



Geochemical constraints on the Laurentide Ice Sheet contribution to Meltwater Pulse 1A

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ABSTRACT

Planktonic and benthic $\delta^{18}\text{O}$ records adjacent to the runoff outlets of the Laurentide Ice Sheet (LIS) indicate that the LIS contributed to the abrupt ~ 20 m rise in sea level ~ 14.6 ka, Meltwater Pulse 1A (MWP-1A). However, the magnitude of the LIS contribution still remains unresolved. Here, I use a freshwater runoff–ocean mixing model to calculate the LIS meltwater required to explain the decreases in planktonic and benthic $\delta^{18}\text{O}$ observed during MWP-1A at the southern, eastern and northern runoff outlets of the LIS. Maximum LIS contributions in equivalent sea level rise for a 500-year long MWP-1A are 2.7 m discharged into the Gulf of Mexico as a combined hyperpycnal and hypopycnal flow, 2.1 m discharged into the North Atlantic, and 0.5 m into the Arctic Ocean, for a total LIS contribution of ≤ 5.3 m. A LIS contribution of $< 30\%$ to MWP-1A supports the hypothesis that a significant component of this MWP was sourced from the Antarctic Ice Sheet.

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1. Introduction

Meltwater Pulse 1A (MWP-1A) occurred ~ 14.6 ka and is an ~ 20 m rise in sea level in < 500 years (Fairbanks, 1989; Bard et al., 1990; Edwards et al., 1993; Hanebuth et al., 2000). Due to its large size, the Laurentide Ice Sheet (LIS) was originally assumed to be the sole source of MWP-1A (Fairbanks, 1989; Peltier, 1994). However, LIS margin reconstructions show relatively small margin retreat during MWP-1A (Fig. 1) and steady state ice sheet models suggest that only a fraction of this meltwater pulse was sourced from the LIS (Clark et al., 1996; Licciardi et al., 1998, 1999; Dyke, 2004), which implies a large contribution from the Antarctic Ice Sheet (Clark et al., 1996). Sea-level fingerprinting and earth model studies suggest that an Antarctic source could account for $\sim 75\%$ of the total sea level rise (Clark et al., 2002a; Bassett et al., 2005), although some LIS contribution cannot be excluded (Bassett et al., 2005).

Supporting a significant LIS contribution, one ice sheet modeling study reconstructed 8–10 m of MWP-1A coming from the LIS (Tarasov and Peltier, 2005, 2006), but still less than the LIS contribution of ~ 16.5 m in the ICE-5G model (Peltier, 2004, 2005). This large ICE-5G LIS contribution would cause a 0.36–0.38 Sverdrup (Sv , $10^6 \text{ m}^3 \text{ s}^{-1}$) increase in LIS meltwater discharge during the course of the event. During MWP-1A, LIS meltwater was routed to the ocean via three outlets, the southern outlet (Mississippi River)

to the Gulf of Mexico, the eastern outlet (Hudson and St. Lawrence Rivers) to the North Atlantic, and the northern outlet (Mackenzie River) to the Arctic Ocean (Fig. 1) (Licciardi et al., 1999; Tarasov and Peltier, 2005). Because a 0.36–0.38 Sv freshwater flux would force a reduction in Atlantic meridional overturning circulation (AMOC) strength (Stouffer et al., 2006) and AMOC increased during MWP-1A (Boyle and Keigwin, 1987; Weaver et al., 2003; McManus et al., 2004; Robinson et al., 2005), Tarasov and Peltier (2005, 2006) hypothesized that the meltwater discharged through the southern and eastern outlets (Fig. 1) entered the ocean as a dense, sediment laden, hyperpycnal flow along the ocean floor, which would presumably not affect AMOC. Note, however, that general circulation model simulations suggest that the southern outlet can only accommodate less than 6 m of sea level rise equivalent discharged as a hyperpycnal flow without reducing AMOC strength (Roche et al., 2007).

