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Southern Laurentide ice-sheet retreat synchronous with rising boreal summer insolation

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ABSTRACT

Establishing the precise timing for the onset of ice-sheet retreat at the end of the Last Glacial Maximum (LGM) is critical for delineating mechanisms that drive deglaciations. Uncertainties in the timing of ice-margin retreat and global ice-volume change allow a variety of plausible deglaciation triggers. Using boulder 10Be surface exposure ages, we date initial southern Laurentide ice-sheet (LIS) retreat from LGM moraines in Wisconsin (USA) to 23.0 ± 0.6 ka, coincident with retreat elsewhere along the southern LIS and synchronous with the initial rise in boreal summer insolation 24–23 ka. We show with climate-surface mass balance simulations that this small increase in boreal summer insolation alone is potentially sufficient to drive enhanced southern LIS surface ablation. We also date increased southern LIS retreat after ca. 20.5 ka likely driven by an acceleration in rising isolation. This near-instantaneous southern LIS response to boreal summer insolation before any rise in atmospheric CO2 supports the Milankovitch hypothesis of orbital forcing of deglaciations.

INTRODUCTION

Determining the timing of Northern Hemisphere ice-sheet retreat relative to changes in insolation, atmospheric CO2, and climate change is key to understanding the mechanisms that give rise to deglaciations (Imbrie et al., 1993). Dating of outermost ice-sheet margins that define the Last Glacial Maximum (LGM) has suggested that most Northern Hemisphere ice sheets were in retreat by ca. 19 ka concurrent with global mean sea-level rise, implicating the rise in boreal summer insolation after 24–23 ka as the primary control on deglaciation (Milanković, 1941; Imbrie et al., 1993; Clark et al., 2009). However, regional differences of up to 7 k.y. in retreat timing may exist in the current chronology (Clark et al., 2009), perhaps implying that localized climate change or dynamic instabilities drove initial retreat rather than a hemispheric forcing. The 4–5 k.y. lag in sea-level rise behind boreal summer insolation has yet to be explained, possibly suggesting that deglacial onset could require a rise in atmospheric CO2 and attendant global warming, which occurred at 18–17.5 ka (Lea et al., 2006; Parrenin et al., 2013). Because the deglacial rise in atmospheric CO2 was likely governed by changes in the Southern Ocean, a later onset of Northern Hemisphere ice-sheet retreat after 20 ka suggests that rising austral spring insolation and Southern Ocean sea-ice extent could be the cause of deglaciations (Timmernann et al., 2009; Wolff et al., 2009). Each of these forcings likely played a role in deglaciation, but determining the trigger of initial ice retreat requires a reduction in temporal uncertainty of current chronologies across extensive LGM ice-sheet margins.

The Laurentide ice sheet (LIS) was the largest of the LGM ice sheets (Fig. 1A) (Clark et al., 2009), with the southern LIS margin terminating in a series of terrestrial ice lobes (Fig. 1B) (Mickelson et al., 1983). The chronology of many of the southern LIS lobes is established by minimum- and maximum-limiting 14C dates on boreal forest wood that bracket the initial timing of retreat (Clayton and Moran, 1982; Mickelson et al., 1983; Hansel and Johnson, 1992; Clark et al., 2009; Curry and Petras, 2011; Glover et al., 2011), but the presence of permafrost along the margins of LIS lobes in Wisconsin (USA) has limited the application of 14C dating in determining when ice retreated (Clayton et al., 2001). Alternative efforts at constraining the timing of LIS retreat in Wisconsin have employed bedrock 10Be exposure ages and optically stimulated luminescence (OSL) ages on proglacial lake deposits (e.g., Colgan et al., 2002; Carson et al., 2012), but large uncertainties could indicate a significant delay in ice retreat in Wisconsin relative to other southern LIS margins. Here, we date the onset of southern LIS retreat from its terminal moraines in Wisconsin with 10Be surface exposure ages from large erratic boulders (Fig. 1C) to test the phasing of southern LIS retreat and deglacial climate forcings and their impact on LIS surface mass balance.

