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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

- in response to changes in the ice sheet's size and configuration, and
- 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 Laurentide Ice Sheet (Clayton *et al.*, 1985), regional climate (Hostetler *et al.*, 2000) and ocean-climate systems (Broecker *et al.*, 1989).

Objective

In this study we use two different types of archives, **porewater** and **cellulose**, to estimate the isotopic composition of Lake Agassiz from a core from the Montcalm site in the middle of the southern basin of Lake Agassiz.

Isotopic Composition of Lake Agassiz

Estimates of the isotopic composition of Lake Agassiz during various phases of its history have been obtained from:

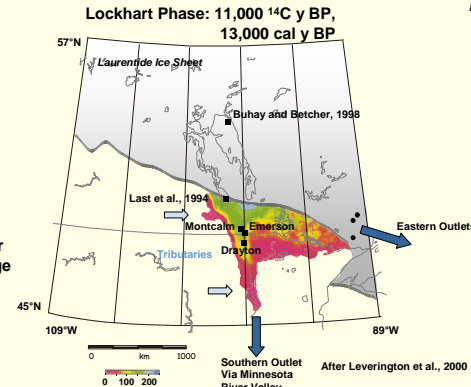
- porewater (Remenda *et al.*, 1994, Montcalm, Emerson and Drayton sites)
- ostracodes (Last *et al.*, 1994)
- cellulose (Buhay and Betcher, 1998)

The isotopic composition of early Lake Agassiz has been used to obtain information about late glacial climate (Remenda *et al.*, 1994). The isotopically depleted, low salinity signature of Lake Agassiz water has also been used to trace meltwater pulses through various drainage networks (Broecker *et al.*, 1989; Dettman *et al.*,).

Montcalm

• The area around Montcalm was subject to two deep-water depositional phases of Lake Agassiz

- **Lockhart Phase:** 11,700 to 10,900 ¹⁴C yr BP
- **Emerson Phase:** 10,200 to 9400 ¹⁴C yr BP



Modelled paleobathymetry of Lake Agassiz for 11,000 ¹⁴C yr BP at the end of the Lockhart phase, just prior to the opening of the eastern outlets. Modern surface water features and the location of the various Lake Agassiz archives are shown.

Lake Agassiz Deposits at Montcalm:

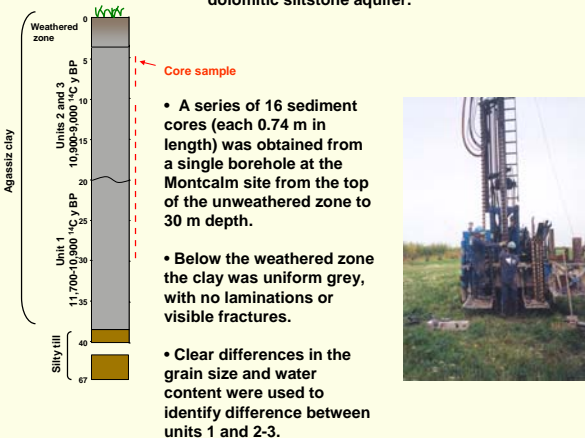
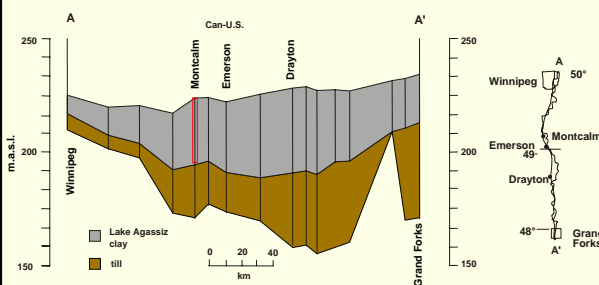


These deep water phases resulted in the deposition of extensive, thick clay units in southern Manitoba.

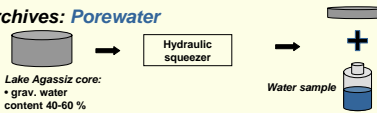
Lake Phase	Time ¹⁴ C yr BP	Approx. Lake Depth (m) ¹	Agassiz Formation
Emerson	9400	125	Unit 3
Moorhead	10,200	50	Unit 2
Lockhart	11,700	175	Unit 1

¹ Approximate lake depth in the vicinity of Montcalm estimated from paleobathymetry maps of Leverington *et al.*, 2000.