Reworked nannofossil records suggest increased southern outlet discharge during MWP-1A (Marchitto and Wei, 1995). Similarly, benthic foraminifera records from the Gulf of Mexico show a 0.9–2.3‰ decrease in $\delta^{18}\text{O}$ during MWP-1A (Fig. 2e), reflecting the input of ^{18}O -depleted terrestrial runoff and meltwater, and indicating that some portion of the LIS contribution entered the ocean as a hyperpycnal flow (Aharon, 2006). In contrast, grain size and sedimentation rate records from the eastern outlet indicate decreased sediment discharge, arguing against a hyperpycnal flow through the eastern outlet during MWP-1A (Keigwin and Jones, 1995). Nevertheless, there is a 0.69‰ light planktonic $\delta^{18}\text{O}$ anomaly observed adjacent to the eastern outlet at

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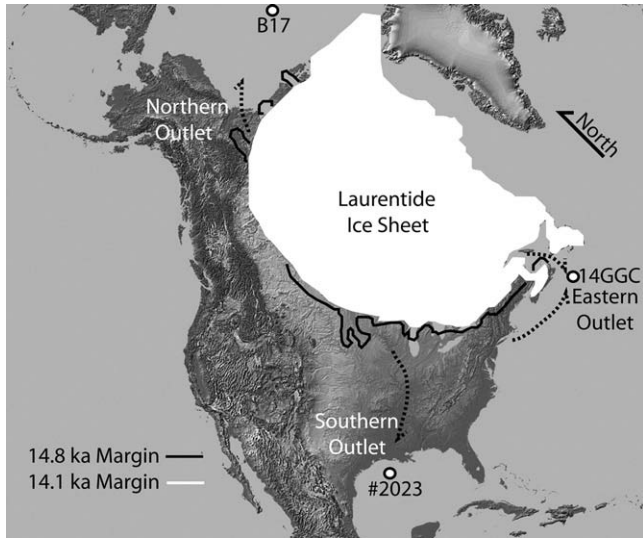


Fig. 1. Map of the Laurentide Ice Sheet extent ~ 14.1 ka (white line filled in) with the additional area covered by ice at ~ 14.8 ka indicated by the black solid lines (Dyke, 2004). Core locations are indicated by black and white dots; LOUIS Core #2023 (27.76°N , 92.59°W , 401 m water depth) (Aharon, 2006), OCE3326-14GGC (14GGC) (43.07°N , 55.83°W , 3525 m water depth) (Keigwin et al., 2005), and 94B-17 (B17) (81.27°N , 178.97°W , 2217 m water depth) (Poore et al., 1999; Hall and Chan, 2004). Dashed lines indicate freshwater routing directions to the southern, eastern and northern outlets.

~ 14.5 ka, suggesting increased freshwater discharge or warming during MWP-1A (Fig. 2c) (Keigwin et al., 2005). A 0.75‰ decrease in planktonic $\delta^{18}\text{O}$ in the Arctic Ocean has been correlated with MWP-1A and indicates increased discharge through the northern outlet (Poore et al., 1999; Hall and Chan, 2004) (Fig. 2b). In contrast, iceberg discharge from the LIS into the Labrador Sea decreased and planktonic $\delta^{18}\text{O}$ increased during MWP-1A implying that the northeastern LIS did not contribute significantly to this MWP (Andrews and Tedesco, 1992; Clark et al., 1996; Hillaire-Marcel and Bilodeau, 2000).

Here, I use a freshwater runoff-ocean mixing model to determine the amount of LIS meltwater and thus the LIS contribution to MWP-1A through the southern, eastern and northern outlets recorded by these light planktonic and benthic $\delta^{18}\text{O}$ anomalies (Figs. 1 and 2). Assuming that no temperature adjustments are necessary (see Section 3), these records suggest increased runoff from the LIS during part or all of MWP-1A through the main outlets. This analysis indicates, however, that the contribution from the LIS was only a small fraction ($<30\%$) of the total sea level rise during MWP-1A, suggesting that the LIS was not the primary source of this MWP.

2. Methods and results

A freshwater runoff-ocean mixing model is employed to calculate the amount of meltwater from the LIS required to explain the decreases in $\delta^{18}\text{O}$ at the various runoff outlets (Aharon, 2003, 2006; Carlson et al., 2007). The $\delta^{18}\text{O}$ of runoff (δ_r) (combined ice melt and precipitation–evaporation (P–E)) is calculated as Eq. (1):

$$\delta_{r-x} = \frac{f_{p-x} \times \delta_p + f_{i-x} \times \delta_i}{f_{p-x} + f_{i-x}} \quad (1)$$

where f_{p-x} (Sv) is the flux of P–E and δ_p its $\delta^{18}\text{O}$, and f_{i-x} (Sv) is the flux of LIS meltwater and δ_i its $\delta^{18}\text{O}$, at time step x ($x = 1$ for pre-MWP-1A, $x = 2$ for during MWP-1A). With the exception of the southern outlet records (see below), f_{p-x} is considered constant for

