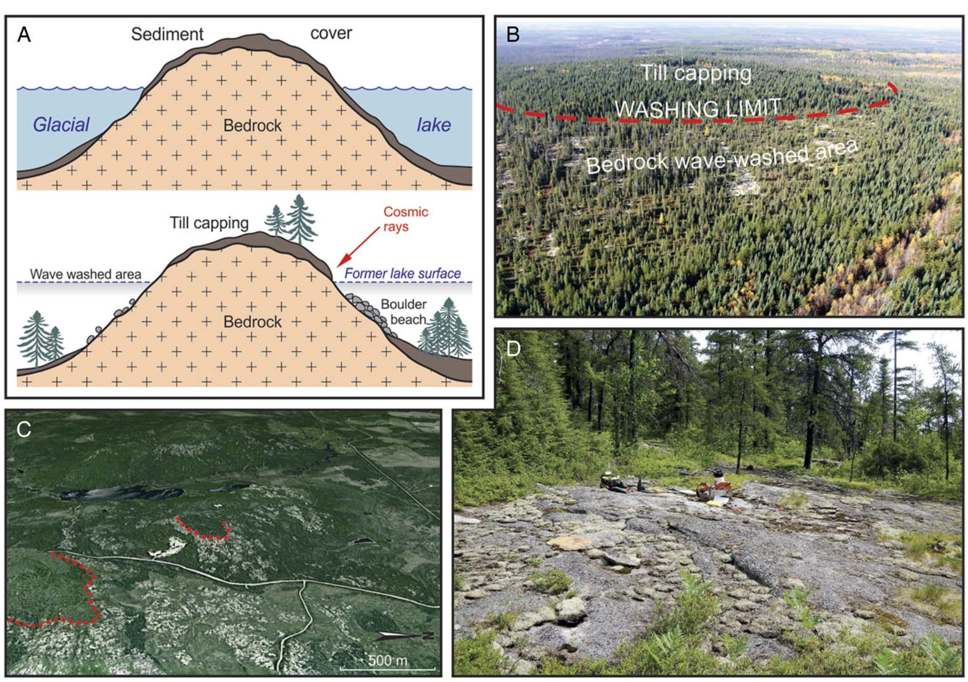

Figure 4. (color online) (A) Schematic model showing the development of lakeshore erosional shorelines known as washing limits (see text for details). (B) Photograph of Michel Lake site showing an oblique aerial view of wave-washed bedrock rim (treeless areas with whitish colors) formed by the lakeshore erosion. Note the presence of a capping of untouched sediments that marks the upper limit reached by the wave erosion. (C) Google Earth satellite image of the washing limit exposed at the Nissing Hills site. (D) Example of a bedrock surface sampled for ^{10}Be surface exposure dating (Nissing Hills; rock saw width is 75 cm). Pictures of the three other sites sampled are showed in Supplementary Figure 1.

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Laboratory (California, USA). Ages were calculated with version 2.2 of the CRONUS Earth online calculator, using the Baffin Bay/Arctic ^{10}Be production rate given in Young et al. (2013), which is similar in value to the North America production rate of Balco et al. (2009), and altitude and latitude scaling according to Lal (1991) and Stone (2000), referred to as "Lm" scaling (Balco et al., 2008). ^{10}Be ages for individual sample are given within 1-sigma analytical errors (Supplementary Table 1). The exposure ages for the raised shorelines were calculated using the arithmetic mean of the individual samples from this landform. The error of the exposure age for this landform includes the standard deviation of this arithmetic mean and the error of the production rate given by Young et al. (2013).

RESULTS

The ^{10}Be ages show analytical uncertainties of typically 2–3% (only two samples yielded a >4% 1-sigma error) (Table 1). Total ^{10}Be blank corrections were below 5000 atoms, boron corrections were below 0.5%, thus the total background corrections for the samples (300,000 – 1,500,000 atoms ^{10}Be total) were smaller than 2%. With the exception of one site (Preissac Hill), the ^{10}Be concentrations of the samples dated within each washing limit (i.e., at each site) show a remarkable internal consistency (Supplementary Table 1). When plotted together, the 15 samples dated show a distribution of ^{10}Be ages falling into two groups (Fig. 5A). The first group is formed by samples from three sites (Joe Lake, Nissing Hills, and East Deloge Hill; n = 9) showing ages ranging from ~9000 to 10,300 yr, with one sample being slightly older (11,100 ± 500 yr) (Fig. 5B). At each of these three sites, the scatter of ages varies between ~1000 and 1500 yr (Table 1). The second group is represented by one site (Michel Lake; n = 3) where ages range from ~15,200 to 16,800 yr (Fig. 5C), for an age spread of ~1600 yr (Table 1). Finally, one last site (Preissac Hill; n = 3) shows a distinctively larger age scatter (4300 yr), with ages of 10,600 ± 500 yr, 13,600 ± 300 yr, and 15,000 ± 500 yr (Fig. 5A, Table 1).

The main group of ages ranging from ~9000 to 11,100 yr is consistent with previous time span estimates presented for Lake Ojibway, which range from ~10,600 and 8,200 cal yr BP according to varve and marine sediment records (e.g., Breckenridge et al., 2012; Jennings et al., 2015). Conversely, the older ages forming the second group, which range between ~15,200 to 16,800 yr, are incompatible with the history of Lake Ojibway and are difficult to reconcile with our current understanding of the regional deglaciation.