Montcalm



The Archives: Porewater



Porewater from each core was sampled using hydraulic squeezers.

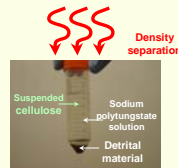
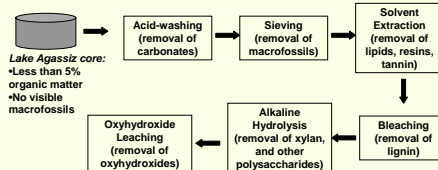
Average linear groundwater velocities calculated from hydraulic conductivities, gradients and porosities measured in the lab and field are within the range of 9-13 m per 10,000 years (Remenda *et al.*, 1994).

- Suggesting that porewater in the mid-section of the clay at the Montcalm site should retain the original porewater present at the time of deposition.

Porewater from aquitards is the only direct archive for both $\delta^{18}O$ and δ^2H available for Lake Agassiz.

The Archives: Cellulose

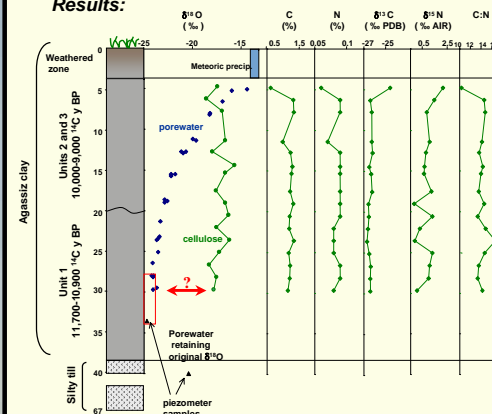
Sediment samples from each core were processed to isolate the cellulose fraction using the method outlined by Wolfe *et al.* (2001).



The $\delta^{18}O$ of the fine grained cellulose fraction can be used to infer the $\delta^{18}O$ of lake water using a well-established, temperature independent fraction factor.

$$\alpha_{\text{cellulose-lakewater}} = 1.028$$

Results:



Discrepancies?

• If porewater preserves Lake Agassiz water present at the time of deposition why does it plot on the MWL? Why doesn't it have an evaporative signal?

• Why doesn't the inferred $\delta^{18}O_{\text{lake water}}$ from cellulose agree with the $\delta^{18}O$ signature preserved in porewater? In the deepest core sample (29.7 m) where the porewater $\delta^{18}O$ was -24.2‰ the cellulose inferred lake water composition was -18.0‰ .

Porewater

• The porewater $\delta^{18}O$ in the unfractured zone (5-30 m) increases from very negative at depth, -24.4‰ , to a value similar to local recharge, -14‰ , near the surface.

• A piezometer located slightly deeper than the deepest core sample had a $\delta^{18}O$ of -24.8‰ , a value that has also been measured at depth at other locations within the same Lake Agassiz unit, and in glacial till deposits (Remenda *et al.*, 1994).

• The gradual increase in $\delta^{18}O$ from this minimum to values similar to modern recharge is consistent with diffusion of water present in the shallow, weathered zone over an 11,000 cal yr time period (Remenda *et al.*, 1994).

• All of the porewater samples plot on the global meteoric water line ($\delta^2H = 8 \delta^{18}O + 10$) indicating that they have not been altered by evaporation.

Cellulose

• The C:N ratios of the organic matter from which the cellulose was derived range from 10.2 to 16.6 indicating that it is not of terrestrial origin (Wolfe *et al.*, 2001).

• The $\delta^{15}N$ of the organic matter is positive (0.7 to 2.3 ‰) suggesting that the system might have been nitrogen limited.

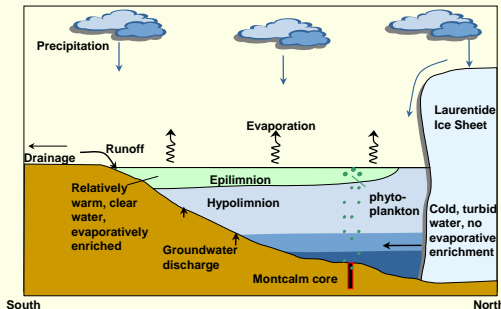
• The $\delta^{18}O$ measured for the cellulose were converted to an inferred lake water $\delta^{18}O$ using a fractionation factor of 1.028. The inferred $\delta^{18}O$ ranges from -18.8 to -15.8‰ with the most enriched values occurring around 15m.