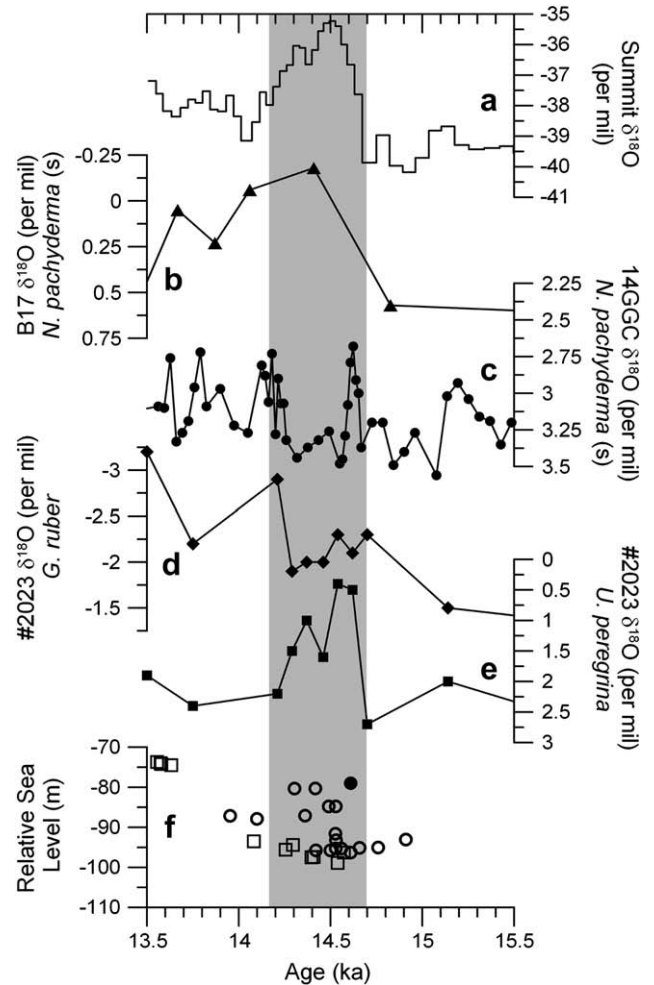


Fig. 2. Deglacial runoff records (see Fig. 1), GISP2 temperature and relative sea level. (a) GISP2 $\delta^{18}\text{O}$ (Grootes et al., 1993). (b) $\delta^{18}\text{O}$ of *N. pachyderma* (s) recording runoff to the northern outlet (B17, triangles) (Poore et al., 1999; Hall and Chan, 2004). (c) *N. pachyderma* (s) $\delta^{18}\text{O}$ recording runoff to the eastern outlet (14GGC, circles) (Keigwin et al., 2005). (d) *G. ruber* $\delta^{18}\text{O}$ recording hypopycnal runoff through the southern outlet (#2023, diamonds) (Aharon, 2003, 2006). (e) *U. peregrina* $\delta^{18}\text{O}$ recording hyperpycnal runoff to the southern outlet (#2023, squares) (Aharon, 2006). (f) Relative sea level data: open squares corals from Barbados (Bard et al., 1990; Peltier and Fairbanks, 2006), open circles mangroves from Sunda Shelf (Hanebuth et al., 2000), and solid circles corals from Huon Peninsula (Edwards et al., 1993). The $\delta^{18}\text{O}$ records are presented on their original published, calibrated age models. Gray bar denotes the timing of Meltwater Pulse 1A.

both time steps (Licciardi et al., 1999). Prior to MWP-1A, f_{i-1} is derived from Licciardi et al. (1999), with the exception of the southern outlet benthic record. During MWP-1A, f_{i-2} is the model-tuned parameter. δ_p and δ_i are considered constants. The mixture $\delta^{18}\text{O}$ at the core site (δ_{m-x}) at time x is calculated as Eq. (2):

$$\delta_{m-x} = \frac{f_o \times \delta_o + (f_{p-x} + f_{i-x}) \times \delta_{r-x}}{f_o + f_{p-x} + f_{i-x}} \quad (2)$$

where f_o (Sv) is the ocean flux and δ_o the ocean $\delta^{18}\text{O}$. Eq. (3) is used to determine the $\Delta\delta^{18}\text{O}$ observed during MWP-1A:

$$\Delta\delta^{18}\text{O} = \delta_{m-2} - \delta_{m-1} \quad (3)$$

with subscripts $m-2$ and $m-1$ indicating the δ_m during MWP-1A ($x = 2$) and before MWP-1A ($x = 1$). The model is forced by varying f_{i-2} in Eqs. (1) and (2) in the time step during MWP-1A ($x = 2$) so

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