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Was the Laurentide Ice Sheet significantly reduced during Marine Isotope Stage 3?

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ABSTRACT

Accurately reconstructing the paleogeography of the Laurentide Ice Sheet (LIS) during Marine Isotope Stage 3 (MIS 3; ca. 57,000 to ca. 29,000 yr B.P.) is critical for understanding glacial growth toward the Last Glacial Maximum (LGM), refining sea-level histories and studying the Earth system response to rapid climate change events. Here, we present a geochronological data set useful for testing hypotheses of global sea level and refining ice sheet configuration through this interval. Data (n = 735) span the entire MIS 3 interval and consist of ^{14}C determinations (n = 651), cosmogenic exposure ages (n = 52), and optically stimulated luminescence dates (n = 32). On that basis, we hypothesize that the central region of the LIS underwent a dramatic reduction in ice from ~52–40 ka. Key to this hypothesis are geological records at sites in the Hudson Bay

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Lowlands that suggest a marine incursion and development of terrestrial landscapes. We show that these landscapes are consistent with recently published glacial isostatic adjustment predictions that include widespread deglaciation of the eastern (Labrador) sector of the LIS with ice build-up over the western (Keewatin) sector at 42 ka. Ice growth from this minimum toward the LGM is likely to have been rapid. The agreement between this data set and modeling predictions prompts the reassessment of key Late Pleistocene records, including Heinrich Events, loess deposition in the continental United States and sedimentological records from the Gulf of Mexico.

INTRODUCTION

The Laurentide Ice Sheet (LIS) was the predominant ice mass over North America through the Late Pleistocene (from ~125 to ~7 ka before present). Despite the importance of this ice sheet, its evolution is very poorly constrained prior to the Last Glacial Maximum (LGM; ~26 ka; Clark et al., 2009), especially during the interstadial of Marine Isotope Stage 3 (MIS 3; 59–27 ka; Lisiecki and Raymo, 2005). Refining ice sheet history through this interval will provide much-needed constraint on glacial growth toward the LGM; will aid in refining highly variable estimates of global mean sea level (GMSL; estimates range from −80m to −30m; Siddall et al., 2008) and; will offer a critical long-term perspective on the response of the Earth System to rapid climate events (e.g. Dansgaard-Oeschger and Heinrich events).

The most recent evaluation of geological data (via a synthesis of ~200 radiocarbon dates; Dyke et al., 2002) inferred that the LIS reached its MIS 3 minimum extent between 30–27 ka and was moderate in size, covering most of eastern and central Canada (Fig. 1). This ice configuration is often taken to represent the minimum extent during the whole of MIS 3. However, since the work of Dyke et al. (2002), significantly more sites have been assigned to MIS 3. Notably, recent chronostratigraphic work in the Hudson Bay Lowlands, Canada (Dalton et al., 2016), lying at the geographic center of the LIS, suggests a significantly earlier and more pronounced interstadial minimum than hitherto recognized. Here, we (1) present an updated synthesis and evaluation of geological data for delineating the ice margin through the MIS 3 interval; (2) discuss the strength of geochronological data that support dramatic ice recession during MIS 3, and; (3) test the feasibility of this hypothesis by comparing geochronological data from the Hudson Bay Lowlands (a coastal plain where marine/terrestrial transitions are directly controlled by the interplay between ice loading, isostatic adjustment and sea level) with outputs from a recently published glacial isostatic adjustment (GIA) model for this time interval (ICE-PC2; Pico et al., 2017).

SYNTHESIS OF MIS 3 GEOLOGICAL DATA

The spatial and temporal extent of MIS 3 geochronological data[1] in the glaciated region (n = 735) has improved substantially since the last collective examination by Dyke et al. (2002). Available data now span all of MIS 3, with the majority of ages (56%) falling between 37.5–47.5 ka (Fig. 1). These sites document diverse and widespread ecosystems during MIS 3 (e.g., boreal forest, peatlands) in regions that were later overrun by ice during the LGM. Samples consist of radiocarbon determinations (88.6%, n = 651), cosmogenic exposure ages (7.1%; n = 52) and luminescence dates (4.4%; n = 32). Preservation of MIS 3 sediments is largely in geological contexts that offered protection from LGM glacial advance, such as river valleys, coastal cliffs and deep lacustrine environments. For this reason, pre-LGM stratigraphic records are rarely preserved on the

Canadian Shield, a granitic geological unit covering a large swath of Canada (Fig. 1; gray shading). Geochronological data from much of the glaciated region are now of sufficient quality to track landscape evolution through MIS 3 at millennial-scales (e.g. Hughes et al., 2016), critical for testing the validity of glaciological models that have been developed for this interval (e.g., Stokes et al., 2012).