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Conceptual Model:



Explains our $\delta^{18}O$ stratification!

We hypothesize that the difference in the two archives reflect isotopic stratification in the south basin of Lake Agassiz during the time of rapid detrital sedimentation with;

- **algal cellulose** recording the isotopic signature of relatively warm, evaporatively-enriched waters of the epilimnion,
- **sediment porewaters** preserving the composition of hypolimnion waters fed by cold, dense non-evaporated glacial meltwater issuing directly from the ice front

Is a 6‰ evaporative enrichment plausible?

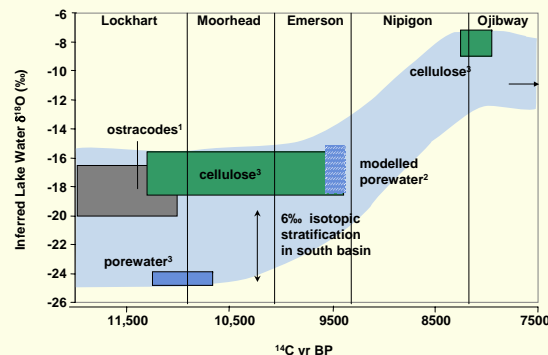
This was evaluated for the period of rapid sedimentation in the south basin, between 11,700 and 11,000 ¹⁴C yr BP using a simple isotopic water balance. Isotopic water balance equations were used to evaluate whether lake water receiving inputs primarily from late glacial precipitation and meltwater with a $\delta^{18}O_p$ of -25‰ could be enriched to $\delta^{18}O_l = -18‰$ using reasonable ranges for ambient conditions: temperature 5-15°C, relative humidity 55-75%, and $\delta^{18}O_A = -29$ to -33‰.

Under these conditions the lake waters could achieve a 6‰ enrichment in $\delta^{18}O$ with E/I ratios between 0.11 to 0.27, a range typical for modern lakes in tundra to forest-tundra settings (Gibson and Edwards, 2002).

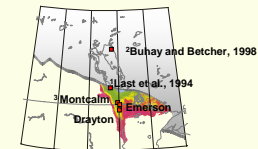
Is there any other evidence that Lake Agassiz was stratified?

- The results of a combined hydrological and heat budget for this time period showed that even though most of the Lake Agassiz basin probably remained fairly cold and polymictic, localized areas, like the southern constricted portion of the basin where Montcalm is located may have been stratified (Mann et al., 1997). Water depths in the vicinity of Montcalm were likely about 175 m (Leverington et al., 2000).

Comparison with Other Agassiz Isotopic Archives: Isotopic Evolution of Glacial Lake Agassiz:



Various estimates of the isotopic composition of Lake Agassiz can be assembled to form a coherent scenario for the isotopic evolution of Lake Agassiz



² Buhay and Betcher (1998)

- Used cellulose in Lake Agassiz sediments from cores from below Lake Winnipeg dated at about 8000 ¹⁴C yr BP to infer a Lake Agassiz $\delta^{18}O$ composition of -7 to -9‰.

- They also compared an extrapolation of their porewater profile to modelled diffusion profiles to estimate the isotopic composition of Lake Agassiz during an earlier, deepwater phase as being between -18 and -15‰.

- According to the time-series bathymetry of Leverington et al. (2000) the deep water phases of Lake Agassiz would have occupied the Lake Winnipeg area for a short interval around 10,300 ¹⁴C yr BP and not again until after 9,500 ¹⁴C yr BP.

•³ this study

- Porewater from the depths retaining connate water are restricted to Unit 1 of Lake Agassiz sediments, deposited during the Lockhart phase.
- The range of inferred cellulose lake water compositions are included for the time period covering the deposition of all three Agassiz units.

¹ Last et al. (1984)

- Measured the $\delta^{18}O$ (PDB) of the coldwater species *Candona subtriangulata* in Lake Agassiz sediment from a core below Lake Manitoba dated between 12,000 and 11,000 ¹⁴C yr BP.