METHODS

We sampled boulder surfaces at seven locations on and near the LIS terminal margin in Wisconsin across varying bed and climate conditions (Fig. 1C). During the LGM, the Chippewa lobe flowed over Precambrian crystalline basement under tundra conditions, while the Green Bay lobe flowed over sedimentary bedrock and extended from tundra conditions in the north to the boreal forest-tundra border in the south (Mickelson et al., 1983; Maher et al., 1998; Clayton et al., 2001). We sampled boulders directly on the terminal moraines to constrain the initial timing of LIS retreat as well as at locations 10–15 km proximal to the terminal moraines to determine the extent of early retreat (Fig. 1C). At each of these sampling regions, no significant moraines exist between our outer and inner sites (Attig et al., 1985), suggesting that the 10Be ages indicate the timing of sustained retreat. In one instance, however, the recessional sample site for the northern part of the Green Bay lobe lies on an extensive recessional moraine system of the correlative Tiger Cat, Flamboue, Summit Lake, Bowler, and Green Lake moraines that extend from the Chippewa lobe to the southern Green Bay lobe (Fig. 1C) (Attig et al., 1985); our samples from this site thus provide an age for the retreat following moraine emplacement of this continuous ice-margin position. We also dated ice retreat past the Gogebic Mountains ~100 km north of the Chippewa lobe LGM moraine to further constrain northward ice retreat. All of the sampling sites had minimal till thickness with local bedrock at or near the surface; the only exceptions are the northern Green Bay lobe sites where boulder surfaces were sampled from the LGM moraine above ice-collapse features.
Figure 1. A: Map of Laurentide ice sheet (LIS) maximum extent at the Last Glacial Maximum (LGM) (Dyke, 2004); box shows location of B.

B: Digital elevation model (DEM) of southern LIS Region. Bold white line indicates LGM ice-margin extent; hashed black lines denote retreat transects as shown in Figure 2 with asterisk indicating starting point of each time-distance transect; box shows location of C. Labeled lobes and margins: JL—James lobe; DL—Des Moines lobe; CL—Chippewa lobe; GBL—Green Bay lobe; LML—Lake Michigan lobe; MSL—Miami-Scioto lobes; NEM—New England margin. C: DEM of Wisconsin region with 10Be ages indicated (red circles; excluded outliers indicated in italics) in relation to ice lobes (general lobe boundaries drawn with hashed gray lines). Sampling sites: sGBL—southern Green Bay lobe terminal margin; i-sGBL—inner southern Green Bay lobe; nGBL—northern Green Bay lobe terminal margin; i-nGBL—inner northern Green Bay lobe; CL—Chippewa lobe terminal margin; i-CL—inner Chippewa lobe; GM—Gogebic Mountains. Also shown is location and mean age of Colgan et al. (2002) 10Be results from the Waterloo site (W, recalculated using regional production rate; Balco et al., 2009), and oldest calibrated 14C date from Valders Quarry (V; Maher et al., 1998). Mean ages (in bold) for larger sample groupings (>2 samples) are expressed using straight mean and standard error for uncertainty, while mean ages for sample groupings with only 2 samples use error-weighted mean and standard deviation as a more complete assessment of joint uncertainty.

WISCONSIN ICE-MARGIN RETREAT

Our new 10Be ages date the onset of retreat from LGM terminal moraines of the southern Green Bay lobe at 22.1 ± 1.5 ka (n = 13, 5 outliers), northern Green Bay lobe at 23.4 ± 0.8 ka (n = 10, 2 outliers), and Chippewa lobe at 23.7 ± 0.7 ka (n = 10, 4 outliers) (Fig. 1C). The southern Green Bay lobe age agrees with the nearby OSL date for ice retreat of 21.4 ± 3.3 ka of Carson et al. (2012), but the 10Be ages have significantly smaller uncertainty. Because our three 10Be sites are along the same LGM moraine (Mickelson et al., 1983), we use the mean and standard error of the combined 22 boulder ages to date the onset of southern LIS retreat from the continuous LGM moraine system in Wisconsin at 23.0 ± 0.6 ka.

Our 10Be ages from 10 to 15 km within the LGM moraine indicate that ice retreated only a short distance over the next 3–5 k.y., with mean ages of 19.4 ± 0.7 ka (n = 2) within the southern Green Bay lobe margin, 18.4 ± 0.8 ka (n = 5, 1 outlier) within the northern Green Bay lobe margin, and 19.9 ± 0.6 ka (n = 2) within the Chippewa lobe margin (Fig. 1C). Previous bedrock 10Be ages ~50 km within the Green Bay lobe LGM extent date ice-margin retreat past this position (Fig. 1C) at 20.7 ± 1.0 ka (n = 4) (Colgan et al., 2002), consistent with our southern Green Bay lobe dates within their uncertainty. The inner northern Green Bay lobe ages of 18.4 ± 0.8 ka from the recessional moraine are also stratigraphically consistent with the other 10Be recessional ages and indicate ~75 km retreat of the southern Green Bay lobe between 19.4 ± 0.7 ka and 18.4 ± 0.8 ka (Fig. 1C). The old-
est calibrated ¹⁴C date from ~170 km within the Green Bay lobe LGM moraine indicates retreat almost out of eastern Wisconsin before 17.7 ± 0.2 ka (Fig. 1C) (Maher et al., 1998). Similarly, our ⁶⁰⁷Be ages from the Chippewa lobe indicate initial 10–15 km of retreat between 23.7 ± 0.7 ka and 19.9 ± 0.6 ka, followed by more rapid retreat of ~70 km to the aforementioned continental recessional moraine by 18.4 ± 0.8 ka, (Fig. 1C). Our Gogebic Mountains ⁶⁰⁷Be ages of 13.2 ± 0.4 ka (n = 7, 1 outlier) record only ~30 km of additional northward retreat of the Chippewa lobe over the next 4–6 k.y. (Fig. 1C).

