

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

April S. Dalton^{1,2}, Sarah A. Finkelstein¹, Steven L. Forman³, Peter J. Barnett⁴, Tamara Pico⁵, and Jerry X. Mitrovica⁵

¹Department of Earth Sciences, University of Toronto, Toronto, Ontario M5S 3B1, Canada

²Department of Geography, Durham University, Durham DH1 3LE, UK

³Department of Geosciences, Baylor University, Waco, Texas 76798, USA

⁴Harquail School of Earth Sciences, Laurentian University, Sudbury, Ontario P3E 2C6, Canada

⁵Department of Earth and Planetary Sciences, Harvard University, Cambridge, Massachusetts 02138, USA

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 ca. 52 to 40 ka. Key to this hypothesis are geological records at sites in the Hudson Bay Lowlands (east central Canada) 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 buildup 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 ca. 125 to ca. 7 ka). Despite the importance of this ice sheet, its evolution is very poorly constrained prior to the Last Glacial Maximum (LGM; ca. 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 –80 m to –30 m relative to modern sea level; Siddall et al., 2008); and will offer a critical long-term perspective on the response of the Earth system to rapid climate change 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 and 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 (see the GSA Data Repository¹) 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 and 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

¹GSA Data Repository item 2019046, table of geochronological data ($n = 735$) and description of the geophysical model, is available online at <http://www.geosociety.org/datarepository/2019/>, or on request from editing@geosociety.org.

CITATION: Dalton, A.S., et al., 2019, Was the Laurentide Ice Sheet significantly reduced during Marine Isotope Stage 3?: *Geology*, v. 47, p. 111–114, <https://doi.org/10.1130/G45335.1>.

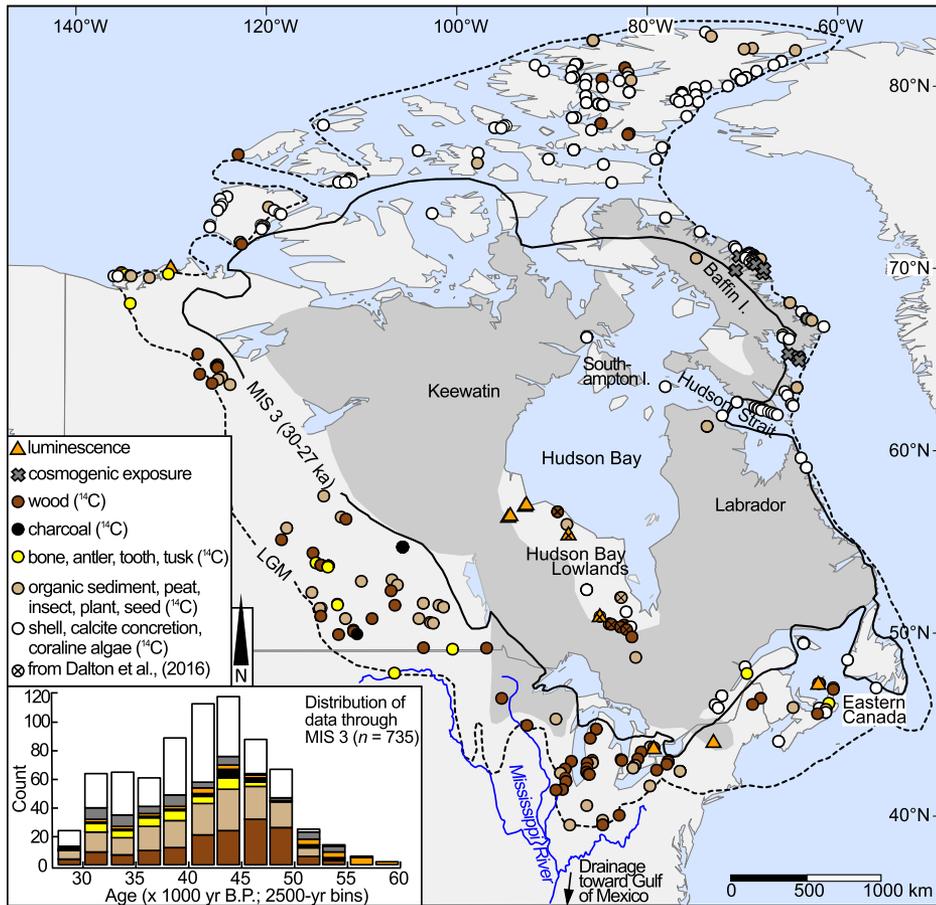


Figure 1. Map showing glacial outline of Laurentide Ice Sheet at 30–27 ka (solid black line; after Dyke et al., 2002) overlaid with currently available geological data from Marine Isotope Stage 3 (MIS 3; $n = 735$). Note large number of dates that lie inside MIS 3 extent (e.g., Hudson Bay Lowlands),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

