

Isotopic evolution of Glacial Lake Agassiz: New insights from cellulose and porewater isotopic archives

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Abstract

Significantly differing estimates of the oxygen-isotope composition of Lake Agassiz have been obtained from two co-existing isotopic archives within a sediment core originating from Montcalm, Manitoba, in the southern basin of the ancient proglacial lake. Oxygen-isotope analysis of cellulose extracted from the sediments, which originated during the Lockhart phase ~11,700–11,000 ¹⁴C yr BP, suggests that phytoplankton lived in surface waters having $\delta^{18}\text{O}$ around $-18 \pm 1\%$ VSMOW, substantially enriched relative to connate porewaters in the same core, which indicate bottom waters had much lower values of around $-24.5 \pm 0.5\%$ VSMOW. This difference may be attributable to seasonal isotopic stratification of the upper part of the water column in the 250 m-deep lake. Modern observations from analogous environments in northern Canada suggest that inflow of evaporatively enriched runoff from the large area of deglaciated terrain contributing to Lake Agassiz, possibly enhanced by evaporation from the surface of the lake itself, could readily account for sufficient seasonal ¹⁸O enrichment in the epilimnion. Sediment porewaters, in contrast, have preserved the isotopic signature of hypolimnion waters supplied by a mixture of glacial meltwater and precipitation-derived runoff from the Laurentide Ice Sheet, and lack discernable isotopic alteration by evaporation. These new estimates are combined with inferred lake water compositions from other isotopic archives to develop a speculative framework for the isotopic evolution of the lake, providing improved constraints on the probable isotopic composition of Lake Agassiz outflow over time, which has important implications for efforts to trace and model its changing discharge.

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1. Introduction

Lake Agassiz occupied large areas of the central Northern Great Plains during Wisconsinan deglaciation, reaching a maximum area of about 260,000 km² and a volume of about 22,700 km³ (Leverington et al., 2000).

The size and extent of Lake Agassiz varied considerably with fluctuations in the margin of the Laurentide Ice Sheet (LIS), both gradually, in response to changes in the ice sheet's size and configuration, and rapidly, as a consequence of the opening and closing of topographically controlled drainage outlets. The lake covered more than 100,000 km² for over 4000 years, and the presence and eventual drainage of this huge body of water are thought to have fundamentally influenced dynamics of the LIS (Clayton et al., 1985), regional

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climate (Hu et al., 1997; Hostetler et al., 2000;) and ocean-climate systems (Broecker et al., 1989; Barber et al., 1999).

Lake Agassiz began to form as water ponded against the LIS upon recession north of the Hudson Bay–Mississippi River divide, $\sim 11,700$ ^{14}C yr BP (Elson, 1967; Bluemle, 1974; Clayton, 1983). Glacial meltwater and contemporary precipitation initially overflowed southwards via the ancestral Mississippi River system into the Gulf of Mexico during the Lockhart phase ($\sim 11,700$ – $11,000$ ^{14}C yr BP), followed by drainage eastwards as ice retreat opened a lower outlet through the Great Lakes and on to the Atlantic during the Moorhead phase ($\sim 11,000$ – $10,100$ ^{14}C yr BP) (Teller and Thorleifson, 1983). The subsequent Marquette readvance brought about the high-level Emerson phase ($\sim 10,100$ – 9400 ^{14}C yr BP), activating an outlet to the northwest through the Mackenzie Valley to the Arctic Ocean. Eastward drainage was initiated during the Nipigon phase (~ 9400 – 8200 ^{14}C yr BP), as lower outlets opened through the Lake Nipigon basin in northwestern Ontario (Elson, 1967; Teller and Thorleifson, 1983). Lake Agassiz eventually coalesced with glacial Lake Ojibway, finally draining upon failure of the glacial ice dam in Hudson Bay at about 7700 ^{14}C yr BP (Barber et al., 1999; Clarke et al., 2004). This generally accepted chronology has recently been challenged with the emergence of new evidence suggesting that Lake Agassiz drained to the northwest to the Arctic Ocean during the Moorhead phase (Tarasov and Peltier, 2005; Teller et al., 2005).

1.1. Isotopic composition of Lake Agassiz

Knowledge or inference about the isotopic composition of Lake Agassiz during various phases of its history has been obtained from only a few sources. These include direct determination of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ of porewaters in low-permeability Lake Agassiz sediments sampled at several sites in the central main southern basin, believed to represent isotopically-unaltered connate waters (Remenda et al., 1994) and estimation from $\delta^{18}\text{O}$ of ostracodes and cellulose preserved in Lake Agassiz sediments underlying present-day lakes Manitoba and Winnipeg (Last et al., 1994; Buhay and Betcher, 1998; Rodrigues and Lewis, 2000; Moore et al., 2000).

The isotopically depleted, low-salinity signature of Lake Agassiz water has also been a useful tool for tracing meltwater pulses through various drainage networks (Broecker et al., 1989; Flower and Kennett, 1990; Lewis et al., 1994; Rea et al., 1994a; Dettman

et al., 1995; Aharon, 2003). Alterations of thermohaline ocean circulation patterns due to the discharge of large volumes of fresh water to the North Atlantic have been proposed as a mechanism for initiating some of the most rapid and abrupt climate changes in the late Pleistocene and Holocene (Rooth, 1982; Broecker et al., 1989; Barber et al., 1999; Clark et al., 1999). The development of a stabilizing layer of low-salinity water due to the influx of meltwater over portions of the North Atlantic may have suppressed thermohaline circulation and prevented the formation of North Atlantic Deep Water. Improved documentation of the timing and magnitude of outflow from the melting LIS via Lake Agassiz to the different ocean sources has thus emerged as a key requirement for testing the hypothesis that sensitivity of ocean circulation to freshwater inputs can trigger climate change (Broecker et al., 1989; Barber et al., 1999).

Estimates for the timing and routing of eastward drainage of Lake Agassiz to the Atlantic Ocean have been developed using records of changing lake levels and inferred lake water isotopic compositions for the Great Lakes. The initial expectation was that drainage of large volumes of meltwater from Lake Agassiz through the Great Lakes would be preserved as a low- $\delta^{18}\text{O}$ signature corresponding to periods of high lake levels. However, comparison of indicators of lake level and the isotopic composition of the water have revealed that highstands were characterized by relatively high inferred lake water $\delta^{18}\text{O}$ whereas the lowest isotopic values were found when lake levels in the Great Lakes were at their lowest (Lewis et al., 1994; Rea et al., 1994a; Dettman et al., 1995; Moore et al., 2000). Lewis et al. (1994) proposed that the association of high lake levels in the Great Lakes with more positive lake water $\delta^{18}\text{O}$ values could be explained if overflow from Lake Agassiz consisted primarily of evaporatively enriched surface waters. A local source of isotopically depleted meltwater was invoked to explain the very negative $\delta^{18}\text{O}$ signals associated with lowstands (Lewis et al., 1994; Rea et al., 1994a).

Here we report intriguing new data from co-existing porewater and cellulose archives from Lake Agassiz sediments obtained near Montcalm, Manitoba, in an area that was deeply submerged by the southern arm of the paleolake (see Fig. 1). In addition to providing new estimates for the oxygen-isotope composition of the lake, the contemporaneous cellulose and porewater isotopic archives have allowed us to test the hypothesis that this important late-glacial water body was stratified isotopically. These data shed fresh light on the paleolimnology of early Lake Agassiz, as well as

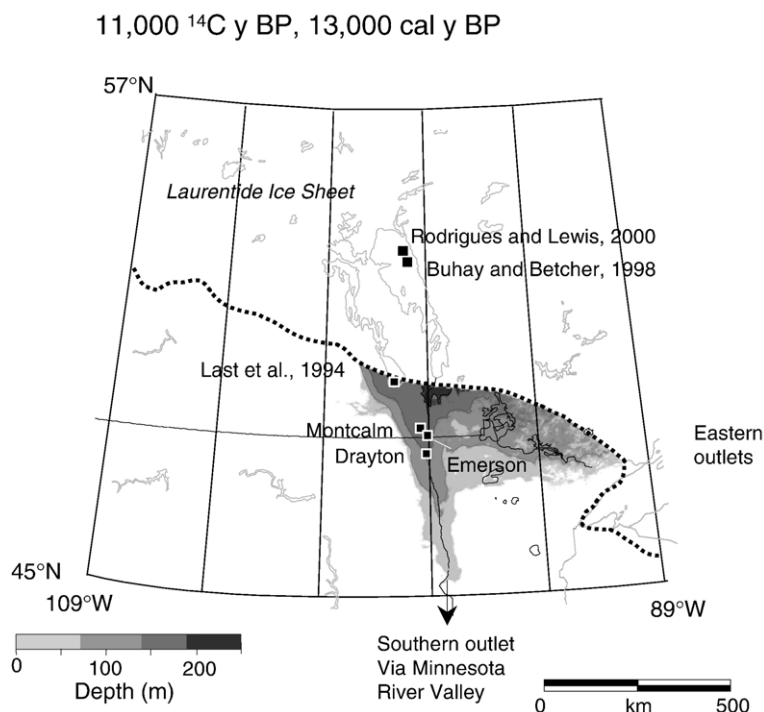


Fig. 1. Lake Agassiz paleobathymetry (Leverington et al., 2000) modelled for 11,000 ^{14}C yr BP, at the end of the Lockhart Phase, immediately prior to the opening of the eastern outlets, or alternatively, opening of a northwestern outlet (Teller et al., 2005). Modern surface water features and the location of the various Lake Agassiz archives: porewater and cellulose from Montcalm (this study), porewater from Drayton and Emerson from (Remenda et al., 1994), ostracode data from beneath southern Lake Manitoba (Last et al., 1994), cellulose and porewater archives from Buhay and Betcher (1998), and ostracode archive from Rodrigues and Lewis (2000) are also included. Archives in the latter two publications are from beneath northern Lake Winnipeg. During the Lockhart Phase, drainage was to the south, and major tributaries to Lake Agassiz included the Old Assiniboine, and Sheyenne Rivers from the west. The thin line of latitude between Emerson and Drayton is 49° N, the international boundary between Canada (north) and the United States (south).

helping to flesh out the framework for its subsequent isotopic history.