ONSET OF SOUTHERN LAURENTIDE RETREAT

The pattern of ice-margin retreat in Wisconsin, with initial ice-margin retreat at ca. 23.0 ka followed by more extensive retreat of the Green Bay lobe after ca. 20 ka, is similar in timing to that of the other southern LIS lobes (Figs. 1B and 2). The existence of numerous moraines and till sheets separated by proglacial sediment in northeastern Illinois suggests fluctuating retreat and re-advance of the Lake Michigan lobe throughout the deglaciation (Hansel and Johnson, 1992; Curry and Petras, 2011; Fig. 2). Minimum-limiting ¹⁴C dates from the terminal environments and ice-recessional features indicate >100 km of Lake Michigan lobe retreat before emplacement of a recessional ice-walled lake plain by 22.1 ± 0.2 ka (laboratory number UCAMS-26261, Table DR2 in the Data Repository), suggesting an onset of retreat at ca. 23 ka (Curry and Petras, 2011) (Fig. 2G). After initial retreat, basal ¹⁴C dates from ice-walled lake plains indicate >200 km of additional retreat prior to a minimum-limiting ¹⁴C date on proglacial lake sediments above till of 19.9 ± 0.4 ka (SISG-A-0164, Table DR2) and before the next re-advance constrained by a ¹⁴C date of 18.5 ± 0.2 ka (ISGS-465, Table DR2) from basal glacial lacustrine sediment over proglacial fluvial deposits (Hansel and Johnson, 1992) (Fig. 2G).

To the east, the Miami-Scioto lobes began retreat northward from LGM positions in southern Indiana-Ohio before 22.4 ± 0.2 ka (Beta-72287, Table DR2), according to the oldest minimum-limiting ¹⁴C date from within the terminal moraine in southern Ohio (Glover et al., 2011) (Fig. 2F). A ¹⁴C date from post-glacial lakes in Ohio suggest ~100 km of Miami-Scioto lobe retreat prior to 19.5 ± 0.2 ka (AA-45079, Table DR2) (Fig. 2F) (Glover et al., 2011). Later readvances by the Green Bay, Lake Michigan, and Miami-Scioto lobes are evidenced by detailed stratigraphy and chronological constraints (Mickelson et al., 1983); however, none of these re-advances reached the LGM moraines.

Further to the east, the timing of New England margin retreat dated by boulder ⁶⁰⁷Be ages (Fig. 1B) is also similar to that of the southern LIS lobes. The New England margin retreated ~10 km between 26.1 ± 0.8 ka (n = 7, 4 outliers) and 20.8 ± 0.4 ka (n = 10), with more extensive retreat after 20.4 ± 0.3 ka (n = 7) (Balco et al., 2002, 2009) (Fig. 2E). The New England margin retreat at ca. 26 ka was previously attributed to dynamic instability reflecting its tidewater setting, with its continued retreat after ca. 21 ka attributed to the onset of deglaciation (Clark et al., 2009).

To the west, the stratigraphy and chronology of the Des Moines and James lobes (Fig. 1B) indicate a more complex retreat history, with evidence for a large re-advance at ca. 17 ka that was more extensive than the LGM extent in some regions (Clayton and Moran, 1982). The ca. 17 ka re-advance is thought to be an anomalous ice surge driven by internal ice dynamics; it is not seen anywhere else across the southern LIS margin (Clayton and Moran, 1982; Mickelson et al., 1983). Other portions of the Des Moines and James lobes were more extensive at the LGM, with retreat beginning between ca. 24 ka and 20 ka (Clayton and Moran, 1982; Clark et al., 2009), consistent with the rest of the southern LIS.

Initial southern LIS retreat from its LGM moraines has been attributed to dynamic instability and ice-margin variability (Clayton and Moran, 1982; Mickelson et al., 1983). However, because of differing local climate settings and underlying substrate, the similar timing of retreat onset across the southern LIS suggests that these ice margins are responding to a larger continental climate forcing rather than a local climate anomaly or dynamic instability. We therefore assign this initial retreat as the onset of deglaciation because the southern LIS never re-advanced to these LGM moraines, noting the potential exception for the Des Moines and James lobe surges.