The large scatter of ^{10}Be ages documented at Preissac Hill seems to underlie a complication with the application of surface exposure dating at this site. This age scatter may be explained by a slight but measureable inheritance of cosmogenic isotopes from previous exposure, which has not been entirely removed by the subsequent glacial erosion of the bedrock surfaces dated. Within this context, the youngest ^{10}Be age at Preissac Hill could possibly provide a minimum-limiting age constraint on the timing of the rock surface exposure at this site during the deglaciation, and, in turn, on the formation of the Angliers shoreline. The youngest age of 10,600 ± 500 yr at Preissac Hill is indeed consistent with the 9 other ^{10}Be ages obtained for Group 1 (Fig. 5A). Therefore, we include this sample into the calculation of the mean age for the younger group of ages (9900 ± 700 yr) (Fig. 5D). The remaining two ^{10}Be ages at Preissac Hill are considered too old to relate to the regional deglaciation. Accordingly, these two samples are excluded from the data set and considered as outliers.

The old ^{10}Be ages obtained at Michel Lake are also likely related to an inherited ^{10}Be signal (and insufficient glacial erosion). However, because these three ^{10}Be ages show a relatively good internal consistency, we cannot exclude that the apparent mean age of ~15,800 yr ± 900 yr may record another geomorphological feature reflecting a slightly earlier

Table 1. Samples information and surface exposure ages.

Site name	Sample no.	Rock type	Latitude (DD)	Longitude (DD)	GPS altitude (m)	Lm ± 1σ (yr)	1σ
East Deloge Hill	13-PMG-02-02	Granite	49.22640	−78.93556	399	8978 ± 254	2.8%
East Deloge Hill	13-PMG-02-03	Granite	49.22666	−78.93529	396	10121 ± 256	2.5%
East Deloge Hill	13-PMG-02-05	Granite	49.22658	−78.93519	395	9189 ± 177	1.9%
Joe Lake	13-PMG-03-01	Tonalite	49.14309	−79.55013	404	9829 ± 188	1.9%
Joe Lake	13-PMG-03-03	Tonalite	49.14247	−79.55063	394	9584 ± 191	2.0%
Joe Lake	13-PMG-03-04	Tonalite	49.14232	−79.55115	393	11110 ± 516	4.6%
Nissing Hills	14-PMG-07-01	Monzonite	48.92992	−78.86851	411	9872 ± 256	2.6%
Nissing Hills	14-PMG-07-03	Monzonite	48.93010	−78.86778	412	10335 ± 264	2.6%
Nissing Hills	14-PMG-07-05	Monzonite	48.93062	−78.86706	411	9310 ± 206	2.2%
Michel Lake	13-PMG-04-01	Tonalite	49.24764	−80.41727	406	15184 ± 249	1.6%
Michel Lake	13-PMG-04-02	Tonalite	49.24775	−80.41731	406	16831 ± 276	1.6%
Michel Lake	13-PMG-04-03	Tonalite	49.24748	−80.41560	395	15480 ± 254	1.6%
Preissac Hill	14-PMG-08-01	Monzogranite	48.33950	−78.40414	393	10645 ± 511	4.8%
Preissac Hill	14-PMG-08-02	Monzogranite	48.33940	−78.40424	396	13644 ± 265	1.9%
Preissac Hill	14-PMG-08-03	Monzogranite	48.33941	−78.40442	397	14973 ± 478	3.2%

