Rapid Laurentide ice-sheet advance towards southern last glacial maximum limit during marine isotope stage 3

Anders E. Carlson a, *, Lev Tarasov b, Tamara Pico c

a College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, USA
b Department of Physics and Physical Oceanography, Memorial University, Canada
c Department of Earth and Planetary Sciences, Harvard University, USA

Abstract

Marine isotope stage (MIS) 3 (~58–28 ka) is a period of intermediate global ice volume between MIS 4 and the last glacial maximum of MIS 2. Here we report geologic evidence for southern Laurentide ice-sheet rapid growth to near its last glacial maximum extent after a period with limited ice in the southernmost Hudson Bay lowland. A 14C age on wood in lacustrine sediments interbedded with glacial tills in central-eastern Wisconsin dates a Laurentide ice-sheet advance southwards to an extent at least equivalent to at least its ~17 ka deglacial limit by 39.1 ± 0.4 ka. This advance ended before 30.4 ± 0.9 ka based on another 14C date on wood in lacustrine sediment overlying the till layers. This advance is consistent with 14C ages from Michigan and Iowa, and Gulf of Mexico runoff records that support a concurrent southern Laurentide ice-sheet advance. We infer changes in North American ice volume using ice-sheet model simulations from a large ensemble that are consistent with 14C-data and Gulf of Mexico-discharge constraints. The simulations show the Laurentide ice sheet growing from a volume equivalent to 25–30 m of global mean sea level (GMSL) before ~40 ka to 40–45 m of GMSL at ~40 ka, and reaching 65–70 m GMSL by ~30 ka, consistent with glacial isostatic adjustment assessments of near-to intermediate-field sea-level data. We thus show from our terrestrial field data and ice-sheet model simulations that an individual ice sheet can grow rapidly, which has only been inferred previously for global ice volume from GSML records.

© 2018 Elsevier Ltd. All rights reserved.

1. Introduction

Following a relative ‘glacial’ period during marine isotope stage (MIS) 4 (~68–58 ka), the globe entered the ‘interglacial’ period of MIS 3 (~58–28 ka) (e.g., Lisiecki and Stern, 2016). Significant ice volume remained in boreal latitudes during MIS 3 that then expanded to its last glacial maximum (LGM) during MIS 2 (e.g., Clark et al., 1993, 2009; Dyke et al., 2002; Stokes et al., 2012; Lambeck et al., 2014). A summary of benthic δ18O and relative sea-level records by Siddall et al. (2008) suggested a global terrestrial ice volume relative to present during MIS 3 that was equivalent to an ~60–80 m fall in global-mean sea level (GMSL), which agrees with Lambeck et al. (2014). In contrast, a recent glacial isostatic adjustment (GIA) analysis of sea-level indicators in the Bohai Sea and the U.S. mid-Atlantic suggested a MIS 3 GMSL highstand of approximately ~38 m during the time interval 50–35 ka (Pico et al., 2016, 2017).

