Glaciation of North America in the James Bay Lowland, Canada, 3.5 Ma

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ABSTRACT

Glaciers expanded in the Northern Hemisphere during the middle Pliocene. However, whether they extended into the midlatitude lowlands remains unknown. A Pliocene sequence from a buried, deep bedrock trench in the midlatitude James Bay Lowland, Canada (52°49.5′N, 83°52.5′W), contains a till and an overlying lacustrine deposit rich in fossil pollen. Magnetostratigraphy together with pollen-derived biostratigraphy constrains it to a time span from 3.6 to 3.0 Ma. Based on multiple lines of evidence, we are able to prove the deposition of the till by an early ice sheet, and hence glaciation of the lowland at ca. 3.5 Ma (3.6–3.4 Ma). After glaciation, rapid warming permitted thermophilic trees now exotic to this area to grow, which include oak, sweetgum, and cypress. Furthermore, pollen analysis indicates alternating Carolinian deciduous and boreal evergreen forests under a climate that oscillated and cooled gradually during a prolonged postglacial period from 3.5 to 3.0 Ma.

INTRODUCTION

Glaciers expanded in the Northern Hemisphere 4–3 Ma during the middle Pliocene as indicated by deep-sea ice-rafted detritus records (Jansen and Sjøholm, 1991; Maslin et al., 1995; Kleiven et al., 2002). However, given a climate much warmer than today (Wolfe, 1980; Lisiecki and Raymo, 2005; Salzmann et al., 2008), a key question remains unanswered because proxies from the marine records are limited in their ability to outline the regional extent of the ice masses: did glaciers extend into the midlatitude lowlands or were they restricted to the circumarctic continents and mountains? Knowing whether extensive glaciations occurred during the middle Pliocene is critical for a better understanding of Earth's climate history and the cause of amplified ice growth and decay beginning in the late Pliocene (3–2.6 Ma).

Here we show that the middle Pliocene ice masses were much more extensive than previously known, based on a record obtained from a site in the James Bay Lowland, Canada (52°49.5′N, 83°52.5′W) (Fig. 1). Based on multiple lines of evidence, we are able to prove the deposition of till by an early ice sheet, and hence continental glaciation in the midlatitude lowlands at ca. 3.5 Ma (3.6–3.4 Ma) of a magnitude probably comparable to Pleistocene glaciations. After the glaciation, rapid warming permitted thermophilic trees now exotic to this area to grow, which included oak, hickory, sweetgum, and cypress. Pollen data depict a climate that oscillated and cooled during a prolonged postglacial period from 3.5 to 3.0 Ma.

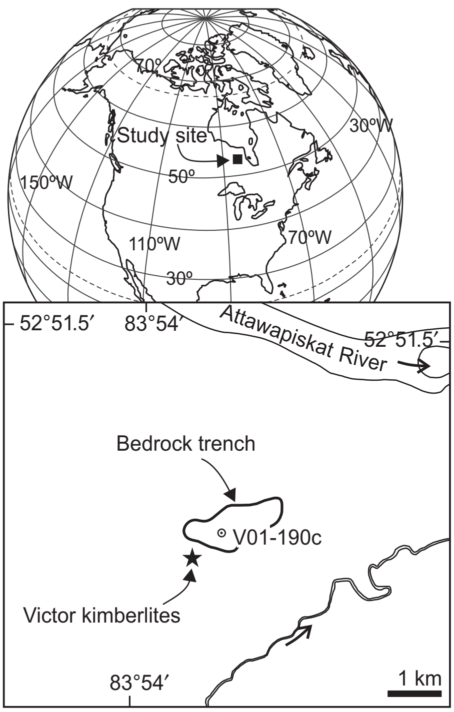

Figure 1. Location of the study site, bedrock trench, and borehole V01-190c in James Bay Lowland, Canada.

PLIOCENE GLACIAL AND NONGLACIAL DEPOSITS

The 170 m thick Pliocene sequence rich in kaolinite fills a buried trench with a floor 192 m below the surface or 108 m below sea level in the Silurian carbonate bedrock, adjacent to a cluster of Jurassic kimberlite pipes, known as the Victor kimberlites, near the Attawapiskat River, northern Ontario (Fig. 1). De Beers Canada is currently extracting the kimberlites for diamonds in an open pit. Several boreholes have been sunk in the trench, and borehole V01-190c is used here to represent the geologic succession (Fig. 2A). The till, up to 50 m thick, consists of compact, noncalcareous clayey to sandy diamict with faceted pebbles, resembling a subglacial till (Figs. 2A and 2B). It contains peat and organic-rich detrital mud with sporadic glaciolacustrine silt and clay horizons. The predominance in pebble lithology of vein quartz, chert, and quartzite suggests a major source from the Jurassic and Cretaceous fluvial sediments in the region (Telford et al., 1991). In the open pit mine, such Jurassic quartz sand and pebbles occur in crevices in the Paleozoic bedrock that was fractured during the emplacement of the kimberlite pipes. As revealed in the boreholes in the trench, abundant limestone fragments occur in areas adjacent to the brecciated Paleozoic bedrock near the pipes.