- Using a 1‰ vital offset (Detman et al., 1994; von Grafenstein et al., 1999) at temperatures between 4 and 10°C (Hostetler et al., 2000 and Mann et al., 1997), gives an inferred lake water $\delta^{18}O$ range of -20 to -16‰ (VSMOW).

Isotopic Evolution of Lake Agassiz:

Changes in the Drainage Basins feeding Lake Agassiz:

• During the Lockhart and Moorhead phases, the lake received inputs from the modern western Hudson Bay catchment and from the headwaters of the Mackenzie River.

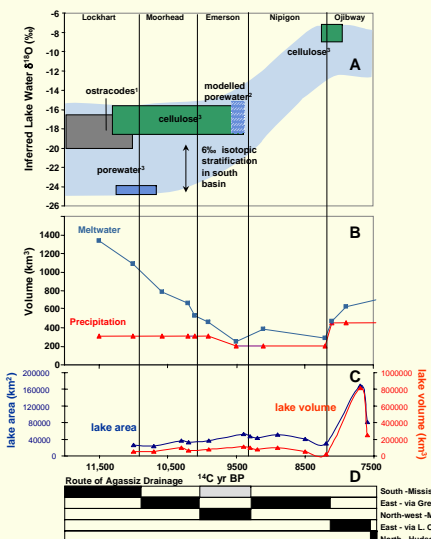
• After about 9,900 ¹⁴C yr BP the Mackenzie River was able to drain to the Arctic Ocean. Lake Agassiz was fed primarily by drainage from the western Hudson Bay basin until after 8,200 ¹⁴C yr BP when it joined with Lake Ojibway, after which the Lake Agassiz-Ojibway received drainage from both the western Hudson Bay and eastern Hudson Bay catchments.

• One would expect the isotopic composition of drainage generated from the Mackenzie basin to be more negative than that generated on the eastern Hudson Bay catchment based on their latitude.

Changing Proportions of Meltwater to Precipitation:

• We used modelled estimates for the volume of precipitation and meltwater generated over each of the basins draining to Lake Agassiz from Teller (1990) to illustrate the changing contribution of the various sources (B).

• Meltwater is the dominate source of water to Lake Agassiz for the Lockhart and Moorhead phases, but by the Emerson phase precipitation inputs are almost equally important.



- Estimate for the inferred isotopic composition of Lake Agassiz.
- Volumes of meltwater and precipitation estimated flowing to Lake Agassiz using calculations from Teller, 1990.
- Lake Agassiz volumes and surface areas from Leverington et al., 2000
- Major routings for overflow from Lake Agassiz.

Is our conceptual model consistent with what is known about climate during that period?

• During this period of increased summer insolation, temperatures remained cold over and immediately adjacent to the ice sheet, however, simulated summer temperatures are higher than present for most of North America including the areas of the lakes catchment area (Bartlein et al., 1998).

• The topography of the Laurentide Ice Sheet established a high-pressure centre located over Lake Agassiz resulting in anticyclonic surface winds over the lake (Bartlein et al., 1998, Hostetler et al., 2000).

• The dry, windy conditions over Lake Agassiz suggest that evaporative enrichment on par with what is currently measured in tundra to forest-tundra settings is not unreasonable.

• During the Lockhart and Emerson phases of Lake Agassiz the modelled lake surface areas range from 117,000 km² to 263,000 km² (Leverington et al., 2000) suggesting that the lake may have acted as a source of moisture for downwind areas, particularly in light of climate simulations suggesting moisture from southern and western areas may have been blocked (Hostetler et al., 2000)

Conclusions

• During the Lockhart phase conditions developed so that the lake was isotopically stratified, at least in the southern basin.

• The ranges for the archives available suggest at least a 6‰ enrichment of the shallow epilimnion waters relative to waters at depth in the lake in the southern basin.

• One explanation for the stratification is that the hypolimnion waters originate as very cold, sediment laden water issued directly from the ice front and continuing along the base of the lake as a density flow (originally proposed by Teller, 1976).

• We have shown that this enrichment can be accounted for by evaporation from the lake and its catchment area, however, changes in the relative contribution of meltwater and precipitation, and which drainage basins were contributing to Lake Agassiz were also likely contributing factors to the isotopic evolution of the lake.

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