2. Field setting

About 38 m of fine-grained Lake Agassiz sediments is present at the Montcalm site, overlying 30 m of silty till of Wisconsinan age, which lies in turn upon Jurassic dolomitic siltstone bedrock (Fig. 2). Prior investigations at the nearby Emerson and Drayton sites have established that the sediment sequence spans the Lockhart, Moorhead and Emerson phases of Lake Agassiz (Remenda et al., 1994), with the majority of the sediment deposited during the two deep-water phases. Unit 1, a fine grained, highly plastic grey clay with occasional silt clasts was deposited during the late Lockhart phase ($\sim 11,700$ – $11,000$ ^{14}C yr BP) in a water depth of about 150 m (Leverington et al., 2000). During the early Moorhead phase ($\sim 10,700$ – $10,200$ ^{14}C yr BP) Lake Agassiz is thought to have retreated north of the international border and was likely less

than 50 m deep in the vicinity of Montcalm (Teller, 1976; Fenton et al., 1983; Leverington et al., 2000). There was no evidence of subaerial exposure in the cores we collected or in stratigraphic logs collected during previous investigations (Remenda et al., 1994), suggesting continuous deposition of Lake Agassiz sediments at Montcalm. In the south-central portion of the basin Unit 2 is often either absent or indistinguishable from Unit 1 (Last, 1974; Teller, 1976). As a result of the Marquette readvance (and/or isostatic rebound of a northwestern outlet), lake levels began to rise again $\sim 10,000$ ^{14}C yr BP, resulting in the high-water Emerson phase and the deposition of Unit 3 (Sherrick formation in North Dakota; Teller, 1976). Distinct increases in clay and moisture contents at ~ 20 m depth in the core mark the transition from Units 1 and 2 to Unit 3, deposited in the much deeper waters of the Emerson phase.

The average annual water table at Montcalm lies about 3–4 m below ground surface, within the 5-m thick weathered zone. Porewaters in the weathered

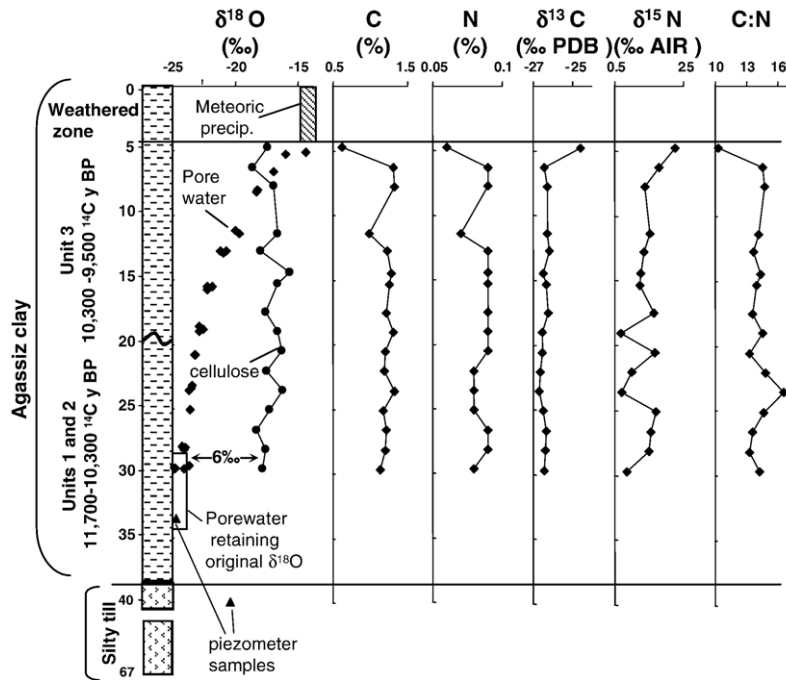


Fig. 2. Stratigraphy and measured $\delta^{18}\text{O}$ of porewater (diamonds) and inferred $\delta^{18}\text{O}_{\text{lake water}}$ (circles) from the cellulose data. Data from piezometer samples located approximately 100 m from the core location are also included (triangles), showing the depth where the most depleted Lake Agassiz porewater sample was obtained at this site (33 m) and the more enriched isotopic composition of the underlying till unit.

zone are isotopically and chemically well-mixed, in marked contrast to those in the underlying Lake Agassiz sediments, which are characterized by highly systematic variations in the distribution of both water isotopes and conservative ions. As shown by Remenda et al. (1994) using samples from monitoring wells, concave-downward profiles for porewater $\delta^{18}\text{O}$ and $\delta^2\text{H}$ in the unweathered clay are consistent with diffusion-controlled mixing of relatively ^{18}O - and ^2H -rich postglacial precipitation with isotopically depleted connate porewaters over the past 9000 years. Average hydraulic conductivities, hydraulic gradients and porosities measured in the lab and field were used to calculate average linear groundwater velocities of 9–13 m per 10,000 years (Remenda et al., 1994).

Lake Agassiz sediments are characterized by their very low organic content, with very low abundances of ostracodes (Curry, 1997), pollen (Namburdiri and Shay, 1986), or siliceous microfossils (Risberg et al., 1999). Analysis of Lake Agassiz sediments below Lake Winnipeg revealed that algal fossil remains consisted mainly of zooplankton fecal pellets (Kling, 1998), suggesting that aquatic cellulose should be recoverable as has been reported by Buhay and Betcher (1998).

3. Methods

Follow-up investigations at Montcalm were undertaken with the aim of using $\delta^{18}\text{O}$ and $\delta^2\text{H}$ of porewater and $\delta^{18}\text{O}$ of algal cellulose extracted from the same sediment sequence to provide independent constraints on the isotopic composition of the waters of early Lake Agassiz. A series of 16 undisturbed sediment increments (each 0.74 m in length) was obtained from a single borehole. Increments were taken every 1.5 m between the base of the weathered zone and 32 m depth, sealed and immediately transported to refrigerated storage at the University of Waterloo.

The use of porewater as an archive of the isotopic composition of lake water in glaciolacustrine sediments requires determining whether the hydrogeological setting (i.e., aquitard thickness, and hydraulic conductivities and gradients) would result in preservation of the original water present during the time of deposition of the unit (Desaulniers et al., 1981; Remenda et al., 1994). Previous work at this site (Remenda et al., 1994) demonstrated that porewaters at the base of Unit 1 of the Montcalm sequence should still retain their original isotopic signature, thus providing a direct measure of the isotopic composition of the waters of Lake Agassiz during the Lockhart phase.

Algal cellulose recovered from sediments can also provide an excellent archive of the oxygen-isotope composition of lake water, analogous to that afforded by lacustrine carbonates (see Edwards, 1993; Wolfe et al., 2001a). Numerous studies have shown that the $\delta^{18}\text{O}$ of cellulose in aquatic and terrestrial plants is controlled by the $\delta^{18}\text{O}$ of associated plant waters (=lake water for aquatic plants and algae) via kinetically-controlled fractionation in the range 1.025–1.029. A fixed value of 1.028 has yielded notably consistent results in mid- and high-latitude settings (e.g., see Edwards and McAndrews, 1989; MacDonald et al., 1993; Edwards et al., 1996; Wolfe and Edwards, 1997; Wolfe et al., 1996, 2000; Sauer et al., 2001; Wolfe et al., 2003; Edwards et al., 2004), including Lake Agassiz (Buhay and Betcher, 1998) and Lake Ontario (Weatherly, 1993; Edwards et al., 1994; Duthie et al., 1996), as well as in lakes of the Bolivian Andes (Wolfe et al., 2001b; Abbott et al., 2003). With the exception of enigmatic variability reported by Sauer et al. (2001) for one species of aquatic moss grown in culture, abundant experimental and empirical evidence supports the existence of a similar constant cellulose-water oxygen-isotope offset in all aquatic and terrestrial plants (DeNiro and Epstein, 1979; Sternberg and DeNiro, 1983; Sternberg et al., 1984, 1986; Yakir and DeNiro, 1990; Yakir, 1992; Sternberg et al., 2003), and even in the cellulose produced by marine tunicates (DeNiro and Epstein, 1981).

An important consideration in the use of sediment cellulose as a lake water $\delta^{18}\text{O}$ archive is the possible presence of cellulose of terrestrial origin, which is likely to have elevated $\delta^{18}\text{O}$ values derived from isotopic enrichment of plant leaf waters during evapotranspiration, as cautioned in the first application of the technique by Edwards and McAndrews (1989). Sauer et al. (2001), for example, provided convincing evidence of terrestrial admixture in the sediment cellulose of several highly unproductive arctic lakes on Baffin Island, although they concluded that this likely constitutes a rare situation, which is supported by the remarkably few data points feasibly attributable to this mechanism reported from the many other studies in more productive systems, including low- and sub-arctic lakes elsewhere in the boreal circumpolar region (e.g., MacDonald et al., 1993; Edwards et al., 1996; Wolfe et al., 2003; and others cited above). As discussed below, carbon and nitrogen elemental and isotopic characterization of the acid-washed bulk sediment from which cellulose originated was used to assess the possibility of terrestrial contamination in our samples.