Dalton et al. (2016) recently argued for ice-free conditions in the southernmost Hudson Bay lowland during MIS 3 prior to ~40 ka based on finite accelerator mass spectrometry (AMS) 14C ages (Fig. 1) and other chronologic constraints, with ice-free conditions extending further to the south (e.g., Bajc et al., 2015). This agrees with earlier interpretations of Thorleifson et al. (1992) of glacial-lacustrine sediments between an LGM till and an older till unit, and other studies that lacked more precise direct chronologic controls on the glacial-lacustrine unit (e.g., Skinner, 1973; Dredge and Thorleifson, 1987; Allard et al., 2012; Dubé-Loubert et al., 2013). Farther north, such proglacial/interglacial sediments are lacking, implying continued ice cover of the central to northern Hudson Bay lowland during MIS 3 (e.g., Nielsen et al., 1986; Dredge et al., 1990; Thorleifson et al., 1992; Roy, 1998; Carlson et al., 2004). After this retracted ice interval of mid MIS 3, Dyke et al. (2002) estimated Laurentide ice-sheet extent during late MIS 3 with an ice margin roughly following the outline of the Canadian Shield.
Uncertainties in ice-sheet extent prior to the LGM are largely due to the destruction of glacial evidence by advancing ice during MIS 2 as well as the limitation of dating techniques (Clark et al., 1993; Dyke et al., 2002; Kleman et al., 2010; Syverson and Colgan, 2011; Stokes et al., 2012; Hughes et al., 2015). The growth of ice-sheet volume towards the LGM is also poorly constrained prior to ~26 ka and would require rapid growth of ice during the latter part of MIS 3 to fit the GMSL fall from approximately /C038 m at ~44 ka to approximately /C0130 m at the LGM (<26 ka; Clark et al., 2009; Austermann et al., 2013; Lambeck et al., 2014) proposed in the model of Pico et al. (2017). Rapid growth of global ice volume has previously been inferred from far-field sea-level indicators (e.g., Clark et al., 2009; Lambeck et al., 2014) but has yet to be assessed at an individual ice-sheet scale. The one exception is the Eurasian ice sheets, which contained <6 m of GMSL across this time period (Hughes et al., 2015). Consequently, GMSL changes during MIS 3 were likely driven by changes in North American and/or Antarctic ice-sheet volume.

Here we discuss evidence for a MIS 3 Laurentide ice-sheet advance in Wisconsin that is 14C dated by AMS (Fig. 1). We use these new age constraints to identify North American ice-sheet model simulations that match the geologic record, and document North American ice-sheet evolution across the latter part of MIS 3. Our findings suggest that at least the southern Laurentide ice sheet advanced to near its LGM extent well prior to the classically defined LGM of 26–19 ka (Clark et al., 2009).

2. Plymouth, Wisconsin glacial sediments

Four rotosonic industry boreholes were drilled in 1999 to examine groundwater contamination from a landfill near Plymouth, Wisconsin (43.75°N, 87.98°W). We were allowed to collect limited samples from the boreholes and describe the units (see Carlson et al., 2011). Additional sampling was not allowed by the industry contractor. Two of the boreholes extended to bedrock with the longest sampling ~100 m of sediment above bedrock. Below the LGM glacial till (the New Berlin till; ~65 m thick) is a sequence of lacustrine sediment (~15 m thick) that is underlain by three till layers interbedded with proglacial silts, sands and gravels (combined thickness of ~24 m). The lower till layers were reddish-gray and had 34±50% sand, 30±46% silt and 15±26% clay content. This lowest glacial unit rests upon dolomite bedrock and was informally named the Plymouth tills (Carlson et al., 2011). An AMS 14C age on wood (Fagus) from a silt layer interbedded between the two lower Plymouth till units dates the till layers to 39.1±0.4 ka (34.61±0.39 14C ka; Beta-129847). Another AMS 14C age on wood (unidentified) from the lacustrine sequence above the three Plymouth tills dates the end of till deposition to before 30.4±0.9 ka (26.40±0.92 14C ka; OS-24520). These 14C dates were calibrated with IntCal13; reported uncertainties for these dates and other dates discussed below are 1 sigma.

The location of these glacial till layers is within the LGM extent of the Lake Michigan lobe of the Laurentide ice sheet suggesting...
that they were deposited by a MIS 3 advance of this lobe southward through the Lake Michigan basin (Fig. 1). The Plymouth site was ice-free by ~17 ka during the last deglaciation (Attig et al., 1985; Maher and Mickelson, 1996; Dyke, 2004; Ullman et al., 2015), suggesting a Laurentide ice-sheet advance in eastern Wisconsin by ~39 ka equivalent to at least its ~17 ka deglacial extent (Fig. 1). Other tills below the LGM New Berlin till are found in central-eastern Wisconsin but are not dated, confounding the further refinement of the extent of this MIS 3 glacial advance (Carlson et al., 2011).