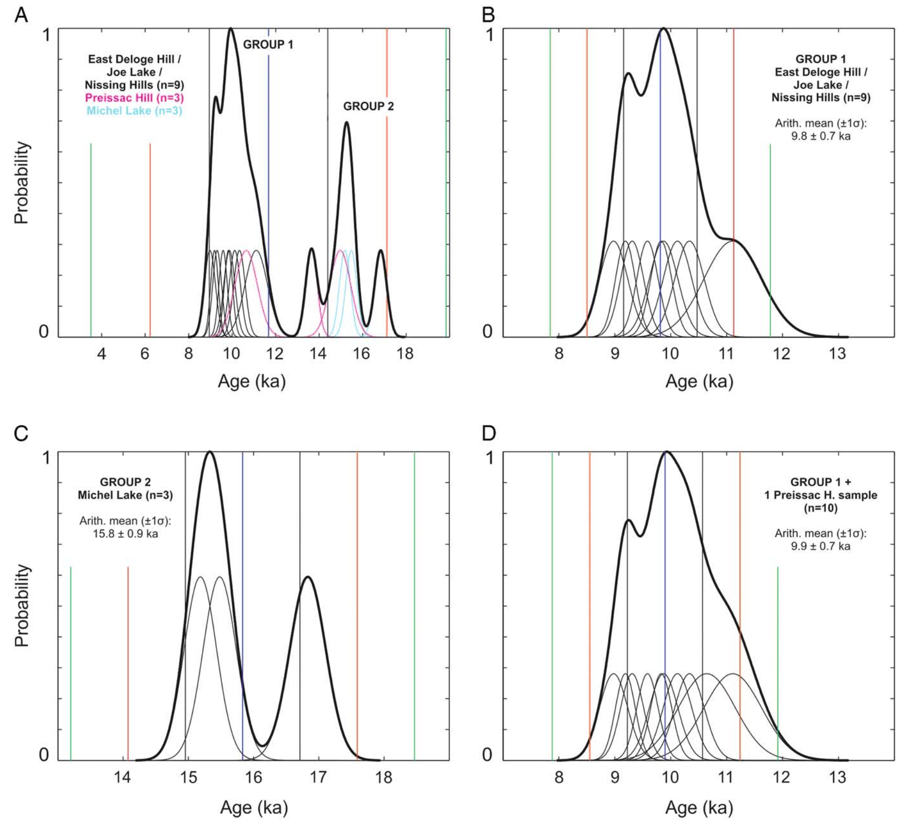

Figure 5. Probability density functions (PDF) plots for ^{10}Be surface exposure ages and associated uncertainties (68%, 1-sigma confidence interval in black; 2-sigma confidence interval in red; and 3-sigma confidence interval in green). The blue vertical line denotes the arithmetic mean value of the age population; thin curves represent individual ages within 1-sigma uncertainties (see Table 1 and Supplementary Table 1 for data). (A) Distributions of all 15 ages obtained from 5 sites in this study. Note that the two oldest ages from Preissac Hill are considered as outliers (see text for details). (B) PDF for the ages forming Group 1 seen in (A). (C) PDF for the older ages forming Group 2. (D) PDF for the population of younger ages composed by the samples forming Group 1 and the younger age obtained at Preissac Hill. We used the arithmetic mean age (blue line) of this PDF as the formation age of the Angliers lake level. Reported errors for these ages are calculated by quadratic propagation of the standard deviation of the respective arithmetic mean and the production rate error given by Young et al. (2013). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

deglaciation process in the region. An alternative interpretation for this second group is discussed below within the framework of the last deglaciation.

DISCUSSION

The 9.9 ka ages and the chronology of lake levels

The well-defined group of ages centered at 9.9 ± 0.7 ka (Fig. 5D) is consistent with the fact that the sampled shorelines belong to the same lake level, as shown by their elevation range (393–412 m) that roughly falls onto the 405 m isobase of this former water plane (Fig. 3B). Previous studies broadly assigned the Angliers lake stage to the onset of the regional deglaciation based on paleogeographic considerations articulated around ^{14}C ages coming from outside the Ojibway basin (Vincent and Hardy, 1979; Veillette, 1994). Current reconstructions place the beginning of ice retreat and the concomitant glaciolacustrine inundation in the study area at ~10.2 cal ka BP (i.e., 9.0 ^{14}C ka in Dyke et al., 2003; Dyke, 2004). The ^{10}Be age thus indicates that the high-elevation Angliers lake level developed during the early stages of the Ojibway invasion, which appears to have occurred rapidly after the withdrawal of the ice margin in the region. Considering the difficulties in identifying the position of the ice margin within the Ojibway basin during the deglaciation and the concomitant lack of chronological constraints on the continent-scale ice-margin histories, these results also yield important data for the deglacial chronology (Dyke, 2004). These ^{10}Be ages provide a minimum-age constraint on ice withdrawal within the basin, which until now has relied on minimum-limiting ^{14}C ages from lake sediment cores that typically document the disappearance of the lake and/or onset of post-glacial sedimentation. These ^{14}C chronologies are also prone to centuries-scale lags with respect to the disappearance of ice (e.g., Ullman et al., 2016).

These ^{10}Be ages bring the first direct constraints on the timing of lake-surface elevation changes in the Ojibway basin. Prior to this study, the overall lack of geochronological data on the three high-elevation lake levels had so far forced glacial lake reconstructions to rely on a chronology based on the above paleogeographic reconstructions, as well as on the assumption that the last (and lowest) lake level that was then defined in the Ojibway basin – the late Kinojévis lake stage – formed the lake surface that preceded the drainage of the coalesced Lake Agassiz-Ojibway, which took place ~8.2 ka (Barber et al., 1999; Roy et al., 2011; Jennings et al., 2015). The mean ^{10}Be age of 9.9 ± 0.7 ka obtained on the Angliers lake level now places an upper age limit on these three closely related Ojibway lake stages. Accordingly, if the assignment of the late Kinojévis lake level to the 8.2 ka time interval of the deglaciation is correct, this would indicate that Lake Ojibway experienced only two lake-level drops over a period of about 1700 yr, which represents about three quarters of the lake's existence. This apparent stable lake configuration seems rather improbable given the overall rapid ice retreat (450 m/yr) of the LIS margin in the region (Veillette, 1994) that likely caused the opening of lower outlets, as well as the occurrence of late-glacial readvances of the ice margin into the lake (Vincent and Hardy, 1979) that may have produced additional lake-level fluctuations during that time interval. More importantly, the recent documentation of well-defined low-elevation shorelines forming water planes projecting below the Kinojévis outlet in the Ojibway basin (Roy et al., 2015) adds to similar findings in the Agassiz basin (Dredge, 1983; Klassen, 1983), which together argue for the existence of significant lake level(s) post-dating the late Kinojévis lake stage. Altogether, this situation could be improved by applying ^{10}Be surface exposure dating to key shoreline sequences, which could potentially refine correlations of lake levels and the chronology of the attendant glacial lake reconstructions.