EVIDENCE SUPPORTING DRAMATIC REDUCTION OF THE LAURENTIDE ICE SHEET

Geochronological data from the Hudson Bay area (n=35) suggest that the LIS underwent large-scale deglaciation during MIS 3. Data from this region (^{14}C and optically stimulated luminescence dating of marine and fluvial strata) support a marine incursion between 52 and 42 ka, along with the subsequent development of terrestrial landscapes during the interval of 48–40 ka (Dalton et al., 2016). Deglaciation in this central region was first hypothesized in the 1980s (Andrews et al., 1983; Dredge and Thorleifson, 1987). However, at that time, this hypothesis was largely dismissed based on suspected inaccuracy of chronological techniques, especially the reliance on ^{14}C dating of shells and amino acid dating. Now, multiple radiocarbon age attempts per site (on wood, where possible), along with confirmatory OSL dating suggests that the MIS 3 age assignment may indeed be correct.

The hypothesis of a significantly reduced ice sheet can be tested by comparing geochronological data from key areas to predictions from a GIA model. In this regard, we note that available geochronological data from the Hudson Bay Lowlands offer a good fit with a glacial-isostatic adjustment simulation forced by ICE-PC2, an ice loading history with widespread deglaciation of the eastern sector of the LIS during MIS 3 (to accommodate high sea level markers of this age along the east coast of the United States) with ice build-up preferentially over Keewatin at 42 ka (Fig. 2; Pico et al., 2017). Notably, the marine-estuarine deposits on the Severn River dated to 42–52 ka (Dalton et al., 2016; Forman et al., 1987), align well with the simulated paleo-shoreline in that region. Further, terrestrial sites dated to this interval (11-PJB-186, 11-PJB-020, 12-PJB-007; Dalton et al., 2016) are all located at sub-aerial elevations in the simulation (Fig. 2A). The discrepancy between the simulated location of the shoreline and the marine sites suggests that adjustments to the ice load may be necessary to accommodate all data, within error. The ICE-PC2 simulation is consistent with mid-MIS 3 dates on non-glacial deposits in the Hudson Bay Lowlands and adopts a mid-MIS 3 relative sea-level highstand at 44 ka with a GMSL value of –38 m (Fig. 2B; Pico et al., 2016; additional details in Data Repository[1]).

DISCUSSION

In support of our hypothesis, insolation in the Northern Hemisphere during MIS 3 was at its most stable point for the entire Late Pleistocene, and slightly higher than present-day (Fig. 3A; Berger and Loutre, 1991) which may suggest that climate forcing was sufficient to drive a prolonged, dynamic reduction of continental ice. This insolation promoted a pronounced recession in the Fennoscandian Ice Sheet (Helmens and Engels, 2010). Fluctuations in global atmospheric methane during MIS 3 (Fig. 3B; Loulergue et al., 2008) could be partly explained by the development of northern peatlands in the Hudson Bay Lowlands during that time (Dalton et al., 2017). Also noteworthy are perturbations in the $\delta^{13}C$ and $\delta^{18}O$ record from Crevice Cave (Dorale et al., 1998) and Devils Hole (Landwehr et al., 2011) during MIS 3 (Figs. 3C–E) that suggest pronounced changes in North American precipitation regimes and vegetation during that interval, possibly as a result of reduced and/or highly variable continental ice. Our hypothesis is also supported by geomorphological records (striations and glacial lineations; Kleman et al., 2010) suggesting the eastern and western sectors of the LIS were independent for an extended period prior to the LGM, which some numerical modeling has failed to reproduce (Stokes et al., 2012) largely due to a lack of geochronological constraints.