(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 [OSL] 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 suggest 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) and ice buildup 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 (sites 11-PJB-186, 11-PJB-020, 12-PJB-007 of Dalton et al., 2016) are all located at subaerial elevations in the simulation (Fig. 2A). The discrepancy between the simulated location of the shoreline and the age/location of 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 nonglacial 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 are provided in the Data Repository).

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 at 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 $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ record from Crevice Cave (Missouri, USA; Dorale et al., 1998) and Devils Hole (Nevada, USA; Landwehr et al., 2011) during MIS 3 (Figs. 3C–3E) 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 that the eastern and western sectors of the LIS were independent from each other 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 (abrupt variability in $\delta^{18}\text{O}$ seen in Fig. 3F) must have been dominated by northward drainage perturbations (as opposed to alternating between northward drainage and drainage toward the Gulf of Mexico; Clark et al., 2001). Geological records from the Mississippi River (central United States) that have been widely assigned to ice advance into the mid-continent may also

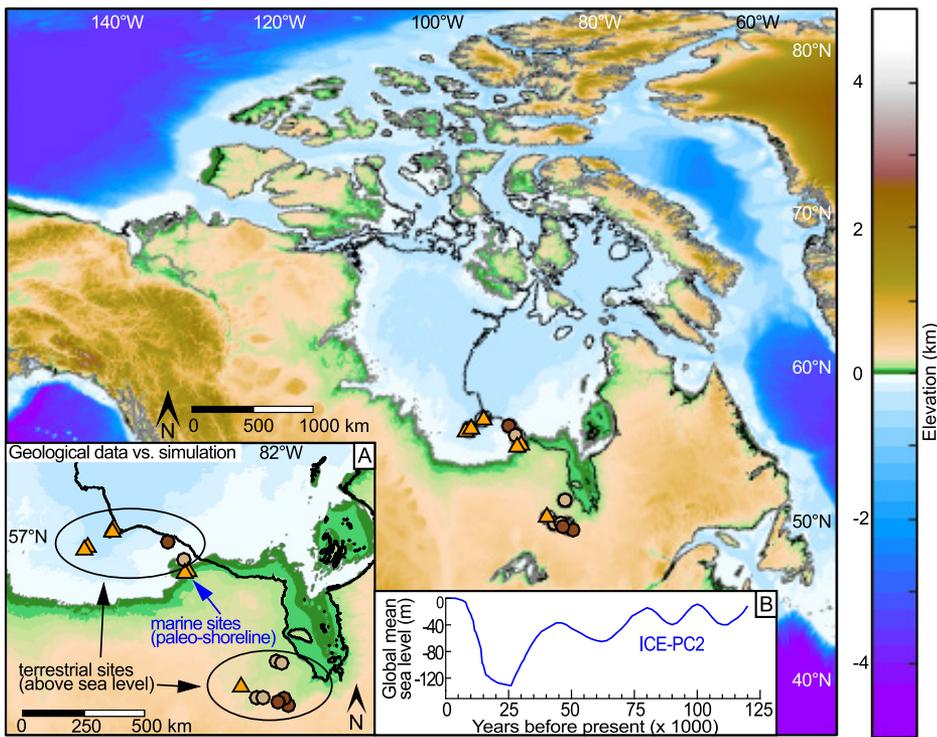


Figure 2. Modeled North American topography at 42 ka using ice history ICE-PC2 (Pico et al., 2017), overlaid with available geological data from Hudson Bay Lowlands (colored as in Fig. 1). Note agreement between available geochronological data and numerical simulation, which supports hypothesis of reduced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

require reinterpretation; these include the widespread Roxana Silt loess deposit (ca. 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 nonglacial 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 events 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 (northeastern and eastern Canada) could have been active contributors to ice rafting events in the northeastern 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 modeling, recent studies have demonstrated that the Labrador sector may have expanded >1000 km southward by ca. 39–37 ka (Carlson et al., 2018; Pico

et al., 2018a, 2018b). 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 modeling supports a significant reduction of the LIS during MIS 3.