Porewater was extracted from selected core intervals using hydraulic squeezers (Patterson et al., 1978) and from monitoring wells by peristaltic pump. The $^{18}\text{O}/^{16}\text{O}$ and $^2\text{H}/^1\text{H}$ ratios of the water were determined in the University of Waterloo Environmental Isotope Laboratory using standard procedures (respectively, equilibration with CO_2 after the method of Epstein and Mayeda (1953) and reduction over hot Zn, after Coleman et al. (1982). Results are reported here in conventional δ notation relative to Vienna Standard Mean Ocean Water (VSMOW) calibrated so that $\delta^{18}\text{O}_{\text{SLAP}} = -55.5\text{‰}$ and $\delta^2\text{H}_{\text{SLAP}} = -428\text{‰}$ as recommended by Coplen (1996). Delta (δ) values are determined by $\delta = [(R_{\text{sample}}/R_{\text{SMOW}}) - 1]/1000$, where R is the $^{18}\text{O}/^{16}\text{O}$ or $^2\text{H}/^1\text{H}$ ratio in the sample and standard. Analytical uncertainties for $\delta^{18}\text{O}$ and $\delta^2\text{H}$ in water are $\pm 0.2\text{‰}$ and 2‰ , respectively.

Sediment samples adjacent to each of the squeezed sections were processed to isolate the cellulose fraction using the method outlined by Wolfe et al. (2001a). After being treated with 10% HCl to remove carbonate material, carbon and nitrogen elemental and isotopic compositions of the residue were determined on a continuous flow isotope ratio mass spectrometer equipped with an elemental analyzer (EA-CF-IRMS). Cellulose for oxygen-isotope analysis was further concentrated using solvent extraction, bleaching and alkaline hydrolysis to remove non-cellulose organic constituents (Edwards et al., 1997). Finally, a sodium polytungstate density separation was performed to remove detrital material from the cellulose. The freeze-dried cellulose residue was analysed by high-temperature EA-CF-IRMS (Wolfe et al., 2001a,b). Stable carbon, nitrogen and oxygen-isotope compositions are expressed as $\delta^{13}\text{C}$, $\delta^{15}\text{N}$ and $\delta^{18}\text{O}$ values relative to the international VPDB, AIR, and VSMOW standards, respectively. Analytical uncertainties are $\pm 0.2\text{‰}$ for $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ and $\pm 0.5\text{‰}$ for cellulose $\delta^{18}\text{O}$. Cellulose $\delta^{18}\text{O}$ values are also expressed as equivalent water $\delta^{18}\text{O}$, assuming a water-cellulose fractionation of 1.028, as noted above.

4. Results

The $\delta^{18}\text{O}$ of porewater in the unfractured zone (5–30 m) increases from very negative at depth (-24.4‰) to a value similar to local recharge (-14.0‰) near the surface. As revealed in Fig. 2, variations in the isotopic composition of porewaters in the Lake Agassiz sequence at Montcalm exactly mirror the concave-downward profiles reported by Remenda et al. (1994) on the basis of their five monitoring-well samples. Both profiles clearly confirm the existence of the highly

depleted “end-member” connate porewaters in the lower part of the Lake Agassiz clay, having $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values, respectively, of -24.4‰ and -189‰ , lying within analytical uncertainty of the Global Meteoric Water Line, as well as a modern local meteoric water line for southern Manitoba (Gimli, $\delta^2\text{H}=7.8\ \delta^{18}\text{O}+6.2$; see Fritz et al., 1987). As reasoned by Remenda et al. (1994), the isotopically depleted end-member within the lower part of the Lake Agassiz sequence (Unit 1 deposited during the Lockhart phase, Fig. 2) almost certainly preserves the isotopic composition of the paleolake. The gradual increase in $\delta^{18}\text{O}$ from this minimum to values similar to modern recharge reflects progressive overprinting of the isotopic signal due to diffusion of isotopically enriched water from the weathered zone.

The cellulose-inferred lake water $\delta^{18}\text{O}$ lacks obvious systematic trends and varies between -18.8 and -15.8‰ for the period covered by the Montcalm sediment sequence (Lockhart, Moorhead and Emerson phases). As expected, elemental C and N are positively correlated because of varying dilution by inorganic detritus, while weak inverse correlation is apparent between the C:N and $\delta^{15}\text{N}$ profiles, perhaps reflecting diagenetic effects judging by the shifts associated with the uppermost sample near the base of the weathered zone. Carbon and nitrogen isotopic and elemental data are typical for undifferentiated organic matter of aquatic origin, including low C:N ratio (cf. Meyers and Lallier-Vergès, 1999; Talbot and Laerdal, 2000) and no consistent correlations exist between cellulose-inferred $\delta^{18}\text{O}$ and other parameters that might indicate mixing of material from two different sources (such as high $\delta^{18}\text{O}$ in response to terrestrial cellulose input). Intriguingly, these data suggest that the cellulose has indeed recorded the oxygen-isotope composition of the lake water in which it formed, and that the $\delta^{18}\text{O}$ value of this water was on the order of 6‰ higher than the isotopically-unaltered connate pore waters preserved in the same sediments near the base of the Agassiz sequence.

5. Discussion

5.1. Explanation for contrasting cellulose and pore-water archives

The contrasting inferred lake water $\delta^{18}\text{O}$ compositions in the southern basin, more negative in the porewater archive and positive in the cellulose archive, can be reconciled using the conceptual model presented in Fig. 3. We hypothesize that the difference in the two contemporaneous archives reflects isotopic enrichment

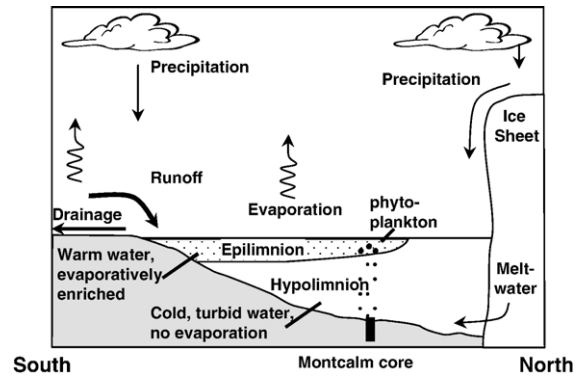


Fig. 3. Conceptual model of a longitudinal transect along the Red River Valley from the ice margin in the north to the southern extent of Lake Agassiz during the high-water Lockhart Phase (11,000 ^{14}C yr BP). The thickness of the epilimnion is greatly exaggerated for purposes of illustration.

of surface waters in the south basin of Lake Agassiz during this time of rapid sedimentation, with algal cellulose recording the isotopic signature of relatively warm, evaporatively enriched waters of the epilimnion, while sediment porewaters in the deep-water trough located in the centre of the lake preserve the composition of hypolimnion waters fed by cold, dense, sediment-laden, non-evaporated glacial meltwater, supplemented by seasonal precipitation and snowmelt, issuing directly from the ice front. This stratification is consistent with Teller's proposal (1976) that meltwater inputs to early Lake Agassiz may have been in the form of density underflows, particularly in the summer when the influx of water and suspended sediment would have been greatest.

There are no direct modern analogs for an extremely large ice-contact lake located in the mid-latitudes. Nonetheless, aspects of the proposed conceptual model for Lake Agassiz can be evaluated qualitatively by comparing the paleolimnology of the lake with modern large lakes and proglacial lakes. In our conceptual model we suggest that Lake Agassiz was well-mixed near the glacier margin, but that the lake was seasonally stratified isotopically in the constricted arm of the southern basin. A combined hydrological and heat budget by Mann et al. (1997) showed that localized areas, including the southern constricted portion of the basin where our porewater and cellulose archives were obtained, may indeed have experienced seasonal thermal stratification. Whether the isotopic stratification suggested by our co-existing archives is thermal or density-driven is not clear; however, modern analogs exist for the development of both situations.

The existence of transient stratification in only a portion of a lake has also been noted in modern ice-contact lakes, as well as in large lakes. In ice-contact lakes polymictic conditions have been observed close to the ice margin with an unstable mixing zone extending beyond the glacier terminus into the lake (Reid and Callender, 1965; Campbell, 1973). There are also examples of seasonal stratification in modern ice-contact lakes with thermal stratification developing in the spring and summer resulting in a turbulent warm epilimnion separated from the deep, cold hypolimnion by a thermocline that decays in the fall and winter (Warren and Kirkbride, 1998). The development of a thermal bar, a narrow transition zone consisting of a nearly vertical 4 °C isotherm, can result in strongly differing thermal structure in different portions of large lakes. When shallow waters around the margins of a lake warm more rapidly than the deeper midsections, for example, stable thermal

stratification can develop in nearshore regions despite the existence of isothermal conditions in the lake's centre (Wetzel, 1983). Examples also exist of proglacial lakes that are density-stratified with respect to suspended sediment content despite isothermal conditions or reversed temperature gradients (Mathews, 1956; Gustavson, 1973, 1975; Gustavson and Boothroyd, 1987).