3. Ice-sheet model simulations

We utilize the ensemble of North American ice-sheet model simulations of Tarasov et al. (2012) that were discussed in Stokes et al. (2012) to convert our inferred extent of the southern Laurentide ice sheet into GMSL. These simulations were forced by a climate index approach, scaling a weighted average of the LGM climate anomalies from PMIP II general circulation climate models relative to present-day climate using a Greenland ice-core based index (Tarasov et al., 2012). For the pre-LGM, the climate forcing was temporally modified to better fit the general evolution of GMSL (Stokes et al., 2012). We sieved this ensemble of glacial-cycle simulations to identify those that have ice-free conditions in the southernmost Hudson Bay lowland when indicated by AMS 14C ages (Figs. 1 and 2a) (Dalton et al., 2016), and a subsequent ice advance to cover the Plymouth tills site and the AMS 14C ages in Michigan from below pre-LGM till (summarized by Colgan et al., 2015) (Figs. 1 and 2a). We also extract from these simulations the meltwater discharge down the Mississippi River to the Gulf of Mexico to compare with a Gulf of Mexico δ18Osw runoff record (Hill et al., 2006) (Figs. 2b and 3). We do not convert changes in δ18Osw into changes in meltwater discharge (e.g., Carlson, 2009) as the Laurentide δ18O-ice end member likely changed across these multi-millenial timescales (e.g., Vetter et al., 2017).

We considered eight simulations from the North American ice-sheet-complex ensemble of ten thousand simulations (Stokes et al., 2012; Tarasov et al., 2012) that best fit the above-mentioned chronological constraints (Figs. 1 and 4b, c) and that also perform reasonably well against LGM and deglacial geological data (relative sea level, marine limit, present-day vertical velocities, lake strand lines, ice-margin chronology) as discussed in Tarasov et al. (2012) and Stokes et al. (2012). The North American ice-volume evolution (in m GMSL) of these simulations is shown in Fig. 2c while the area/thickness of one simulation (ID 5919) is shown in Fig. 4b (44 ka) and Fig. 4c (40 ka).

Comparison of the resulting simulated meltwater discharge to the Gulf of Mexico with the Hill et al. (2006) Gulf of Mexico δ18Osw record based on Globigerinoides ruber (pink) (Fig. 3a), which lives in the summer, identifies two of the eight simulations that best agree with the geologic record. While all eight simulations have meltwater events to the Gulf of Mexico, only simulations 5919 and 5939 agree in timing with the decreases in δ18Osw (Fig. 3a) with smoothing to a millennial timescale (Hill et al., 2006). The raw δ18Osw runoff record (Hill et al., 2006) is highlighted in black (5939; see Fig. 3). The two simulations that match the Gulf of Mexico meltwater events (5919 & 5939) to de...
Two conventional radiocarbon ages from above this Lake Michigan lobe till unit date the advance ending before 37.4 ± 2.3 ka, noting the added inherent uncertainty in conventional 14C ages (Kehew et al., 2005; Colgan et al., 2015). Deposition of the Plymouth tills may also be concurrent with Superior lobe ice advance that resulted in the deposition of the Roxana loess in the Mississippi River valley after −45 k (Fig. 1) (Clark et al., 1993; Syverson and Colgan, 2011; Muhs et al., 2018). Similarly, an advance of the Des Moines lobe into Iowa is 14C dated to after −41 ka that ended by −29 ka (Fig. 1) (Kerr et al., 2017; Muhs et al., 2018).

Meltwater from the Lake Michigan, Superior and Des Moines lobes would drain through the Mississippi River into the Gulf of Mexico because the advance of the Lake Michigan lobe into Lake Michigan that we document would block eastward meltwater drainage via the lower Great Lakes forcing drainage southwards (Fig. 1) (e.g., Hansel and Mickelson, 1988; Licciardi et al., 1999). Our 14C constraints for Plymouth tills deposition (along with the advance of the other ice lobes) is concurrent with decreased δ18Osw in the Gulf of Mexico that is interpreted to predominantly record advance of the Laurentide ice sheet into the Mississippi River drainage basin and attendant addition of 18O-depleted meltwater to the river (Fig. 2a and b) (Kennett and Shackleton, 1975; Leventer et al., 1982; Hill et al., 2006; Carlson, 2009; Williams et al., 2012; Wickert et al., 2013; Wickert, 2016; Vetter et al., 2017).