The 16 ka ages and the regional deglaciation

Current understanding of the deglaciation suggests that the mean age of 15.8 ± 0.9 ka obtained at Michel Lake (Fig. 5C) is too old to be related to Lake Ojibway, whose initial formation is ascribed to ~10,600 cal yr BP by a varve chronology (Antevs, 1925; Breckenridge et al., 2012). Furthermore, paleogeographic reconstructions indicate that the area was still covered by ice at that time, with the southern LIS margin located into the Great Lakes basin (~700 km from the study area) at ~16 cal ka BP (c.f., the 13 ^{14}C ka time slice in Dyke et al., 2003; Dyke, 2004). These data are consistent with the interpretation attributing these older ^{10}Be ages to the inheritance of cosmogenic isotopes from previous exposure due to limited glacial erosion of the bedrock surfaces (washing limits) dated, a phenomenon commonly encountered in glaciated terrains (e.g., Stroeven et al., 2002; Harbor et al., 2006), and evidenced here by the large scatter of ^{10}Be ages at Preissac Hill. As for the intensity of glacial erosion with respect to former ice-flow movements (Veillette et al., 1999; Veillette et al., 2017), our results do not show a clear trend between the occurrence of old ages and the position of a sample site on the bedrock topographic high versus the orientation of the main ice flows. Although Preissac Hill is located in a down-ice (sheltered) position from the dominant ice flows, the sites of Joe Lake and Nissing Hills were sampled in a similar setting and yielded a tight cluster of young ages. Furthermore, the washing limits of Michel Lake and East Deloge sites were both sampled on the up-ice (stoss) side of topographic highs and should thus have been subjected to severe glacial erosion; yet, they revealed contrasting results (Table 1). Consequently, the intensity of glacial erosion seems to be site-specific and is likely dependent on a combination of local macro- and micro-topographical features influencing the degree of abrasion and plucking in the subglacial processes.

An alternative explanation could be related to the fact that the sites sampled are located on the highest topographic rises in the region (Fig. 3B). At about 16 ka (~13 ^{14}C ka), the deglaciation was well underway and the latitudinal retreat of the LIS southern ice margin was apparently accompanied by a significant increase in surface melting (Carlson et al., 2009; Ullman et al., 2015) consistent with marked changes in global ice volumes and sea level across this interval (e.g., Tarasov and Peltier, 2004; Lambeck et al., 2014). If so, significant thinning of this sector of the ice sheet could have caused these hills to emerge (break) at the ice surface as "nunataks," and then be exposed to cosmic rays early in the deglaciation (see model in Fig. 6). Comparable deglaciation processes have been documented in Fennoscandia, Greenland, and Antarctica (Brook et al., 1996; Stone et al., 2003; Rinterknecht et al., 2004; Goehring et al., 2008). Yet, topographic rises in the study area show a relatively small elevation difference (~80–120 m) with respect to the lower clay plain, indicating that the ice cover had to be very thin to allow these moderate hills to break through the ice surface. Such an ice margin configuration appears incompatible with an active ice retreat and the damming of a large lake, and remains largely unsupported by available field evidence, geomorphological data, and existing ice retreat patterns. Furthermore, this thinning mechanism would also require the absence of a sediment cover on the hills dated (or a very thin one) in order to have a significant exposure of the bedrock surface and allow the onset of the ^{10}Be clock. However, the geomorphological setting at the site of Michel Lake shows about the same sediment cover as the other sites dated.

Consequently, based on these arguments, we believe that the ~16 ka ages obtained at Michel Lake are best explained by a slight inherited ^{10}Be signal related to insufficient glacial erosion of the bedrock surfaces dated. This small cluster of older ^{10}Be ages thus calls for further investigations involving additional surface exposure dating of important topographic hills in the region, as the existing set of ^{10}Be ages cannot entirely resolve this issue.

CONCLUSIONS

The application of ^{10}Be surface exposure dating to raised shorelines marking a major stage of Lake Ojibway provides the first direct geochronological constraints on the glaciolacustrine episode and the associated history of lake-level changes in the north-central region of the LIS during the last deglaciation. The ^{10}Be ages indicate that the Angliers lake

https://doi.org/10.1017/qua.2017.40 Published online by Cambridge University Press