Modern observations in analogous hydroclimatic settings also readily support the plausibility of ~6‰ evaporative enrichment in the epilimnion waters of Lake Agassiz, as shown from a survey of lakes spanning the boreal forest, forest–tundra and sub-arctic tundra regions of northern Canada reported by Gibson and Edwards (2002; Fig. 6), as well as detailed studies in subcatchments of the Coppermine River basin conducted by Maric (2003). Indeed, as highlighted by Edwards et al. (2004; Fig. 4), evaporatively enriched runoff generated within the tundra catchment of Yamba

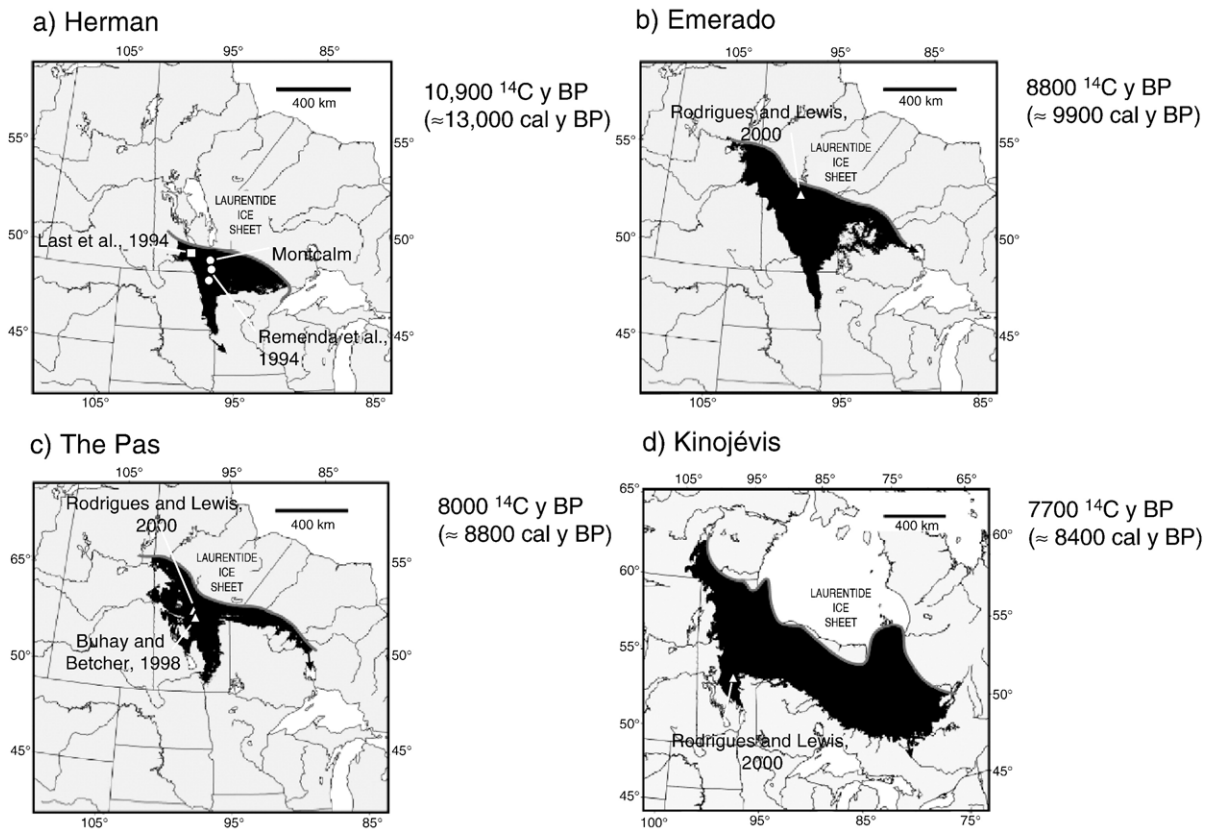


Fig. 4. Modelled depictions of the extent of Lake Agassiz from Teller and Leverington (2004) for time periods for which paleolake $\delta^{18}\text{O}$ archives are available. a) Porewater, cellulose and ostracode $\delta^{18}\text{O}$ archives are available for the Herman Lake stage. b) Lake Agassiz was present in the Lake Winnipeg area by the Emerado stage, corresponding with the beginning of the ostracode record reported by Rodrigues and Lewis (2000). c) The Rodrigues and Lewis (2000) ostracode record reaches a minimum between approximately 8700 and 8600 ^{14}C yr BP. d) By this late Lake Agassiz stage the cellulose and ostracode archives available from the Lake Winnipeg cores are from an isolated southern branch of the lake and are likely representative of conditions along the southern shore of the lake.

Lake (65°N; 111°) maintains the $\delta^{18}\text{O}$ of this lake at -18.0‰ versus local precipitation of -23.7‰ , yielding an almost exact analog for the inferred isotopic enrichment (and composition) of local runoff entering the southern arm of Lake Agassiz. The isotopic composition of neighbouring Lac de Gras, one of the largest lakes in the region (surface area of 578 km²), is similarly influenced by evaporatively-altered runoff, also sustaining close to 6‰ steady-state enrichment in ^{18}O relative to local precipitation under current conditions (see data in Maric, 2003).

A remarkably similar past analog for the hypothesized situation in Lake Agassiz may also exist in isotope paleorecords from Lake Ontario reported by Edwards et al. (1994), manifested by pronounced deviation in lake water $\delta^{18}\text{O}$ changes recorded by cellulose and carbonate (*Pisidium* sp.) archives in the same core at the time of the “Nipissing Flood” (~5000–4000 ¹⁴C yr BP), possibly signalling the influence of evaporatively enriched surface waters discharging from the upper Great Lakes through Lake Erie. Eyles and Schwarcz (1991) and Schwarcz and Eyles (1991) also invoked stratification to account for systematic $\delta^{18}\text{O}$ differences between deep- and shallow-water ostracode species in isotope paleorecords from Lake Ontario.

5.2. Other estimates of the $\delta^{18}\text{O}$ composition of Lake Agassiz

Our porewater and cellulose-inferred $\delta^{18}\text{O}$ compositions of Lake Agassiz can be compared with other

estimates obtained from ostracodes (Last et al., 1994; Rodrigues and Lewis, 2000; Moore et al., 2000) and cellulose (Buhay and Betcher, 1998) from different parts of the basin over the history of the glacial lake (Table 1 and Fig. 4a–d). The reported $\delta^{18}\text{O}$ values for the benthic ostracode species *Candona subtriangulata* were converted to lake water $\delta^{18}\text{O}$ values using fractionation factors (α) calculated using $10^3 \ln \alpha = 2.78(10^6/T_K^2) - 2.89$ (O’Neil et al., 1969) where T_K is the temperature (Kelvin). *Candona triangulata* is a benthic ostracode species that is found in cold (<7 °C), dilute lake waters typical of deep water in large lakes (Curry, 1997). Ranges for the inferred lake water $\delta^{18}\text{O}$ were determined from the *C. subtriangulata* data using a temperature range of 4 and 10 °C and applying a 2‰ vital offset (von Grafenstein et al., 1999). This conversion gives results similar to the approximation $\delta^{18}\text{O}_{\text{water}} (\text{VSMOW}) = \delta^{18}\text{O}_{\text{ostracode}} (\text{VPDB}) - 3.5\text{‰}$ used by Dettman et al. (1994) and Rea et al. (1994b) but allows for a range of $\delta^{18}\text{O}_{\text{water}}$ values to be determined based on a range of temperatures.

The only other estimates for the isotopic composition of early Lake Agassiz exist in the form of $\delta^{18}\text{O}$ values measured on *C. subtriangulata* originating from Lake Agassiz sediments preserved below modern Lake Manitoba (see Figs. 1 and 4a), dating between 12,000 and 10,000 ¹⁴C yr BP (Last et al., 1994). The values reported by Last et al. (1994) suggests that the *C. subtriangulata* were living in lake water with a $\delta^{18}\text{O}$ composition in the range of -21 to -18‰ (VSMOW). The intermediate isotopic composition of this ostracode record is consistent with its location outside of

Table 1
Summary of the paleolake $\delta^{18}\text{O}$ archives presented in Fig. 5a

Archive/study site	Date (¹⁴ C yr BP)	Archive $\delta^{18}\text{O}$	Inferred $\delta^{18}\text{O}$	Reference
<i>*C. subtriangulata</i>		(‰ VPDB)	(‰ VSMOW)	
Lake Manitoba	12,000 to 10,000	-15.3 to -16.4	-21.3 to -18.7	(Last et al., 1994)
Lake Winnipeg, (cores 205, 206)	≈ 9000 to 7500	-23.5 to -13.5	-28.6 to -16.8	(Moore et al., 2000; Rodrigues and Lewis, 2000; Lewis et al., 2004)
Great Lakes	11,000 to 10,200 (Algonquin)	-16 to -11	-18.8 to -14.2	(Lewis et al., 1994; Rea et al., 1994a; Dettman et al., 1995)
	9000 to 8000 (main Mattawa)	-10 to -5	-15.7 to -8.0	
<i>**Cellulose</i>		(VSMOW)	(VSMOW)	
Lake Winnipeg, (core 107)	≈ 8000	21.4 to 18.8	-6.6 to -9.2	(Buhay and Betcher, 1998)

**C. subtriangulata* $\delta^{18}\text{O}$ (‰ VPDB) values were converted to an inferred lake water $\delta^{18}\text{O}$ range (‰ VSMOW) using an equilibrium fractionation factor ($\alpha_{\text{calcite-water}}$) calculated using $10^3 \ln \alpha = 2.78(10^6/T_K^2) - 2.89$ (O’Neil et al., 1969). Lake water temperatures were assumed to be between 4 and 10 °C (Mann et al., 1997; Hostetler et al., 2000) and a vital offset of +2‰ was used (von Grafenstein et al., 1999).

***Cellulose* $\delta^{18}\text{O}$ (‰ VSMOW) values were converted to an inferred lake water $\delta^{18}\text{O}$ (‰ VSMOW) assuming $\alpha_{\text{cellulose-water}}$ of 1.028 (Edwards and McAndrews, 1989; Sauer et al., 2001; Wolfe et al., 2001a).

the deep central trough and near the ice margin and entry points of western tributaries where the lake was likely well-mixed.