Southern Laurentide ice-sheet advance in the latter part of MIS 3 must have been rapid. Finite AMS 14C dates from the southernmost Hudson Bay lowland (Dalton et al., 2016) suggest ice-free conditions up until −40 ka (Fig. 1) (Skinner, 1973; Dredge and Thorleifson, 1987; Thorleifson et al., 1992; Allard et al., 2012; Dubé-Loubert et al., 2013). This is the region from which MIS 3 ice-flow indicators suggest ice advance to central Wisconsin and Michigan would be sourced (e.g., Thorleifson et al., 1992; Veillette et al., 1999; Klemman et al., 2010; Dubé-Loubert et al., 2013). The youngest MIS 3 AMS 14C date from the southernmost Hudson Bay lowland is 37.6 ± 0.9 ka (Figs. 1 and 2a), which is consistent with our AMS 14C date from the Plymouth tills of 39.1 ± 0.4 ka, when two sigma uncertainties are considered. One additional 14C date from the southernmost Hudson Bay lowland is −28.6 ka, but samples adjacent to this date yield infinite 14C ages suggesting this sample is anomalous. The youngest robust AMS 14C age from the southernmost Hudson Bay lowland and the older Plymouth tills age therefore imply minimum ice-margin advance rates of −800 km ka −1 (2

4. Discussion and conclusions

With the Plymouth tills likely deposited by the Lake Michigan lobe, one would expect to find an equivalent till unit on the eastern side of Lake Michigan in western Michigan. Colgan et al. (2015) summarized the pre-LGM stratigraphy of western Michigan and suggested ice-free conditions until after −29 ka. However, the youngest 14C date constraining this range falls outside the −17 ka Lake Michigan lobe limit and thus does not conflict with our findings. Indeed, four AMS 14C ages below a pre-LGM till layer, which are within the 17-ka ice-margin extent, constrain a MIS 3 Lake Michigan lobe advance to after 41.9 ± 0.5 ka (Figs. 1 and 2a) (Monaghan et al., 1986; Colgan et al., 2015).
American ice-sheet volume is still slower than the average and similar to the end of the LGM (Ullman et al., 2015). Pollen data from that the advance was a response to an external forcing mechanism, 'ice-sheet model also simulates (Fig. 4b). These local ice caps could Thorleifson (1987) hypothesized that mid MIS 3 ice caps may coalesce with the larger ice sheet as the latter expands (Fig. 4c) to for the rapid ice growth inferred from the GIA model and U.S. east coast is most sensitive. The proposed ice-loading history is consistent with an ice-free southernmost Hudson Bay lowland before ~40 ka (Fig. 4a), with the Laurentide ice sheet containing ~16 m GMSL at ~44 ka followed by rapid Laurentide ice-sheet growth to reach its LGM volume by ~26 ka (Fig. 2c) (Clark et al., 2009).