An important corollary of our hypothesis is that it prompts the reassessment of key Late Pleistocene records. Reduced continental ice likely caused meltwater to flow northward toward the Arctic Ocean during some of MIS 3. Thus, any meltwater-based control over Dansgaard-Oeschger Events through this interval (Fig. 3F) must have been dominated by northward drainage perturbations (as opposed to alternating with the Gulf of Mexico; Clark et al., 2001). Geological records from the Mississippi River that have been widely assigned to ice advance into the mid-continent may also require reinterpretation; these include the widespread Roxana Silt loess deposit (~60–30 ka interval; see Forman and Pierson, 2002, and references therein), pronounced fluvial aggradation along the Mississippi River (Rittenour et al., 2007) and sedimentological shifts in the Gulf of Mexico (Sionneau et al., 2013). Possible non-glacial explanations for the increased sediment flux and aggradation include changes in catchment vegetation, seasonality of rainfall and variable hydrology rather than a direct meltwater signature (Leigh et al., 2004). Our hypothesis also suggests that full glaciation of Hudson Bay is not necessarily a prerequisite for Heinrich Events given that both Heinrich Event 5 (H5; 50–47 ka) and 4 (H4; 40.2–38.3 ka) (Sanchez Goñi and Harrison, 2010) took place around the time interval of interest. It is possible that Baffin Island, Southampton Island or Labrador could have been active contributors to ice rafting events in the north-eastern LIS (Hefter et al., 2017; Roy et al., 2009). In this case, adjustments to the modeled Labrador sector may be needed (Fig. 2).

Growth of the LIS from this receded position was likely very rapid. Using a combination of geological constraints and numerical modelling, recent studies have demonstrated that the Labrador sector may have expanded >1000 km southward by ~39–37 ka (Carlson et al., 2018; Pico et al., 2018a,b). We acknowledge that continued work is needed to understand the evolution of the MIS 3 landscape, study the impact of reduced continental ice on global systems, and delineate precise ice growth toward the LGM. Nevertheless, the agreement between available geological data, GMSL and geophysical modelling supports a significant reduction of the LIS during MIS 3.

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FIGURE CAPTIONS

Figure 1. Map showing the glacial outline of the Laurentide Ice Sheet at 30–27 ka (after Dyke et al., 2002), overlaid with currently available geological data from Marine Isotope Stage 3 (MIS 3; n = 735). Note the large number of dates that lie inside the MIS 3 extent (e.g., Hudson Bay Lowlands), which likely indicate an earlier and significantly more pronounced ice reduction prior to the 30–27 ka interval. Shaded region is the Canadian Shield. Last Glacial Maximum (LGM) ice extent after Dyke (2004). Some sites have multiple ages that overlap on this plot; all geological data are available in Table DR1. Inset figure shows the age distribution of chronology data spanning MIS 3 with data binned into 2500-year increments. NB: data plotted here are not necessarily in conflict with the work of Dyke et al., (2002) since the ice perimeter in the 2002 study was intended to represent only the 30 –27 ka interval.

Figure 2. Predicted North American topography at 42 ka using ice history ICE-PC2, overlaid with available geological data from the Hudson Bay Lowlands (colored as in Fig. 1). Note the agreement between available geochronological data and the numerical simulation, which supports the hypothesis of reduced ice cover during this interval. Present-day coastline shown by black contours. Shoreline at 42 ka (0 m contour) shown by gray outline. A: Zoom into local topography of the Hudson Bay Lowlands. B: Global mean sea level change adopted in ice history ICE-PC2 (Pico et al., 2017).

Figure 3. Paleoclimate and orbital parameters spanning the Late Pleistocene (100 ka to present-day). A: July insolation at 60°N after Berger and Loutre (1991). B: Atmospheric methane estimates from the EPICA Dome C ice core (Loulergue et al., 2008). C–D: Carbon and oxygen isotope data from Crevice Cave (Dorale et al., 1998). E–F: Oxygen isotope data from Devils Hole speleothem (Landwehr et al., 2011) and a northern Greenland ice core (North Greenland Ice Core Project members, 2004). Arrows indicate Heinrich Events (Sanchez Goñi and Harrison, 2010).

1GSA Data Repository item 2018xxx, table of geochronological data (n=735) and description of the geophysical model, is available online at http://www.geosociety.org/datarepository/2018/, or on request from editing@geosociety.org.