By about 10,000 ^{14}C yr BP the LIS had retreated northward so that Lake Agassiz occupied the modern Lake Winnipeg basin (Fig. 4b). Detailed stratigraphic investigations, geophysical surveys and sediment samples retrieved as part of the Lake Winnipeg Project (Todd et al., 1998) have provided a complete Lake Agassiz sequence for this later time period. The Lake Agassiz sequence from below the north basin of Lake Winnipeg has supplied two separate lakewater $\delta^{18}\text{O}$ archives; an ostracode record spanning almost the entire sequence (Rodrigues and Lewis, 2000; Moore et al., 2000) and a shorter cellulose record (Buhay and Betcher, 1998).

The chronology for the composite record of *C. subtriangulata* $\delta^{18}\text{O}$ values reported in Rodrigues and Lewis (2000), Moore et al. (2000) and Lewis et al. (2004) was developed using varves and anchored by a paleomagnetic anomaly. The resulting record provides a history of changes in lake water isotopic composition between 9000 ^{14}C yr BP and 7500 ^{14}C yr BP (Fig. 4b,c and d). The inferred $\delta^{18}\text{O}$ chronology reported by Moore et al. (2000) and Lewis et al. (2004) suggests that the composition of early Lake Agassiz decreased from a value of about -20‰ at 9000 ^{14}C yr BP, when the ice sheet first retreated north of this point, to a very low value of -27‰ by about 8000 ^{14}C yr BP (Fig. 5a). Following this minimum the inferred lake water composition became more enriched, eventually reaching values of -16‰ by 7500 ^{14}C yr BP.

Buhay and Betcher (1998) used cellulose extracted from a single core of Lake Agassiz sediment from below Lake Winnipeg to infer $\delta^{18}\text{O}$ estimates for the paleolake using similar methods and the same fractionation factor as used for our cellulose data. The chronology of their cellulose-inferred lake water $\delta^{18}\text{O}$ estimates is not as well-constrained as the ostracode record from Lake Winnipeg, but the sediments are thought to correspond to about 8500 to 8000 ^{14}C yr BP (Fig. 4c). These estimates were far more enriched ($\delta^{18}\text{O} = -7$ to -9‰) than any of the previous Lake Agassiz $\delta^{18}\text{O}$, and provided the first evidence for isotopically-enriched epilimnion waters in Lake Agassiz. This enriched estimate becomes even more remarkable in light of the very depleted ostracode-inferred $\delta^{18}\text{O}$ values presented by Rodrigues and Lewis (2000) and Moore et al. (2000) for the same time period (Fig. 5a). However, the offset between the depleted $\delta^{18}\text{O}$ estimates inferred from benthic ostracodes and the enriched cellulose-inferred

lake water $\delta^{18}\text{O}$ estimates can again be explained as an indication of isotopic enrichment of water present in the epilimnion preserved by the cellulose compared to the depleted bottom water $\delta^{18}\text{O}$ estimates obtained from ostracodes.

5.3. Isotopic evolution of Lake Agassiz

Recognition of the potential for differing isotopic compositions of water both within the water column (epilimnion versus hypolimnion) and from different portions of the lake basin (lake edge versus central trough) helps explain the apparent discrepancies existing between the various water isotopic archives available for Lake Agassiz. With this in mind, the various data support a remarkably consistent and coherent picture of the isotopic evolution of epilimnion and hypolimnion waters (Fig. 5a).

The relatively small variations in the $\delta^{18}\text{O}$ (and 18‰ to and 15‰) of epilimnion water inferred from cellulose from the Montcalm site suggests only minor shifts in the isotopic composition of surface waters in the central portion of the basin during the Lockhart to Emerson phases, despite a general decline in the proportion of meltwater entering the lake and increasing lake volume and area.

As suggested by Lewis et al. (1994) and Buhay and Betcher (1998), the strong $\delta^{18}\text{O}$ increase of Lake Agassiz waters between the earlier lake phases and the Nipigon–Ojibway phase can be largely attributed to changes in the relative contribution of isotopically depleted meltwater and increasingly ^{18}O -enriched precipitation, reflecting ongoing climate warming. Modelled estimates by Teller (1990) for the volume of precipitation and meltwater generated over each of the basins draining to Lake Agassiz illustrate the changing contribution of the two sources (Fig. 5b). During the Lockhart and Moorhead phases meltwater is the dominant source of water to Lake Agassiz, but by the Emerson phase precipitation inputs are almost equally important.

Over the 4000-year time span that Lake Agassiz existed there were also significant changes in the catchments feeding the lake. During the Lockhart and Moorhead phases the lake received drainage from both the western Hudson Bay and Mackenzie basins, but by the Nipigon phase Lake Agassiz was fed by the more southern Hudson Bay basin. Modern precipitation $\delta^{18}\text{O}$ fields for North America (Birks et al., 2002; Bowen and Wilkinson, 2002) suggest that runoff generated over the northern catchments would be 1–2‰ lower than the southern catchments.

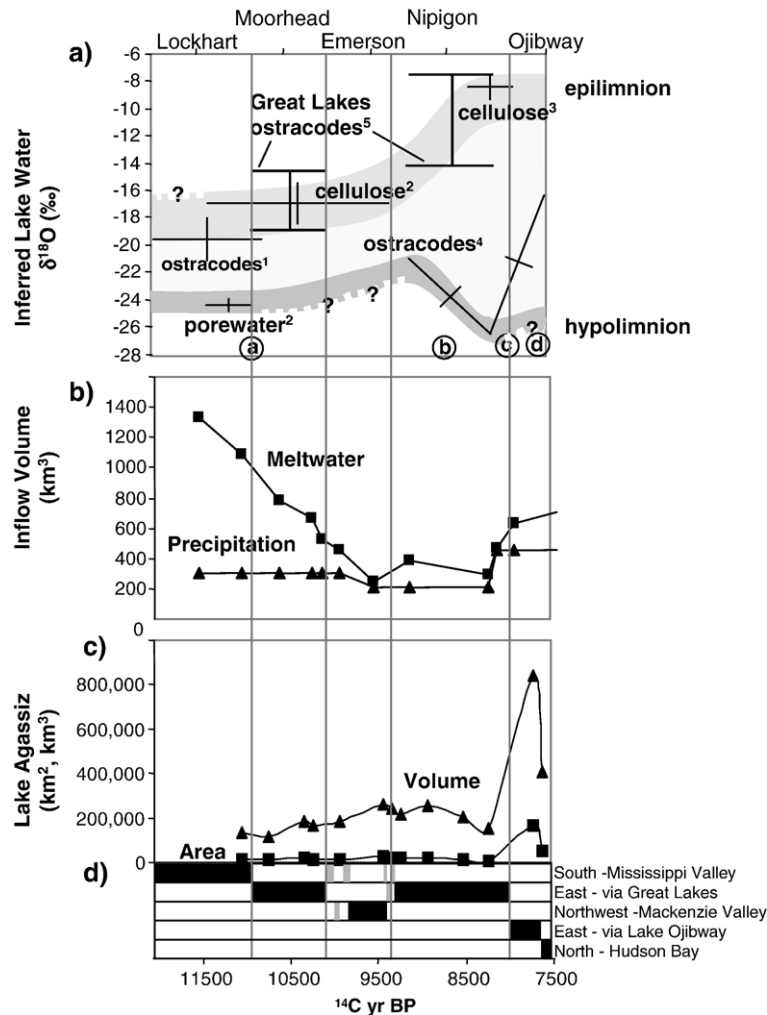


Fig. 5. History of Lake Agassiz's isotopic composition, meltwater and precipitation inflow, and its area, volume and outlet usage. a) Inferred isotopic history of Lake Agassiz, based on ¹ostracode data from Last et al. (1994), ²porewater and cellulose from Montcalm (this study), Drayton and Emerson (Remenda et al., 1994), ³measured cellulose and modelled porewater (Buhay and Betcher, 1998) and ⁴ostracode data (Rodrigues and Lewis, 2000) (summarised in Table 1). Each archive is indicated as a cross giving the range of archive-inferred $\delta^{18}\text{O}$ lake water values and the approximate time period. Also included are ranges for the inferred $\delta^{18}\text{O}$ of lake water in Georgian Bay and Lake Huron based on ⁵ostracodes for high-water periods when the Great Lakes received drainage from Lake Agassiz (Lewis et al., 1994; Rea et al., 1994; Dettman et al., 1995). Circled letters refer to approximate time periods presented in Fig. 4. b) Estimated volumes of meltwater and precipitation flowing to Lake Agassiz, from Teller, 1990. Prior to 9000 ^{14}C yr BP, Lake Agassiz received drainage generated within the Mackenzie and Agassiz basins (A and B in Teller, 1990). Following this the Mackenzie basin drained to the Arctic Ocean and only precipitation and meltwater generated within the Agassiz basin were included. By 8200 ^{14}C yr BP, the combined Lake Agassiz–Ojibway was receiving drainage from both the Agassiz basin and the area north of the Great Lakes basin. c) Modelled changes in the volume and surface area of Lake Agassiz are from Leverington et al. (2002). The large increase in both parameters after 8000 ^{14}C yr BP occurred when Lake Agassiz joined with Lake Barlow–Ojibway. d) Major (black) and possible minor (grey) routings for overflow from Lake Agassiz (after Leverington and Teller, 2003; Teller, 2004).

Evaporative enrichment also likely played a role in the progressive $\delta^{18}\text{O}$ increase in Lake Agassiz between 11,700 and 7800 ^{14}C yr BP. This period was characterized by maximum summer insolation and simulated summer temperatures higher than present for most of North America (Bartlein et al., 1998).