ACKNOWLEDGMENTS

This research was funded by grants to Finkelstein from the Natural Sciences and Engineering Research Council (Canada) and the Ontario Geological Survey; and to Dalton from the Northern Scientific Training Program (Canada), the University of Toronto Centre for Global Change Science, and the Ontario Graduate Scholarship. We acknowledge the support of the U.S. National Science Foundation to Pico and support from Harvard University to Pico and Mitrovica. We thank Chris Stokes for insightful comments, Art Dyke for providing some chronology data, John Andrews for conversations about Heinrich events, and three anonymous reviewers for constructive comments.

REFERENCES CITED

- Andrews, J.T., Shilts, W.W., and Miller, G.H., 1983, Multiple deglaciations of the Hudson Bay Lowlands, Canada, since deposition of the Missinaibi (last-interglacial?) Formation: *Quaternary Research*, v. 19, p. 18–37, [https://doi.org/10.1016/0033-5894\(83\)90025-X](https://doi.org/10.1016/0033-5894(83)90025-X).
- Berger, A., and Loutre, M.F., 1991, Insolation values for the climate of the last 10 million years:

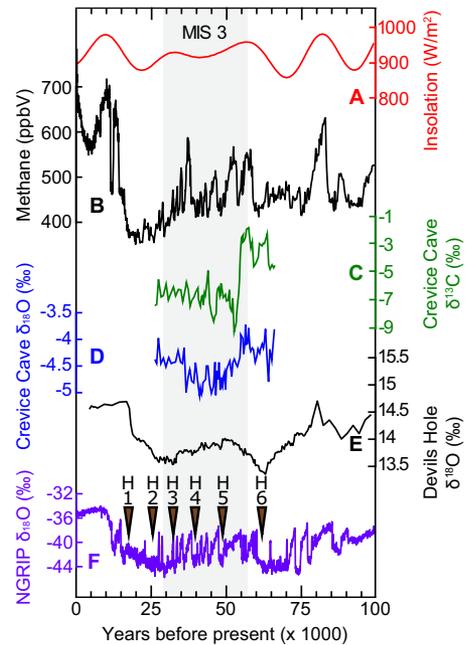


Figure 3. Paleoclimate and orbital parameters spanning Late Pleistocene (100 ka to present day). **A:** July insolation at 60°N after Berger and Loutre (1991). **B:** Atmospheric methane estimates (ppbV—parts per billion by volume) from European Project for Ice Coring in Antarctica Dome C ice core (Loulergue et al., 2008). **C, D:** Carbon and oxygen isotope data from Crevice Cave (Missouri, USA; Dorale et al., 1998). **E, F:** Oxygen isotope data from Devils Hole speleothem (Nevada, USA; Landwehr et al., 2011) and a North Greenland Ice Core Project (NGRIP) core (North Greenland Ice Core Project members, 2004). Arrows indicate Heinrich events (Sanchez Goñi and Harrison, 2010). **MIS 3—Marine Isotope Stage 3.**

- Quaternary Science Reviews*, v. 10, p. 297–317, [https://doi.org/10.1016/0277-3791\(91\)90033-Q](https://doi.org/10.1016/0277-3791(91)90033-Q).
- Carlson, A.E., Tarasov, L., and Pico, T., 2018, Rapid Laurentide ice-sheet advance towards southern last glacial maximum limit during marine isotope stage 3: *Quaternary Science Reviews*, v. 196, p. 118–123, <https://doi.org/10.1016/j.quascirev.2018.07.039>.
- Clark, P.U., Marshall, S.J., Clarke, G.K.C., Hostetler, S.W., Licciardi, J.M., and Teller, J.T., 2001, Freshwater forcing of abrupt climate change during the last glaciation: *Science*, v. 293, p. 283–287, <https://doi.org/10.1126/science.1062517>.
- Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrovica, J.X., Hostetler, S.W., and McCabe, A.M., 2009, The Last Glacial Maximum: *Science*, v. 325, p. 710–714, <https://doi.org/10.1126/science.1172873>.
- Dalton, A.S., Finkelstein, S.A., Barnett, P.J., and Forman, S.L., 2016, Constraining the Late Pleistocene history of the Laurentide Ice Sheet by dating the Missinaibi Formation, Hudson Bay Lowlands, Canada: *Quaternary Science Reviews*, v. 146, p. 288–299, <https://doi.org/10.1016/j.quascirev.2016.06.015>.
- Dalton, A.S., Välranta, M., Barnett, P.J., and Finkelstein, S.A., 2017, Pollen and macrofossil-inferred paleoclimate at the Ridge Site, Hudson Bay Lowlands, Canada: Evidence for a dry climate and significant recession of the Laurentide Ice Sheet during Marine Isotope Stage 3: *Boreas*, v. 46, p. 388–401, <https://doi.org/10.1111/bor.12218>.