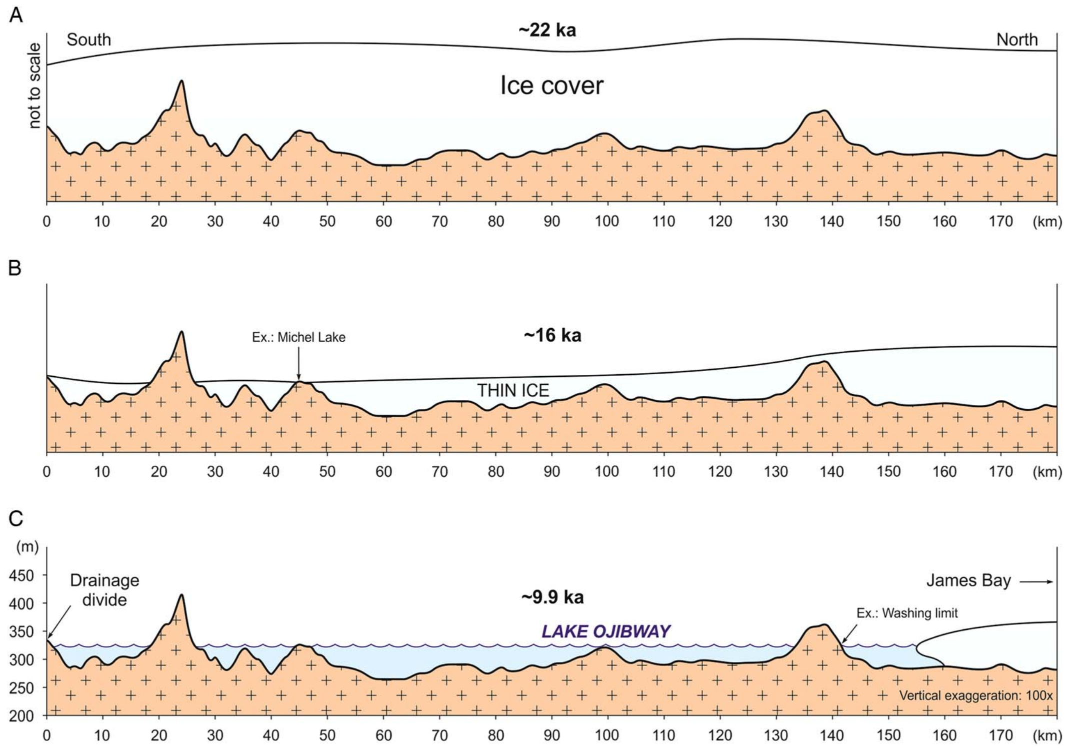

Figure 6. (color online) Schematic model showing the deglacial thinning mechanism considered as an explanation for the small group of ^{10}Be ages centered at ~16 ka. (A) Cross section depicting the ice cover during the full glacial conditions (ice thickness not to scale, unlike the underlying topography). (B) As the deglaciation proceeds, significant ice-mass loss is thought to occur through surface melting, causing the high-elevation terrains to be exposed to subareal conditions and cosmic rays. (C) Submersion by meltwater as the ice margin retreats north of the continental drainage divide. Several geological considerations indicate that this model cannot be retained (see Discussion for details).

level formed at around 9.9 ± 0.7 ka, thus assigning the development of this high-elevation lake stage to the early part of the history of Lake Ojibway. This study also adds new data to deglacial chronologies documenting the recession of the ice margin across the Ojibway basin (c.f., Dyke, 2004), whereby the results provide minimum-limiting ages on the onset of ice withdrawal in this large region, which otherwise is difficult to constrain due to the overall lack of ice-margin features and the scarcity of material for ^{14}C dating.

These results bring important constraints on the timing of lake-surface elevation changes associated with the three high-elevation lake levels in the Ojibway basin, in which the lowest lake level has long been associated with the drainage of Lake Agassiz-Ojibway. The ^{10}Be ages obtained for the uppermost (Angliers) lake level tend to place this sequence to the early segments of the lake history and, combined with evidence for low-elevation lake levels in both Agassiz and Ojibway basins (Klassen, 1983; Roy et al., 2015), argue for a lake configuration involving a substantially less extensive and lower lake surface than the one presented in previous reconstructions for the late stages of the deglaciation. Accordingly, these results motivate further investigations focussing on the ^{10}Be dating of key shoreline sequences that will facilitate correlations of lake levels and improve the overall chronology of the final stages of these glacial lakes.

This study demonstrates that ^{10}Be surface exposure dating of raised shorelines represents an important step towards improving temporal reconstructions of glacial lakes. The approach outlined here could potentially be applied to other important ice-dammed lakes that formed and drained during the LIS deglaciation. Obtaining new chronological constraints on shorelines associated with particular lake stages and/or lake-level drawdowns could lead to more robust estimates of meltwater volumes for specific time intervals of the last deglaciation, thereby refining fundamental input data for ocean models that assess the impact of freshwater discharges on the North Atlantic thermohaline circulation and Earth's climate (e.g., Bauer et al., 2004; Renssen et al., 2007; Böning et al., 2016).

ACKNOWLEDGMENTS

This research was supported by a NSERC grant to MR and a FRQNT PhD fellowship to PMG. JMS and MR acknowledge support by the LDEO Climate Center. I. Randour contributed to fieldwork and M. Laithier provided assistance in the production of figures. Constructive comments and suggestions from journal Senior Editor N. Lancaster, Associate Editor T. Lowell and two anonymous reviewers were greatly appreciated and contributed to improve the manuscript.

SUPPLEMENTARY MATERIAL

To view supplementary material for this article, please visit https://doi.org/10.1017/qua.2017.40

REFERENCES

Alley, R.B., Mayewski, P.A., Sowers, T., Stuiver, M., Taylor, K.C., Clark, P.U., 1997. Holocene climatic instability: A prominent, widespread event 8200 yr ago. *Geology* 25, 483–486.

Antevs, E., 1925. Retreat of the last ice-sheet in eastern Canada. *Geological Survey of Canada Memoir* 146, 142.

Balco, G., Briner, J., Finkel, R.C., Rayburn, J.A., Ridge, J.C., Schaefer, J.M., 2009. Regional beryllium-10 production rate calibration for late-glacial northeastern North America. *Quaternary Geochronology* 4, 93–107.