Existing information about the climate during the duration of Lake Agassiz is consistent with the lake having acquired an evaporated isotopic signal through evaporation from the lake surface itself as well as from the inflows of evaporatively enriched catchment runoff. Regional climate models suggest that the topography of

the LIS established a high-pressure centre located over Lake Agassiz, resulting in anticyclonic surface winds and concomitant increased cyclonic flow in the upper atmosphere, which would have blocked the penetration of winds and moisture from the south and west, the net result being lower annual precipitation over the lake, ice sheet and Superior lobe during large phases of the lake (Hostetler et al., 2000). Evidence that the lake served as a significant source of moisture for downwind areas (e.g., see Hu et al., 1997) provides further support that there was a significant evaporative component to the water budget of the lake.

Additional evidence for a dry climate during later phases of Lake Agassiz is emerging from detailed histories of lake levels in the Great Lakes (King et al., 2003; Lewis et al., 2004). These studies have confirmed the existence of dramatically lower lake levels in lakes Huron and Michigan, beyond that attributable to isostatic effects, which have been linked to an episode of particularly dry climate about 7900–7000 ^{14}C yr BP, coinciding with the very enriched surface waters indicated by the cellulose archive.

The isotopic evolution of the hypolimnion waters is not as well-constrained as the epilimnion time-series, but suggests a decrease from about -25‰ during the Lockhart phase to a minimum of -27‰ by the Nipigon phase (Rodrigues and Lewis, 2000). The isotopic evolution of Lake Agassiz would start with the composition of original inflow waters, a mixture of late-glacial precipitation and meltwater. The consistent and widespread occurrence of the $\sim -25\text{‰}$ $\delta^{18}\text{O}$ signature in three sites in Unit 1 of the Agassiz deposits, and in tills in Saskatchewan, and glaciolacustrine deposits in northern Ontario (Remenda et al., 1994), suggests that this value is representative of the initial inflow waters at the southern margin of the LIS during early phases of the lake. The more negative $\delta^{18}\text{O}$ estimates for the hypolimnion waters obtained from the benthic ostracode record from Rodrigues and Lewis (2000) at about 8700 to 8600 ^{14}C yr BP could indicate that the portion of the LIS melting at this period had a lower $\delta^{18}\text{O}$ composition than the ice sheet meltwater characterizing early Lake Agassiz. Alternatively, the minimum $\delta^{18}\text{O}$ in the ostracode record could indicate a larger ratio of meltwater to precipitation during this period of rapid retreat of the LIS. After the minimum at 8000 ^{14}C yr BP the ostracode record from Moore et al. (2000) indicates a rapid increase to more enriched conditions in the hypolimnion. However, during this period the ice margin continued to retreat northward and the location of the sampling site became increasingly isolated from the main body of the lake as well as being

more distal from the source of meltwater (Fig. 4d). Accordingly the estimates obtained from beneath Lake Winnipeg for this time period are likely more representative of water at the southern margin of the lake rather than the hypolimnion waters in deeper portions of the basin.

5.4. Isotopic composition of Lake Agassiz overflows

The isotopic stratification and proposed isotopic evolution of Lake Agassiz have important implications for identifying the presence of meltwater in downstream catchments and for estimating the magnitude of the freshwater fluxes to the oceans (Moore et al., 2000; Aharon, 2003). The lake water $\delta^{18}\text{O}$ inferred from cellulose provides an estimate of the most isotopically-enriched waters in the water column, but this value may be more representative of the isotopic composition of overflow waters than the very depleted waters present in the hypolimnion.

The proposed isotopic evolution of the Lake Agassiz epilimnion waters (Fig. 5a) is in harmony with signals detected in lakes downstream at times of eastward drainage, most notably the strong positive shift between the Main Algonquin and Mattawa phases (corresponding to the transition from the Moorhead to the Nipigon Agassiz phases) of Lake Huron and Georgian Bay inferred from ostracode $\delta^{18}\text{O}$ measurements (Lewis et al., 1994; Rea et al., 1994a; Dettman et al., 1995). Closer examination of the main Mattawa highstand ostracode record reveals a gradual increase in the $\delta^{18}\text{O}$ values over the duration of the lake highstands (~ 9000 to 8000 ^{14}C yr BP) providing further support that surface waters became evaporatively enriched during the Nipigon phase. The large increase between the cellulose-inferred lake water compositions for the Emerson and Ojibway phases indicates significant enrichment of surface waters in the intervening time period.

Estimates of the magnitude of water discharged to the oceans based on changes in $\delta^{18}\text{O}$ are particularly sensitive to the value of $\delta^{18}\text{O}$ used to approximate meltwater. Moore et al. (2000) used inferred estimates of the isotopic composition of the Great Lakes and Lake Agassiz meltwater in a box model to estimate the outflow from the Great Lakes to the North Atlantic. In their simulations the $\delta^{18}\text{O}$ of Lake Agassiz waters was based on archives present in the hypolimnion; specifically the porewater (Remenda et al., 1994) and ostracode (Rodrigues and Lewis, 2000; Moore et al., 2000) archives. The use of these estimates based only on hypolimnion archives would substantially

underestimate the volume of outflow from the lake during those periods. Even more depleted estimates of the isotopic composition of drainage from North America ($\delta^{18}\text{O} = -35\text{‰}$) have been used to calculate the discharge rate of water entering the Gulf of Mexico during the last deglaciation (Aharon, 2003). Our results emphasize that a distinction should be made between the isotopic composition of LIS meltwater and the isotopic composition of water actually discharging from Lake Agassiz.

6. Conclusions

The inferred isotopic composition of Lake Agassiz obtained from two contemporaneous archives yields new information about the paleolimnology of this major glacial lake and provides grounds for a unifying conceptual model that reconciles differing estimates of Lake Agassiz water isotopic composition. In the southern lobe of Lake Agassiz, during the lake highstand represented by our core ($\sim 11,700\text{--}11,000$ ^{14}C yr BP), the cellulose produced by phytoplankton living in the epilimnion evidently captured an evaporatively enriched surface-water signature while sediment porewater retained the signature of hypolimnion water unaffected by evaporation. This model lends support to the proposal by Lewis et al. (1994) that relatively high $\delta^{18}\text{O}$ values in outflow from the lake detected in archives downstream can be attributed to evaporative enrichment.

Robust trends are evident in the developing isotopic history of Lake Agassiz, particularly the recognition that outflowing waters may have had higher $\delta^{18}\text{O}$ values than previously assumed, which is a highly significant parameter for correct modelling of discharge scenarios. Further testing and enhancement of this speculative history is certainly warranted to improve our understanding of Lake Agassiz's influence on early Holocene hydrology and climate.

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References

- Abbott, M.B., Wolfe, B.B., Wolfe, A.P., Seltzer, G.O., Aravena, R., Mark, B.G., Polissar, P.J., Rodbell, D.T., Rowe, H.D., Vuille, M., 2003. Holocene paleohydrology and glacial history of the central Andes using multiproxy lake sediment studies. *Palaeogeography, Palaeoclimatology, Palaeoecology* 194, 123–138.
- Aharon, P., 2003. Meltwater flooding events in the Gulf of Mexico revisited: implications for rapid climate changes during the last deglaciation. *Paleoceanography* 18, 1029. doi:10.1029/2002PA000840.
- Barber, D.C., Dyke, A., Hillaire-Marcel, C., Jennings, A.E., Andrews, J.T., Kerwin, M.W., Bilodeau, G., McNeely, R., Southon, J., Morehead, M.D., Gagnon, J.-M., 1999. Forcing of the cold event of 8,200 years ago by catastrophic drainage of Laurentide lakes. *Nature* 400, 344–348.
- Bartlein, P.J., Anderson, K.H., Anderson, P.M., Edwards, M.E., Mock, C.J., Thompson, R.S., Webb, R.S., Webb III, T., Whitlock, C., 1998. Paleoclimate simulations for North America over the past 21,000 years: features of the simulated climate and comparisons with paleoenvironmental data. *Quaternary Science Reviews* 17, 549–585.
- Birks, S.J., Gibson, J.J., Gourcy, L., Aggarwal, P.K., Edwards, T.W.D., 2002. Maps and animations offer new opportunities for studying the global water cycle. *Eos, Transactions, American Geophysical Union, Electronic Supplement* 83 http://www.agu.org/eos_elec/020082e.html.
- Bluemle, J.P., 1974. Early history of Lake Agassiz in southeast North Dakota. *Geological Society of America Bulletin* 85, 811–814.
- Bowen, G.J., Wilkinson, B., 2002. Spatial distribution of $\delta^{18}\text{O}$ in meteoric precipitation. *Geology* 30, 315–318.
- Broecker, W.S., Kennett, J.P., Flower, B.P., Teller, J.T., Trumbore, S., Bonani, G., Wolfli, W., 1989. Routing of meltwater from the Laurentide Ice Sheet during the Younger Dryas cold episode. *Nature* 341, 318–321.
- Buhay, W.M., Betcher, R.N., 1998. Paleohydrologic implications of ^{18}O -enriched Lake Agassiz water. *Journal of Paleolimnology* 19, 285–296.
- Campbell, W.J., 1973. Structure and inferred circulation of South Cascade Lake, Washington, U.S.A. *International Association of Scientific Hydrology Publication* 95, 259–292.
- Clark, P.U., Alley, R.B., Pollard, D., 1999. Northern Hemisphere ice-sheet influences on global climate change. *Science* 286, 1104–1111.
- 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 8200 BP cold event. *Quaternary Science Reviews* 23, 389–407.
- Clayton, L., 1983. Chronology of Lake Agassiz drainage to Lake Superior. In: Teller, J.T., Clayton, L. (Eds.), *Glacial Lake Agassiz*. Geological Association of Canada Special Paper, vol. 26, pp. 291–307.
- Clayton, L., Teller, J.T., Attig, J.W., 1985. Surging of the southwestern part of the Laurentide ice sheet. *Boreas* 14, 235–241.
- Coleman, M.L., Shepherd, T.J., Durham, J.J., Rouse, J.E., Moore, G.R., 1982. Reduction of water with zinc for hydrogen isotope analysis. *Analytical Chemistry* 54, 993–995.
- Coplen, T.B., 1996. New guidelines for reporting stable hydrogen, carbon, and oxygen isotope ratio data. *Geochimica et Cosmochimica Acta* 60, 3359–3360.