In Fig. 2c, we compare the Laurentide ice-volume evolution of 5919 & 5939 with the Laurentide ice-volume history of Pico et al. (2017). The two GMSL histories differ by <20 m before 38 ka, with the Pico et al. (2017) falling between the 5919 & 5939 histories after 38 ka (Fig. 2c). In terms of ice extent before 40 ka (Fig. 4), there is disagreement on the amount of ice in the western Canadian Cordillera. However, east of ~120°W the two different approaches show a similar pattern with ice volume located mainly in the central to northern Hudson Bay and its lowland, which is consistent with geologic evidence for ice cover and deposition of rhythms in the southernmost Hudson Bay lowland (e.g., Skinner, 1973; Dubé-Loubert et al., 2013). Both ice histories include a glaciated Hudson Strait (Fig. 4a and b), which would allow ice-sheet discharge of detrital carbonate during the Heinrich events of MIS 3 (e.g., Bond et al., 1992; Hemming, 2004; Channell et al., 2012). The 5919 ice-sheet model simulation has more extensive ice over eastern Labrador (Fig. 4b), which would agree with Laurentide ice-sheet erosion records from the Labrador Sea (e.g., Channell et al., 2012). Consequently, these ice-sheet model simulations provide support for the rapid ice growth inferred from the GIA model and U.S. east coast-sea-level data (Pico et al., 2017), as they demonstrate the physical potential for rapid ice-sheet growth. Dredge and Thorleifson (1987) hypothesized that mid MIS 3 ice caps may have existed outside the contiguous Laurentide ice sheet, which the ice-sheet model also simulates (Fig. 4b). These local ice caps could promote such rapid ice-volume growth as these local ice caps can coalesce with the larger ice sheet as the latter expands (Fig. 4c) to the late MIS 3 extent of Dyke et al. (2002). While we use the term ‘rapid growth’, we note that the simulated growth of North American ice-sheet volume is still slower than the average and peak rates deglacial North American ice-volume loss (Tarasov et al., 2012).

We conclude by asking what forcing may have driven this MIS 3 advance of the southern Laurentide ice sheet. The advance of multiple southern Laurentide ice-sheet lobe after 40 ka suggests that the advance was a response to an external forcing mechanism, similar to the end of the LGM (Ullman et al., 2015). Pollen data from Iowa indicate the establishment of spruce by ~39 ka, which may extend to Illinois and Wisconsin, suggesting colder and wetter climate conditions that are conducive for ice-sheet growth (Clayton et al., 2001; Baker et al., 2015). We note that atmospheric CO2 also declined on a multi-millennial timescale over MIS 3 (Fig. 2d) while boreal summer insolation increased 45–35 ka before dropping at the end of MIS 3 (in Fig. 2e we show June 21 intensity but a similar evolution is in the summer average). Nevertheless, what drove this colder and wetter climate, and potentially southern Laurentide ice-sheet advance, is difficult to discern at present and will require global climate model simulations across MIS 3 with transient changes in Earth’s orbit and greenhouse gases, similar to what has been performed for the last deglaciation (e.g., Liu et al., 2009, 2012; He et al., 2013), that can be used to assess the potential forcing(s) of rapid Laurentide ice-sheet growth.

Acknowledgements

A.E.C. acknowledges support from the United States National Science Foundation. L.T. is supported by the Natural Sciences and Engineering Research Council of Canada. T.P. acknowledges support from United States National Science Foundation Graduate Research Fellowship Program and Harvard University. Comments by two anonymous reviewers improved an earlier version of this manuscript. This paper resulted from collaborations through the PAleo focus group. This paper resulted from collaborations through the PAleo fellowship Program and Harvard University. Comments by two anonymous reviewers improved an earlier version of this manuscript. This paper resulted from collaborations through the PALeo fellowship Program and Harvard University. Comments by two anonymous reviewers improved an earlier version of this manuscript.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.quascirev.2018.07.039.

References


Dredge, L.A., Morgan, A.V., Nielsen, E. 1990. Sangamon and pre-sangamon inter-


Dyke, A.S., Morgan, A.V., Nielsen, E., 1990. Sangamon and pre-sangamon inter-

Glasser, N., 2010. North American Ice Sheet build-up during the last glacial


Hill, H.W., Flowers, B.P., Quinn, T.M., Hollander, D.J., Guilderson, T.P., 2006. Lau-


Kleman, J., Jansson, K., De Angelis, H., Stroeven, A.P., H


Licciardi, J.M., Talbot, J.T., Clark, P.U. 1999. Freshwater Routing by the Laurentide Ice Sheet during the Last Deglaciation, 112. American Geophysical Union Mono-


Monaghan, G.W., Larson, G.J., Gephart, G.D., 1986. Late wisconsinan drift stratig-


Pico, T., Creveling, J.R., Mitrovica, J.X., 2017. Sea-level records from the U.S. Mid-


Roy, M. 1998. Pleistocene Stratigraphy of the Lower Nelson River Area — Implica-