FORCING OF LAURENTIDE RETREAT

We test whether the rise in boreal summer insolation after ca. 24 ka could drive southern LIS retreat by forcing a surface-energy balance model with climate model output to simulate southern LIS surface mass balance (see the Data Repository). We simulated climate at 24, 21, 19, and 16.5 ka using the fully coupled atmosphere-ocean general circulation model NASA Goddard Institute for Space Studies ModelE2-R (www.giss.nasa.gov/tools/modelE/) to produce a climate state in equilibrium with ice-sheet boundary conditions. Because greenhouse gases and ice margins are largely constant across this time period (within model resolution of topography), we change only insolation due to orbital forcing at the LGM, with retreat beginning between ca. 24 ka and 20 ka (Clayton and Moran, 1982; Hansel and Johnson, 1992) (see the Data Repository). Question marks indicate unknown magnitude of retreat, while re-advance positions are constrained by ¹⁴C data and till stratigraphy.

Figure 2. Deglacial forcing and southern Laurentide ice sheet (LIS) retreat chronologies. A, Latitudinal variation (A) and rate of change (B) in boreal summer insolation anomalies (relative to 0 ka) (Laskar et al., 2004). C, Modeled surface mass balance (SMB) anomalies relative to 24 ka simulation (red circles). D, Atmospheric CO₂ (black circles) (Parrenin et al., 2013). E, Distance south of New England margin (NEM; see Fig. 1B) dated by ⁶⁰⁷Be (Balco et al., 2002, 2006) (magenta squares show site averages with standard error as uncertainty). F: Distance south of Miami-Scioto lobes (MSL, orange line) based on ¹⁴C dates (orange error bars) (Glover et al., 2011) (see the Data Repository [see footnote 1]). G: Distance south of Lake Michigan lobe (LML, green line) based on ¹⁴C dates (green error bars) (Curry and Petras, 2011; Hansel and Johnson, 1992) (see the Data Repository). Question marks indicate unknown magnitude of retreat, while re-advance positions are constrained by ¹⁴C data and till stratigraphy.
of Licciardi et al. (1998), which was selected because it best resolves topographic inferences of ice-lobe elevation from geologic constraints along the southern margin. Because our model design does not include ice-sheet dynamics, we test only the influence of boreal summer insolation on surface mass balance, neglecting any additional mass loss from ice-sheet dynamics.

From 24 to 21 ka, southern LIS surface mass balance decreases by ~210 Gt yr$^{-1}$ (equivalent to ~58 cm k.y.$^{-1}$ equivalent eustatic sea level, esl), and from 21 to 19 ka by an additional ~150 Gt yr$^{-1}$ (~42 cm k.y.$^{-1}$ esl) (Fig. 2C; Figs. DR10a and DR10b in the Data Repository), indicating that the change in insulation by 21 ka could have increased southern LIS surface ablation. The climate-surface mass balance model simulation for 16.5 ka shows a significant decrease in southern LIS surface mass balance of an additional 630 Gt yr$^{-1}$ (~175 cm k.y.$^{-1}$ esl) relative to 19 ka (Fig. 2C; Fig. DR10c). This further increased southern LIS ablation after ca. 20 ka likely reflects a response to the accelerating rise in boreal summer insolation (Fig. 2B) and increased greenhouse gas forcing (Fig. 2D), and such elevated mass loss is concurrent with rising global mean sea level (Clark et al., 2009). We note that the onset of retreat we date at ca. 23 ka occurs at least ~1 k.y. after Heinrich event 2 and so is not likely related to this instability in the Hudson Bay sector of the northeast LIS (Clark et al., 2009). Heinrich event 2 climate change was also spatially variable, likely cooling the southern LIS lobes but warming over New England (Hostetler et al., 1999). Future coupled dynamic ice sheet–climate model simulations could further test the impact of Heinrich events on the southern LIS.

Our climate–surface mass balance simulations demonstrate that changes in boreal summer insolation by ca. 21 ka alone were capable of triggering initial surface mass loss and concurrent southern LIS margin retreat, which supports the Milanković hypothesis as the trigger for the last deglaciation (Milanković, 1941; Imbrie et al., 1993). Because initial southern LIS retreat occurred prior to any change in atmospheric CO$_2$, or Antarctic, Southern Ocean, or tropical warming, the rise in greenhouse gases and attendant climate impacts must have acted only as positive feedbacks on deglaciation, not as the trigger. Initial southern LIS retreat at ca. 23 ka was small relative to later retreat after ca. 20 ka, but so was the rate of change in boreal summer insolation relative to its acceleration from 20 ka to 18 ka. We therefore show for the first time that the southern LIS responded almost instantaneously to boreal summer insolation forcing, suggesting a high sensitivity of land-terminating ice margins to small changes in climate forcing.

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