- Curry, B.B., 1997. Paleochemistry of lakes Agassiz and Manitoba based on ostracodes. *Canadian Journal of Earth Sciences* 34, 699–708.
- DeNiro, M.J., Epstein, S., 1979. Relationship between the oxygen isotope ratios of terrestrial plant cellulose, carbon dioxide, and water. *Science* 204, 51–53.
- DeNiro, M.J., Epstein, S., 1981. Isotopic composition of cellulose from aquatic organisms. *Geochimica et Cosmochimica Acta* 45, 1885–1894.
- Desaulniers, D.E., Cherry, J.A., Fritz, P., 1981. Origin, age and movement of pore water in argillaceous Quaternary deposits at four sites in southwestern Ontario. *Journal of Hydrology* 50, 231–257.
- Dettman, D.L., Smith, A.J., Rea, D.K., Moore Jr., T.C., Lohmann, K.C., 1994. The oxygen isotope record of glacial melt water in Lake Huron and Georgian Bay, 10,600 to 7600 yr bp. Geological Society of America, 1994 Annual Meeting. Geological Society of America, Boulder, p. 178.
- Dettman, D.L., Smith, A.J., Rea, D.K., Moore Jr., T.C., Lohmann, K.C., 1995. Glacial meltwater in Lake Huron during early postglacial time as inferred from single valve analysis of oxygen isotopes in ostracodes. *Quaternary Research* 43, 297–310.
- Duthie, H.C., Yang, J.R., Edwards, T.W.D., Wolfe, B.B., Warner, B.G., 1996. Hamilton Harbour, Ontario; 8300 years of limnological and environmental change inferred from microfossil and isotopic analyses. *Journal of Paleolimnology* 15, 79–97.
- Edwards, T.W.D., 1993. Interpreting past climate from stable isotopes in continental organic matter. In: Swart, P.K., Lohmann, K.C., McKenzie, J.A., Savin, S.M. (Eds.), *Climate Change in Continental Isotopic Records*. Geophysical Monograph, vol. 78. American Geophysical Union, Washington, pp. 333–341.
- Edwards, T.W.D., McAndrews, J.H., 1989. Paleohydrology of a Canadian Shield lake inferred from ^{18}O in sediment cellulose. *Canadian Journal of Earth Sciences* 26, 1850–1859.
- Edwards, T.W.D., Weatherly, H., Terry, S., Drimmie, R.J., Frape, S.K., 1994. Isotopic Expression of the “Nipissing Flood” in Lake Ontario. Geological Association of Canada and Mineralogical Association of Canada, p. A33.
- Edwards, T.W.D., Wolfe, B.B., MacDonald, G.M., 1996. Influence of changing atmospheric circulation on precipitation $\delta^{18}\text{O}$ temperature relations in Canada during the Holocene. *Quaternary Research* 46, 211–218.
- Edwards, T.W.D., Elgood, R.J., Wolfe, B.B., 1997. Cellulose extraction from lake sediments for $^{18}\text{O}/^{16}\text{O}$ and $^{13}\text{C}/^{12}\text{C}$ analysis. Technical Procedure 28.0. University of Waterloo, Waterloo.
- Edwards, T.W.D., Wolfe, B.B., Gibson, J.J., Hammarlund, D., 2004. Use of water isotope tracers in high latitude hydrology and paleohydrology. In: Pienitz, R., Douglas, M.S.V., Smol, J.P. (Eds.), *Long Term Environmental Change in Arctic and Antarctic Lakes*. Springer, Dordrecht, pp. 187–207.
- Elson, J.A., 1967. Geology of glacial Lake Agassiz. In: Mayer Oakes, W. (Ed.), *Life, Land, and Water*. University of Manitoba Press, Winnipeg, pp. 36–96.
- Epstein, S., Mayeda, T., 1953. Variation of ^{18}O content of waters from natural sources. *Geochimica et Cosmochimica Acta* 4, 213–224.
- Eyles, N., Schwarcz, H.P., 1991. Stable isotope record of the last glacial cycle from lacustrine ostracodes. *Geology* 19, 257–260.
- Fenton, M.M., Moran, S.R., Teller, J.T., Clayton, L., 1983. Quaternary stratigraphy and history in the southern part of the Lake Agassiz basin. In: Teller, J.T., Clayton, L. (Eds.), *Glacial Lake Agassiz*. Geological Association of Canada Special Paper, vol. 26, pp. 49–74.
- Flower, B.P., Kennett, J.P., 1990. The Younger Dryas cool episode in the Gulf of Mexico. *Paleoceanography* 5, 949–961.
- Fritz, P., Drimmie, R.J., Frape, S.K., O’Shea, K.J., 1987. The isotopic composition of precipitation and groundwater in Canada. *Isotope Techniques in Water Resources Development*. International Atomic Energy Agency, Vienna, pp. 539–550.
- Gibson, J.J., Edwards, T.W.D., 2002. Regional water balance trends and evaporation transpiration partitioning from a stable isotope survey of lakes in northern Canada. *Global Biogeochemical Cycles* 16. doi:10.1029/2001GB001839.
- Gustavson, T.C., 1973. Sedimentation and physical limnology in proglacial Malaspina Lake, southeastern Alaska. In: Jopling, A.V., McDonald, B.C. (Eds.), *Glaciofluvial and Glaciolacustrine Sedimentation*. Society of Economic Paleontologists and Mineralogists, Tulsa, Oklahoma, pp. 249–263.
- Gustavson, T.C., 1975. Bathymetry and sediment distribution in proglacial Malaspina Lake, Alaska. *Journal of Sedimentary Petrology* 45, 450–461.
- Gustavson, T.C., Boothroyd, J.C., 1987. A deposition model for outwash, sediment sources, and hydrologic characteristics, Malaspina Glacier, Alaska: a modern analog of the southeastern margin of the Laurentide Ice Sheet. *Geological Society of America Bulletin* 99, 187–200.
- Hostetler, S.W., Bartlein, P.J., Clark, P.U., Small, E.E., Solomon, A.M., 2000. Simulated influences of Lake Agassiz on the climate of central North America 11,000 years ago. *Nature* 405, 334–336.
- Hu, F.S., Wright Jr., H.E., Ito, E., Lease, K., 1997. Climatic effects of glacial Lake Agassiz in the Midwestern United States during the last deglaciation. *Geology* 25, 207–210.
- King, J.W., Lewis, C.F.M., Hubeny, J.B., Moran, K., Coleman, D., Coakley, J.P., 2003. Understanding sensitivity of Great Lakes water levels to climate forcing: closedlake status 8.4–6.8 ka (9400–7700 cal BP). *Third International Limnogeology Congress, Tuscon*, p. 143.
- Kling, H.J., 1998. A summary of past and recent plankton of Lake Winnipeg, Canada using algal fossil remains. *Journal of Paleolimnology* 19, 298–307.
- Last, W.M., 1974. Clay mineralogy and stratigraphy of offshore Lake Agassiz sediments in southern Manitoba. M.Sc. Thesis, University of Manitoba, Winnipeg.
- Last, W.M., Teller, J.T., Forester, R.M., 1994. Paleohydrology and paleochemistry of Lake Manitoba, Canada; the isotope and ostracode records. *Journal of Paleolimnology* 12, 269–282.
- Leverington, D.W., Teller, J.T., 2003. Paleotopographic reconstructions of the eastern outlets of glacial Lake Agassiz. *Canadian Journal of Earth Sciences* 40, 1259–1278.
- Leverington, D.W., Mann, J.D., Teller, J.T., 2000. Changes in the bathymetry and volume of glacial Lake Agassiz between 11,000 and 9300 ^{14}C yr BP. *Quaternary Research* 54, 174–181.
- Leverington, D.W., Mann, J.D., Teller, J.T., 2002. Changes in the bathymetry and volume of Glacial Lake Agassiz between 9200 and 7700 ^{14}C yr BP. *Quaternary Research* 57, 244–252.
- Lewis, C.F.M., Moore Jr, T.C., Rea, D.K., Dettman, D.L., Smith, A.M., Mayer, L.A., 1994. Lakes of the Huron Basin; their record of runoff from the Laurentide ice sheet. *Quaternary Science Reviews* 13, 891–922.
- Lewis, C.F.M., Moore Jr., T.C., Rea, D.K., King, J.W., Heil Jr., C.W., Hubeny, J.B., Blasco, S.M., McCarthy, F.M.G., 2004. Revisiting Hough’s Stanley Unconformity in Lake Huron reveals climate-driven closed, low-level lake conditions about 7900–7000 BP. *International Association for Great Lakes Research, Waterloo*, pp. 88–89.