Balco, G., Stone, J.O., Lifton, N.A., Dunai, T.J., 2008. A complete and easily accessible means of calculating surface exposure ages or erosion rates from 10 Be and 26 Al measurements. *Quaternary Geochronology* 3, 174–195.

Barber, D.C., Dyke, A., Hillaire-Marcel, C., Jennings, A.E., Andrews, J.T., Kerwin, M.W., Bilodeau, G., *et al*. 1999. Forcing of the cold event of 8,200 years ago by catastrophic drainage of Laurentide lakes. *Nature* 400, 344–348.

Bauer, E., Ganopolski, A., Montoya, M., 2004. Simulation of the cold climate event 8200 years ago by meltwater outburst from Lake Agassiz. *Paleoceanography* 19, PA3014. http://dx.doi.org/10.1029/2004PA001030.

Böning, C.W., Behrens, E., Biastoch, A., Getzlaff, K., Bamber, J.L., 2016. Emerging impact of Greenland meltwater on deepwater formation in the North Atlantic Ocean. *Nature Geoscience* 9, 523–528.

Breckenridge, A., 2012. The Tintah-Campbell gap and implications for glacial Lake Agassiz drainage during the Younger Dryas cold interval. *Quaternary Science Reviews* 117, 124–134.

Breckenridge, A., Lowell, T.V., Stroup, J.S., Evans, G., 2012. A review and analysis of varve thickness records from glacial Lake Ojibway (Ontario and Quebec, Canada). *Quaternary International* 260, 43–54.

Brook, E.J., Nesje, A., Lehman, S.J., Raisbeck, G.M., Yiou, F., 1996. Cosmogenic nuclide exposure ages along a vertical transect in western Norway: implications for the height of the Fennoscandian ice sheet. *Geology* 24, 207–210.

Carlson, A.E., Anslow, F.S., Obbink, E.A., LeGrande, A.N., Ullman, D.J., Licciardi, J.M., 2009. Surface-melt driven Laurentide Ice Sheet retreat during the early Holocene. *Geophysical Research Letters* 36, L24502. http://dx.doi.org/10.1029/2009GL040948.

Clarke, G.K.C., Leverington, D.W., Teller, J.T., Dyke, A.S., 2004. Paleohydraulics of the last outburst flood from glacial Lake Agassiz and the 8200BP cold event. *Quaternary Science Reviews* 23, 389–407.

Coleman, A.P., 1909. Lake Ojibway: Last of the great glacial lakes. *Ontario Bureau of Mines Annual Report* 18, 284–293.

Daubois, V., Roy, M., Veillette, J.J., Ménard, M., 2014. The drainage of Lake Ojibway in glaciolacustrine sediments of northern Ontario and Quebec, Canada. *Boreas* 44, 305–318.

Dredge, L.A., 1983. Character and Development of Northern Lake Agassiz and Its Relation to Keewatin and Hudsonian Ice Regimes. In: Teller, J.T., Clayton, L. (Eds.), *Glacial Lake Agassiz*. Geological Association of Canada, Special Paper 26, 117–131.

Dyke, A.S., 2004. An outline of North American Deglaciation with emphasis on central and northern Canada. In Ehlers, J., Gibbard, P.L. (Eds.), *Quaternary Glaciations – Extent and Chronology, Part II: North America*. Elsevier B.V, New York, pp. 371–406.

Dyke, A.S., Moore, A., Robertson, L., 2003. Deglaciation of North America. *Geological Survey of Canada Open File* 1574.

Dyke, A.S., Prest, V.K., 1987. Late Wisconsinan and Holocene History of the Laurentide Ice Sheet. *Géographie physique et Quaternaire* 41, 237–263.

Ellison, C.R., Chapman, M.R., Hall, I.R., 2006. Surface and deep ocean interactions during the cold climate event 8200 years ago. *Science* 312, 1929–1932.

Elson, J.A., 1967. Geology of Glacial Lake Agassiz. In Mayer-Oakes, W.J. (Ed.), *Life, Land and Water*. University of Manitoba Press, Winnipeg, Manitoba, Canada, pp. 36–95.

Fisher, T.G., Waterson, N., Lowell, T.V., Hajdas, I., 2009. Deglaciation ages and meltwater routing in the Fort McMurray region, northeastern Alberta and northwestern Saskatchewan, Canada. *Quaternary Science Reviews* 28, 1608–1624.

Goehring, B.M., Brook, E.J., Linge, H., Raisbeck, G.M., Yiou, F., 2008. Beryllium-10 exposure ages of erratic boulders in southern Norway and implications for the history of the Fennoscandian Ice Sheet. *Quaternary Science Reviews* 27, 320–336.

Grafenstein, U.V., Erlenkeuser, H., Müller, J., Jouzel, J., Johnsen, S., 1998. The cold event 8200 years ago documented in oxygen isotope records of precipitation in Europe and Greenland. *Climate Dynamics* 14, 73–81.

Harbor, J., Stroeven, A.P., Fabel, D., Clarhäll, A., Kleman, J., Li, Y., Elmore, D., Fink, D., 2006. Cosmogenic nuclide evidence for minimal erosion across two subglacial sliding boundaries of the late glacial Fennoscandian ice sheet. *Geomorphology* 75, 90–99.

Hardy, L., 1976. Contribution à l'étude géomorphologiques de la portion québécoise des Basses Terres de la Baie de James. PhD dissertation, Mcgill University, Montréal, Québec, Canada.