- Dorale, J.A., Edwards, R.L., Ito, E., and González, L.A., 1998, Climate and vegetation history of the midcontinent from 75 to 25 ka: A speleothem record from Crevice Cave, Missouri, USA: *Science*, v. 282, p. 1871–1874, <https://doi.org/10.1126/science.282.5395.1871>.
- Dredge, L.A., and Thorleifson, L.H., 1987, The Middle Wisconsinan history of the Laurentide Ice Sheet: *Géographie Physique et Quaternaire*, v. 41, p. 215–235, <https://doi.org/10.7202/032680ar>.
- Dyke, A.S., 2004, An outline of North American deglaciation with emphasis on central and northern Canada, in Ehlers, J., and Gibbard, P.L., eds., *Quaternary Glaciations—Extent and Chronology, Part II: North America: Amsterdam, Elsevier, Developments in Quaternary Sciences*, v. 2, Part B, p. 373–424, [https://doi.org/10.1016/S1571-0866\(04\)80209-4](https://doi.org/10.1016/S1571-0866(04)80209-4).
- Dyke, A.S., Andrews, J.T., Clark, P.U., England, J.H., Miller, G.H., Shaw, J., and Veillette, J.J., 2002, The Laurentide and Innuitian ice sheets during the Last Glacial Maximum: *Quaternary Science Reviews*, v. 21, p. 9–31, [https://doi.org/10.1016/S0277-3791\(01\)00095-6](https://doi.org/10.1016/S0277-3791(01)00095-6).
- Forman, S.L., and Pierson, J., 2002, Late Pleistocene luminescence chronology of loess deposition in the Missouri and Mississippi river valleys, United States: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 186, p. 25–46, [https://doi.org/10.1016/S0031-0182\(02\)00440-6](https://doi.org/10.1016/S0031-0182(02)00440-6).
- Forman, S.L., Wintle, A.G., Thorleifson, L.H., and Wyatt, P.H., 1987, Thermoluminescence properties and age estimates for Quaternary raised marine sediments, Hudson Bay Lowland, Canada: *Canadian Journal of Earth Sciences*, v. 24, p. 2405–2411, <https://doi.org/10.1139/e87-226>.
- Hefter, J., Naafs, D.A., and Zhang, S., 2017, Tracing the source of ancient reworked organic matter delivered to the North Atlantic Ocean during Heinrich Events: *Geochimica et Cosmochimica Acta*, v. 205, p. 211–225, <https://doi.org/10.1016/j.gca.2017.02.008>.
- Helmens, K.F., and Engels, S., 2010, Ice-free conditions in eastern Fennoscandia during early Marine Isotope Stage 3: Lacustrine records: *Boreas*, v. 39, p. 399–409, <https://doi.org/10.1111/j.1502-3885.2010.00142.x>.
- Hughes, A.L.C., Gyllencreutz, R., Lohne, Ø.S., Mangerud, J., and Svendsen, J.I., 2016, The last Eurasian ice sheets—A chronological database and time-slice reconstruction, DATED-1: *Boreas*, v. 45, p. 1–45, <https://doi.org/10.1111/bor.12142>.
- Kleman, J., Jansson, K., De Angelis, H., Stroeven, A.P., Hättestrand, C., Alm, G., and Glasser, N., 2010, North American Ice Sheet build-up during the last glacial cycle, 115–21 kyr: *Quaternary Science Reviews*, v. 29, p. 2036–2051, <https://doi.org/10.1016/j.quascirev.2010.04.021>.
- Landwehr, J.M., Sharp, W.D., Coplen, T.B., Ludwig, K.R., and Winograd, I.J., 2011, The chronology for the $\delta^{18}\text{O}$ record from Devils Hole, Nevada, extended into the mid-Holocene: *U.S. Geological Survey Open-File Report 2011-1082*, 5 p.
- Leigh, D.S., Srivastava, P., and Brook, G.A., 2004, Late Pleistocene braided rivers of the Atlantic Coastal Plain, USA: *Quaternary Science Reviews*, v. 23, p. 65–84, [https://doi.org/10.1016/S0277-3791\(03\)00221-X](https://doi.org/10.1016/S0277-3791(03)00221-X).
- Lisiecki, L.E., and Raymo, M.E., 2005, A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}\text{O}$ records: *Paleoceanography*, v. 20, PA1003, <https://doi.org/10.1029/2004PA001071>.