- MacDonald, G.M., Edwards, T.W.D., Moser, K.A., Pienitz, R., Smol, J.P., 1993. Rapid response of treeline vegetation and lakes to past climate warming. *Nature* 361, 243–246.
- Mann, J.D., Leverington, D., Rayburn, J.A., Grant, N., Teller, J.T., 1997. Calculating the volume and heat budget of glacial Lake Agassiz. Geological Society of America, 1997 Annual Meeting. Geological Society of America, Boulder, p. 111.
- Maric, R., 2003. Coupled isotope-mass balance studies in tundra lakes, Lac de Gras area, N.W.T., Canada. Master's Thesis, University of Waterloo, Waterloo, 145 pp.
- Mathews, W.H., 1956. Physical limnology and sedimentation in a glacial lake. *Bulletin of the Geological Society of America* 67, 537–552.
- Meyers, P.A., Lallier-Vergès, E., 1999. Lacustrine sedimentary organic matter records of late Quaternary paleoclimates. *Journal of Paleolimnology* 21, 345–372.
- Moore Jr, T.C., Walker, J.C.G., Rea, D.K., Lewis, C.F.M., Shane, L.C.K., Smith, A.J., 2000. Younger Dryas interval and outflow from the Laurentide ice sheet. *Paleoceanography* 15, 4–18.
- Namburdiri, E.M.V., Shay, C.T., 1986. Late Pleistocene and Holocene pollen stratigraphy of the Lake Manitoba basin, Canada. *Palaeontographica Abteilung B Paläophytologie* 202, 155–177.
- O'Neil, J.R., Clayton, R.N., Mayeda, T.K., 1969. Oxygen isotope fractionation in divalent metal carbonates. *Journal of Chemical Physics* 51, 5547–5558.
- Patterson, R.J., Frappe, S.K., Dykes, L.S., McLeod, R.A., 1978. A coring and squeezing technique for the detailed study of subsurface water chemistry. *Canadian Journal of Earth Sciences* 15, 162–169.
- Rea, D.K., Moore Jr, T.C., Anderson, T.W., Lewis, C.F.M., Dobson, D.M., Dettman, D.L., Smith, A.J., Mayer, L.A., 1994a. Great Lakes paleohydrology: complex interplay of glacial meltwater, lake levels, and sill depths. *Geology* 22, 1059–1062.
- Rea, D.K., Moore Jr, T.C., Lewis, C.F.M., Mayer, L.A., Smith, A.J., Dobson, D.M., 1994b. Stratigraphy and paleolimnologic record of lower Holocene sediments in northern Lake Huron and Georgian Bay. *Canadian Journal of Earth Sciences* 31, 1586–1605.
- Reid, J.R., Callender, E., 1965. Origin of debris-covered icebergs and mode of flow of ice into 'Miller Lake', Martin River Glacier, Alaska. *Journal of Glaciology* 5, 497–503.
- Remenda, V.H., Cherry, J.A., Edwards, T.W.D., 1994. Isotopic composition of old ground water from Lake Agassiz: implications for late Pleistocene climate. *Science* 226, 1975–1978.
- Risberg, J., Sandgren, P., Teller, J.T., Last, W.M., 1999. Siliceous microfossils and mineral magnetic characteristics in a sediment core from Lake Manitoba, Canada: a remnant of glacial Lake Agassiz. *Canadian Journal of Earth Sciences* 36, 1299–1314.
- Rodrigues, C.G., Lewis, C.F.M., 2000. Stable isotope composition of ostracode valves from Lake Winnipeg North Basin. In: Todd, B.J., Lewis, C.F.M., Forbes, D.L., Thorleifson, L.H. (Eds.), 1996 Lake Winnipeg Project: Cruise Report and Scientific Results. Geological Survey of Canada Open File, vol. 3470. Geological Survey of Canada, Ottawa, pp. 792–794.
- Rooth, C., 1982. Hydrology and ocean circulation. *Progress in Oceanography* 11, 131–149.
- Sauer, P.E., Miller, G.H., Overpeck, J.T., 2001. Oxygen isotope ratios of organic matter in arctic lakes as a paleoclimate proxy: field and laboratory investigations. *Journal of Paleolimnology* 25, 43–64.
- Schwarz, H.P., Eyles, N., 1991. Laurentide Ice Sheet extent inferred from stable isotopic composition (O, C) of ostracodes at Toronto Canada. *Quaternary Research* 35, 305–320.
- Sternberg, L.D.L., DeNiro, M.J., 1983. Biogeochemical implications of the isotopic equilibrium fractionation factor between the oxygen atoms of acetone and water. *Geochimica et Cosmochimica Acta* 47, 2271–2274.
- Sternberg, L.D.L., DeNiro, M.J., Keeley, J.E., 1984. Hydrogen, oxygen, and carbon isotope ratios of cellulose from submerged aquatic Crassulacean acid metabolism and non-Crassulacean acid metabolism plants. *Plant Physiology* 76, 68–70.
- Sternberg, L.D.L., DeNiro, M.J., Sloan, M.E., Black, C.C., 1986. Compensation point and isotopic characteristics of C₃/C₄ intermediates and hybrids in Panicum. *Plant Physiology* 80, 242–245.
- Sternberg, L.D.L., Anderson, W.T., Morrison, K., 2003. Separating soil and leaf water ¹⁸O isotopic signals in plant stem cellulose. *Geochimica et Cosmochimica Acta* 67, 2561–2566.
- Talbot, M.R., Laerdal, T., 2000. The Late Pleistocene–Holocene palaeolimnology of Lake Victoria, East Africa, based upon elemental and isotopic analyses of sedimentary organic matter. *Journal of Paleolimnology* 23, 141–164.
- Tarasov, L., Peltier, W.R., 2005. Arctic freshwater forcing of the Younger Dryas cold reversal. *Nature* 435, 662–665.
- Teller, J.T., 1976. Lake Agassiz deposits in the main offshore basin of southern Manitoba. *Canadian Journal of Earth Sciences* 13, 27–43.
- Teller, J.T., 1990. Volume and routing of late-glacial runoff from the southern Laurentide ice sheet. *Quaternary Research* 34, 12–23.
- Teller, J.T., 2004. Controls, history, outbursts, and impacts of large late Quaternary proglacial lakes in North America. Chapter 3. In: Giles, A., Porter, S., Atwater, B. (Eds.), *The Quaternary Period in the United States. Developments in Quaternary Science*, vol. 1. Elsevier, pp. 45–61.
- 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., 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*, vol. 26, pp. 261–290.
- Teller, J.T., Boyd, M., Yang, Z., Kor, P.S.G., Fard, A.M., 2005. Alternative routing of Lake Agassiz overflow during the Younger Dryas: new dates, paleotopography and a reevaluation. *Quaternary Science Reviews* 24, 1890–1905.
- Todd, B.J., Lewis, C.F.M., Thorleifson, L.H., Nielsen, E., Last, W.M., 1998. Paleolimnology of Lake Winnipeg. *Journal of Paleolimnology* 19, 211–213.
- von Grafenstein, U., Erlenkeuser, H., Trumborn, P., 1999. Oxygen and carbon isotopes in modern fresh-water ostracod valves; assessing vital offsets and autecological effects of interest for palaeoclimate studies. *Palaeogeography, Palaeoclimatology, Palaeoecology* 148, 133–152.
- Warren, C.R., Kirkbride, M.P., 1998. Temperature and bathymetry of ice-contact lakes in Mount Cook National Park, New Zealand. *New Zealand Journal of Geology and Geophysics* 41, 133–143.
- Weatherly, H., 1993. Stable isotope stratigraphy of Lake Ontario sediments. B.Sc. Thesis, University of Waterloo, Waterloo, 29 pp.
- Wetzel, R.G., 1983. *Limnology*. Saunders College Publishing, Philadelphia. 860 pp.
- Wolfe, B.B., Edwards, T.W.D., 1997. Hydrologic control on the oxygen-isotope relation between sediment cellulose and lake water, western Taimyr Peninsula, Russia; implications for the use of surface-sediment calibrations in paleolimnology. *Journal of Paleolimnology* 18, 283–291.

- Wolfe, B.B., Edwards, T.W.D., Aravena, R., MacDonald, G.M., 1996. Rapid Holocene hydrologic change along boreal treeline revealed by $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ in organic lake sediments, Northwest Territories, Canada. *Journal of Paleolimnology* 15, 171–181.
- Wolfe, B.B., Edwards, T.W.D., Aravena, R., Forman, S.L., Warner, B.G., Velichko, A.A., MacDonald, G.M., 2000. Holocene paleohydrology and paleoclimate at treeline, north-central Russia, inferred from oxygen isotope records in lake sediment cellulose. *Quaternary Research* 53, 319–329.
- Wolfe, B.B., Edwards, T.W.D., Beuning, K.R.M., Elgood, R.J., 2001a. Carbon and oxygen isotope analysis of lake sediment cellulose: methods and applications. In: Last, W.M., Smol, J.P. (Eds.), *Tracking Environmental Change Using Lake Sediments: Physical and Chemical Techniques*, Developments in Paleoenvironmental Research. Kluwer, Dordrecht, The Netherlands, pp. 373–400.
- Wolfe, B.B., Aravena, R., Abbott, M.B., Seltzer, G.O., Gibson, J.J., 2001b. Reconstruction of paleohydrology and paleohumidity from oxygen isotope records in the Bolivian Andes. *Palaeogeography, Palaeoclimatology, Palaeoecology* 176, 177–192.
- Wolfe, B.B., Edwards, T.W.D., Jiang, H.B., MacDonald, G.M., Gervais, B.R., Snyder, J.A., 2003. Effect of varying oceanicity on early to mid Holocene paleohydrology, Kola Peninsula, Russia: isotopic evidence from treeline lakes. *The Holocene* 13, 153–160.
- Yakir, D., 1992. Variations in the natural abundance of oxygen-18 and deuterium in plant carbohydrates. *Plant, Cell and Environment* 15, 1005–1020.
- Yakir, D., DeNiro, M.J., 1990. Oxygen and hydrogen isotope fractionation during cellulose metabolism in *Lemna gibba* L. *Plant Physiology* 93, 325–332.