Hillaire-Marcel, C., de Vernal, A., Piper, D.J.W., 2007. Lake Agassiz Final drainage event in the northwest North Atlantic. *Geophysical Research Letters* 34, L15601. http://dx.doi.org/10.1029/2007GL030396.

Hughes, O.L., 1955. Surficial geology of Smooth Rock and Iroquois Falls maps-areas, Cochrane District, Ontario. PhD dissertation, University of Kansas, Lawrence.

Hughes, O.L., 1965. Surficial geology of part of the Cochrane District, Ontario, Canada. In: Wright, H.E., Jr., Frey, D. G. (Eds.), *International Studies on the Quaternary: Papers Prepared on the Occasion of the 7th Congress of the International Association for Quarternary Research Boulder, Colorado*. Geological Society of America, Special Papers 84, 535–565.

Jennings, A., Andrews, J., Pearce, C., Wilson, L., Ólfasdótttir, S., 2015. Detrital carbonate peaks on the Labrador shelf, a 13–7ka template for freshwater forcing from the Hudson Strait outlet of the Laurentide Ice Sheet into the subpolar gyre. *Quaternary Science Reviews* 107, 62–80.

Johnston, W.A., 1946. Glacial Lake Agassiz with special reference to the mode of deformation of the beaches. *Geological Survey of Canada Bulletin* 7, 20.

Klassen, R.W., 1983. Glacial Lake Agassiz. In: Teller, J.T., Clayton, L. (Eds.), *Glacial Lake Agassiz*. Geological Association of Canada Special Paper 26, pp. 97–115.

Kleiven, H.K., Kissel, C., Laj, C., Ninnemann, U.S., Richter, T.O., Cortijo, E., 2008. Reduced North Atlantic deep water coeval with the glacial Lake Agassiz freshwater outburst. *Science* 319, 60–64.

Lal, D., 1991. Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion models. *Earth and Planetary Science Letters* 104, 424–439.

Lambeck, K., Rouby, H., Purcell, A., Sun, Y., Sambridge, M., 2014. Sea level and global ice volumes from the Last Glacial Maximum to the Holocene. *Proceedings of the National Academy of Sciences* 111, 15296–15303.

Leverington, D.W., Mann, J.D., Teller, J.T., 2002. Changes in the Bathymetry and Volume of Glacial Lake Agassiz between 9200 and 7700 14C yr B.P. *Quaternary Research* 57, 244–252.

Lewis, C.F.M, Anderson, T.W., 1989. Oscillations of levels and cool phases of the Laurentian Great Lakes caused by inflows from glacial Lakes Agassiz and Barlow-Ojibway. *Journal of Paleolimnology* 2, 99–146.

Lewis, C.F.M, Blasco, S.M., Gareau, P.L., 2005. Glacial isostatic adjustment of the Laurentian Great Lakes basin: using the empirical record of strandline deformation for reconstruction of early Holocene paleo-lakes and discovery of a hydrologically closed phase. *Géographie physique et Quaternaire* 59, 187–210.

Rasmussen, S.O., Andersen, K.K., Svensson, A., Steffensen, J.P., Vinther, B.M., Clausen, H.B., Siggaard-Andersen, M.L., Johnsen, S.J., Larsen, L.B., Dahl-Jensen, D., 2006. A new Greenland ice core chronology for the last glacial termination. *Journal of Geophysical Research* 111, D06102. http://dx.doi.org/10.1029/2005JD006079.

Renssen, H., Goosse, H., Fichefet, T., 2007. Simulation of Holocene cooling events in a coupled climate model. *Quaternary Science Reviews* 26, 2019–2029.

Richard, P.J., Veillette, J.J., Larouche, A.C., 1989. Palynostratigraphie et chronologie du retrait glaciaire au Témiscamingue: évaluation des âges 14C et implications paléoenvironnementales. *Canadian Journal of Earth Sciences* 26, 627–641.

Rinterknecht, V., Clark, P., Raisbeck, G., Yiou, F., Brook, E., Tschudi, S., Lunkka, J., 2004. Cosmogenic ^{10}Be dating of the Salpausselkä I Moraine in southwestern Finland. *Quaternary Science Reviews* 23, 2283–2289.

Roy, M., Dell'Oste, F., Veillette, J.J., de Vernal, A., Hélie, J.F., Parent, M., 2011. Insights on the events surrounding the final drainage of Lake Ojibway based on James Bay stratigraphic sequences. *Quaternary Science Reviews* 30, 682–692.

Roy, M., Veillette, J.J., Daubois, V., Ménard, M., 2015. Late-stage phases of glacial Lake Ojibway in the central Abitibi region, eastern Canada. *Geomorphology* 248, 14–23.

Satterly, J., 1937. Glacial Lakes Ponask and Sachigo District of Kenora (Patricia Portion), Ontario. *The Journal of Geology* 45, 790–796.

Schaefer, J.M., Denton, G.H., Kaplan, M., Putnam, A., Finkel, R.C., Barrell, D.J., Andersen, B.G., *et al*., 2009. High-frequency Holocene glacier fluctuations in New Zealand differ from the northern signature. *Science* 324, 622–625.