- Loulergue, L., Schilt, A., Spahni, R., Masson-Delmotte, V., Blunier, T., Lemieux, B., Barnola, J.-M., Raynaud, D., Stocker, T.F., and Chappellaz, J., 2008, Orbital and millennial-scale features of atmospheric CH_4 over the past 800,000 years: *Nature*, v. 453, p. 383–386, <https://doi.org/10.1038/nature06950>.
- North Greenland Ice Core Project members, 2004, High-resolution record of Northern Hemisphere climate extending into the last interglacial period: *Nature*, v. 431, p. 147–151, <https://doi.org/10.1038/nature02805>.
- Pico, T., Mitrovica, J.X., Ferrier, K.L., and Braun, J., 2016, Global ice volume during MIS 3 inferred from a sea-level analysis of sedimentary core records in the Yellow River Delta: *Quaternary Science Reviews*, v. 152, p. 72–79, <https://doi.org/10.1016/j.quascirev.2016.09.012>.
- Pico, T., Creveling, J.R., and Mitrovica, J.X., 2017, Sea-level records from the U.S. mid-Atlantic constrain Laurentide Ice Sheet extent during Marine Isotope Stage 3: *Nature Communications*, v. 8, 15612, <https://doi.org/10.1038/ncomms15612>.
- Pico, T., Mitrovica, J.X., Braun, J., and Ferrier, K.L., 2018a, Glacial isostatic adjustment deflects the path of the ancestral Hudson River: *Geology*, v. 46, p. 591–594, <https://doi.org/10.1130/G40221.1>.
- Pico, T., Birch, L., Weisenberg, J., and Mitrovica, J.X., 2018b, Refining the Laurentide Ice Sheet at Marine Isotope Stage 3: A data-based approach combining glacial isostatic simulations with a dynamic ice model: *Quaternary Science Reviews*, v. 195, p. 171–179, <https://doi.org/10.1016/j.quascirev.2018.07.023>.
- Rittenour, T.M., Blum, M.D., and Goble, R.J., 2007, Fluvial evolution of the lower Mississippi River valley during the last 100 k.y. glacial cycle: Response to glaciation and sea-level change: *Geological Society of America Bulletin*, v. 119, p. 586–608, <https://doi.org/10.1130/B25934.1>.
- Roy, M., Hemming, S.R., and Parent, M., 2009, Sediment sources of northern Québec and Labrador glacial deposits and the northeastern sector of the Laurentide Ice Sheet during ice-rafting events of the last glacial cycle: *Quaternary Science Reviews*, v. 28, p. 3236–3245, <https://doi.org/10.1016/j.quascirev.2009.08.008>.
- Sanchez Goñi, M.F., and Harrison, S.P., 2010, Millennial-scale climate variability and vegetation changes during the Last Glacial: Concepts and terminology: *Quaternary Science Reviews*, v. 29, p. 2823–2827, <https://doi.org/10.1016/j.quascirev.2009.11.014>.
- Siddall, M., Rohling, E.J., Thompson, W.G., and Waelbroeck, C., 2008, Marine Isotope Stage 3 sea level fluctuations: Data synthesis and new outlook: *Reviews of Geophysics*, v. 46, RG4003, <https://doi.org/10.1029/2007RG000226>.
- Sionneau, T., Bout-Roumazeilles, V., Meunier, G., Kissel, C., Flower, B.P., Bory, A., and Tribouillard, N., 2013, Atmospheric re-organization during Marine Isotope Stage 3 over the North American continent: Sedimentological and mineralogical evidence from the Gulf of Mexico: *Quaternary Science Reviews*, v. 81, p. 62–73, <https://doi.org/10.1016/j.quascirev.2013.10.002>.
- Stokes, C.R., Tarasov, L., and Dyke, A.S., 2012, Dynamics of the North American Ice Sheet Complex during its inception and build-up to the Last Glacial Maximum: *Quaternary Science Reviews*, v. 50, p. 86–104, <https://doi.org/10.1016/j.quascirev.2012.07.009>.

Printed in USA