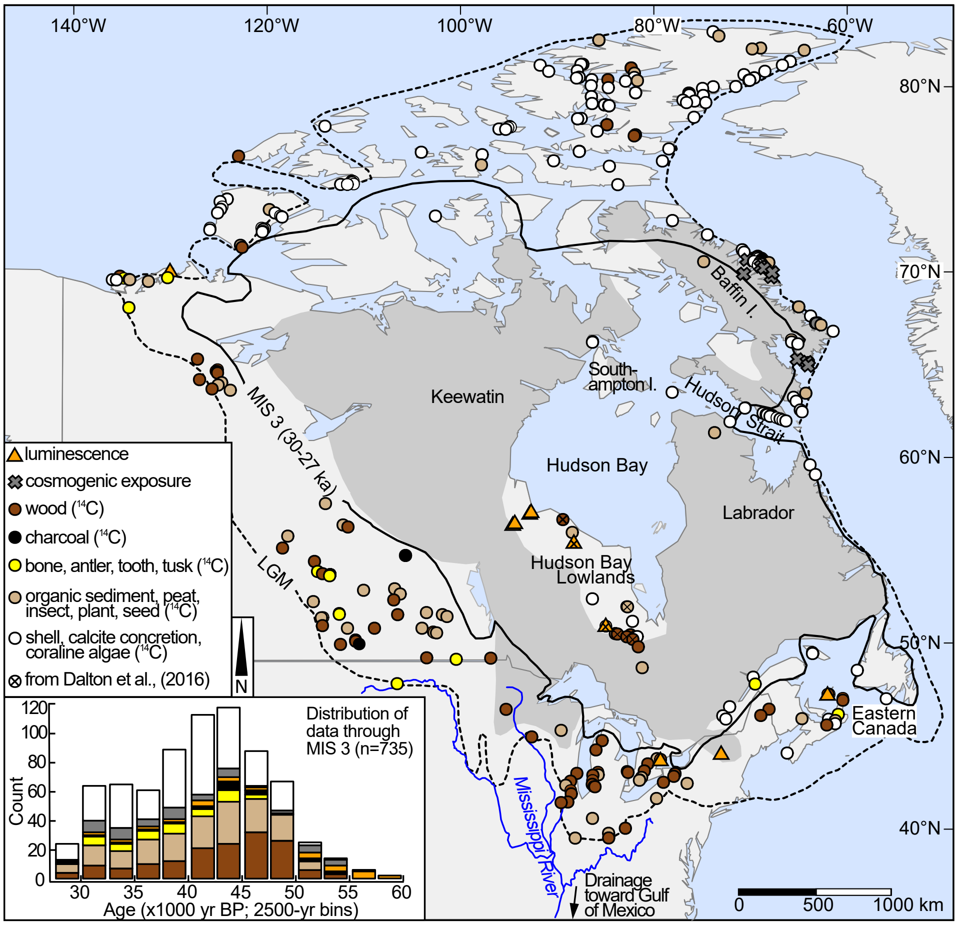

Figure 1

Dalton et al. (in press)

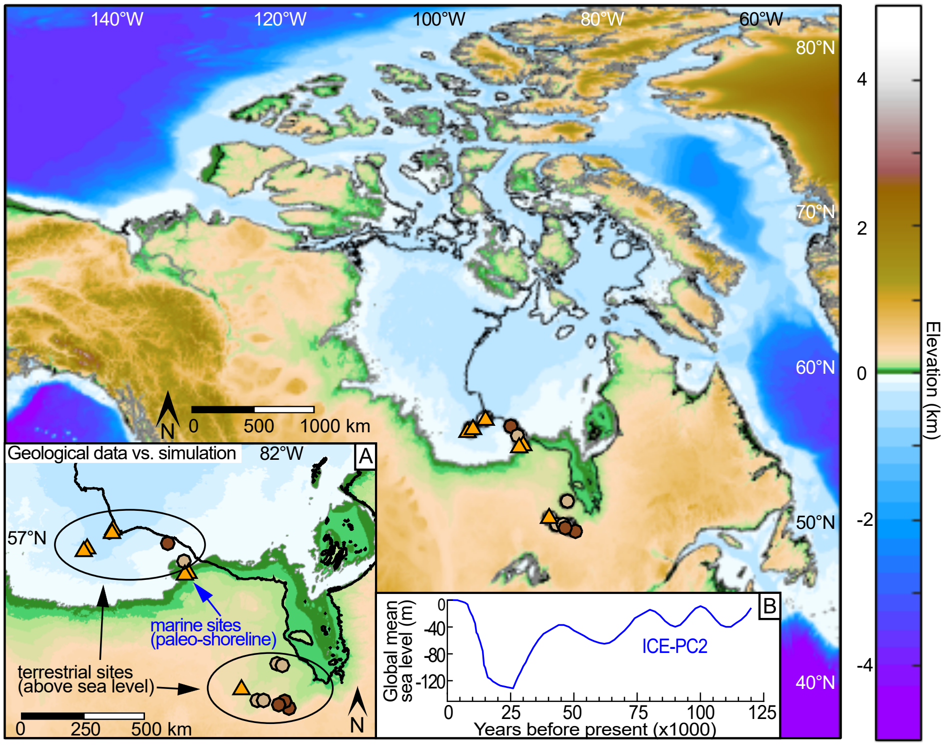

Figure 2

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Figure 3

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