Shoemaker, E.M., 1992. Water sheet outburst floods from the Laurentide Ice Sheet. *Canadian Journal of Earth Sciences* 29, 1250–1264.

Smith, D.G., Fisher, T.G., 1993. Glacial Lake Agassiz: The northwestern outlet and paleoflood. *Geology* 21, 9–12.

Stewart, K.W., Lindsey, C.C., 1983. Postglacial dispersal of lower vertebrates in the Lake Agassiz region. In: Teller, J.T., Clayton, L. (Eds.), *Glacial Lake Agassiz*. Geological Association of Canada Special Paper 26, pp. 391–419.

Stone, J.O., 2000. Air pressure and cosmogenic isotope production. *Journal of Geophysical Research: Solid Earth* 105, 23753–23759.

Stone, J.O., Balco, G.A., Sugden, D.E., Caffee, M.W., Sass, L.C. III, Cowdery, S.G., Siddoway, C., 2003. Holocene deglaciation of Marie Byrd Land, West Antarctica. *Science* 299, 99–102.

Stroeven, A.P., Fabel, D., Harbor, J., Hättestrand, C., Kleman, J., 2002. Quantifying the erosional impact of the Fennoscandian ice sheet in the Torneträsk–Narvik corridor, northern Sweden, based on cosmogenic radionuclide data. *Geografiska Annaler: Series A, Physical Geography* 84, 275–287.

Stroup, J.S., Lowell, T.V., Breckenridge, A., 2013. A model for the demise of large, glacial Lake Ojibway, Ontario and Quebec. *Journal of Paleolimnology* 50, 105–121.

Tarasov, L., Peltier, W.R., 2004. A geophysically constrained large ensemble analysis of the deglacial history of the North American ice-sheet complex. *Quaternary Science Reviews* 23, 359–388.

Teller, J.T., 1987. Proglacial lakes and the southern margin of the Laurentide Ice Sheet. In Ruddiman, W. F., Wright, H.E., Jr. (Eds.), *North America and adjacent oceans during the last deglaciation*. Geological Survey of America, The Geology of North America K-3, Boulder, Colorado, pp. 39–69.

Teller, J.T., Leverington, D.W., 2004. Glacial Lake Agassiz: A 5000 yr history of change and its relationship to the δ18O record of Greenland. *Geological Society of America Bulletin* 116, 729–742.

Teller, J.T., Leverington, D.W., Mann, J.D., 2002. Freshwater outbursts to the oceans from glacial Lake Agassiz and their role in climate change during the last deglaciation. *Quaternary Science Reviews* 21, 879–887.

Teller, J.T., Thorleifson, L.H., 1983. The Lake Agassiz-Lake Superior connection. In Teller, J.T., Clayton, L. (Eds.), *Glacial Lake Agassiz*. Geological Association of Canada Special Paper 26, 261–290.

Thorleifson, L.H., 1996. Review of Lake Agassiz history. In Teller, J. T., Thorleifson, L. H., Matile, G., Brisbin, W. C. (Eds.), *Sedimentology, Geomorpholoy and History of the Central Lake Agazzis Basin: Field Trip B2*. Geological Association of Canada, Winnipeg, pp. 55–84.

Ullman, D.J., Carlson, A.E., Anslow, F.S., LeGrande, A.N., Licciardi, J.M., 2015. Laurentide ice-sheet instability during the last deglaciation. *Nature Geoscience* 8, 534–537.

Ullman, D.J., Carlson, A.E., Hostetler, S.W., Clark, P.U., Cuzzone, J., Milne, G.A., Winsor, K., Caffee, M., 2016. Final Laurentide ice-sheet deglaciation and Holocene climate-sea level change. *Quaternary Science Reviews* 152, 49–59.

Upham, W., 1895. *The Glacial Lake Agassiz*. United States Geological Survey, Monograph 25.United States Government Printing Office, Washington DC.

Veillette, J.J., 1983. Déglaciation de la vallée supérieure de l'Outaouais, le lac Barlow et le sud du lac Ojibway, Québec. *Géographie physique et Quaternaire* 37, 67–84.

Veillette, J.J., 1988. Déglaciation et évolution des lacs proglaciaires post-Algonquin et Barlow au Témiscamingue, Québec et Ontario. *Géographie physique et Quaternaire* 42, 7–31.

Veillette, J.J., 1994. Evolution and paleohydrology of glacial lakes Barlow and Ojibway. *Quaternary Science Reviews* 13, 945–971.

Veillette, J.J., Dyke, A.S., Roy, M., 1999. Ice-flow evolution of the Labrador Sector of the Laurentide Ice Sheet: a review, with new evidence from northern Quebec. *Quaternary Science Reviews* 18, 993–1019.

Veillette, J.J., Roy, M., Paulen, R.C., Ménard, M., St-Jacques, G., 2017. Uncovering the hidden part of a large ice stream of the Laurentide Ice Sheet, northern Ontario, Canada. *Quaternary Science Reviews* 155, 136–158.

Vincent, J.S., Hardy, L., 1979. The evolution of glacial lakes Barlow and Ojibway, Quebec and Ontario. *Geological Survey of Canada Bulletin* 316, 18.

Young, N.E., Schaefer, J.M., Briner, J.P., Goehring, B.M., 2013. A ^{10}Be production-rate calibration for the Arctic. *Journal of Quaternary Science* 28, 515–526.