The overlying lacustrine sequence fines upward and has a thickness up to 120 m, with its lower contact 142 m below the ground surface. It contains laminated sand and silt with peat, indicating gradual infilling of a lake basin (Fig. 2A). Cobble-sized lag clasts exist at the base of the sequence, probably resulting from meltwater erosion in front of the retreating ice sheet. Woody peat ranging from 1 to 30 m in thickness occurs in the upper part of the sequence. At the top of the sequence, silt and clay with fine lamination contains debris of clustered coarse sand grains that probably derived from ice rafting (Figs. 2C and 2D). This fining-upward sequence as a whole suggests increasing water depth over time in a lake basin probably much larger than the current trench, and that the present sequence is the erosional remnant of a much thicker lacustrine succession. Analysis of foraminifera was conducted in both the lacustrine and till deposits at a dozen levels, but none were found to indicate marine influence (D.H. McNeil, 2008, personal commun.).

GEOMAGNETIC POLARITY TIME SCALE

The geomagnetic inclination in the upper part of the lacustrine sequence agrees well with the

GEOLOGY, November 2012; v. 40; no. 11; p. 975–978; Data Repository item 2012277 | doi:10.1130/G33092.1 | Published online 4 September 2012

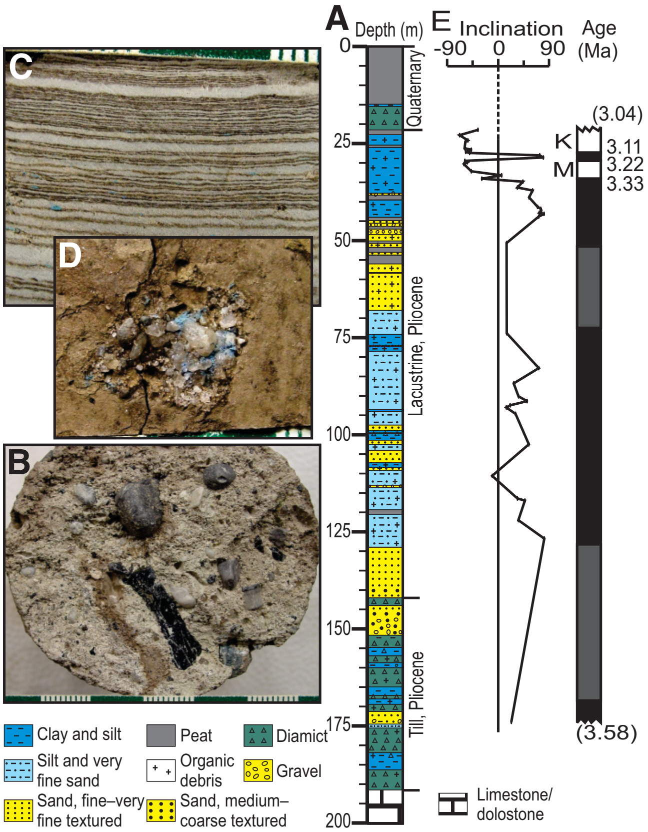

Figure 2. Geologic succession from the buried bedrock trench. A: Borehole V01-190c. B: Close-up of Pliocene till at the depth of 180 m. C: Silt and clay with fine lamination at the depth of 26 m. D: Debris of clustered coarse sand grains in the laminated silt and clay at the depth of 24 m. Greenish material is amorphous sulfide. Scale in centimeters for B–D. E: Magnetostratigraphy derived from magnetic inclination. Black indicates periods of positive geomagnetic polarity, and white indicates polarity reversal. Gray indicates areas without data. K and M are Kaena and Mammoth reversed subchrons, respectively.

expected dipole value for the latitude of this site (78°, positive for normal and negative for reversed) (Fig. 2E). In the lower part, the low-angle inclinations of ~45° are probably related to cross-bedding in the section where the bedding angle of fine sand locally exceeds 30°. However, this does not affect the overall geomagnetic polarity. The geomagnetic data show normal or positive polarity with reversals in the upper part of the sequence (Fig. 2E). A clay sample of glaciolacustrine origin in the till also shows positive polarity (Fig. 2E).

Compared with the standard magnetostratigraphy (Cande and Kent, 1995), this succession matches the lower half of the Gauss geomagnetic chron (Fig. 2E). At the top of the lacustrine sequence, a sedimentary rate of 3.5 cm $k.y.^{-1}$ is calculated based on the chronologically constrained Mammoth and Kaena reversed subchrons, and the upper contact of the sequence is estimated at 3 Ma. This estimate slightly truncates the upper boundary of the Kaena at 3.04 Ma (Fig. 2E). This minor inconsistency may be explained by postdepositional compaction that likely occurred in the argillaceous sediments. The actual sedimentary rate would have been much greater there. The sandy material in the lower part of the lacustrine deposit should have accumulated more rapidly than the argillaceous fines. Because of the heterogeneous lithology, the rate above cannot be applied linearly through the deposit to build an age model. Nonetheless, the geomagnetic succession suggests a time frame for the entire sequence from 3.6 to 3.0 Ma and an age of the till at ca. 3.5 Ma (3.6–3.4 Ma) between the onset of the Gauss chron and Mammoth subchron (Fig. 2E).

MICROTEXTURE ANALYSIS

Under a scanning electron microscope (SEM), microtextures from 70 quartz grains 0.25–1 mm in size include crushing to grinding features, such as parallel to arc-shaped steps, bent grooves, and troughs, formed typically in a subglacial environment (Figs. 3A–3C) (Mahaney, 2002). Key evidence for a subglacial process comes from coaxial crescentic gouges, parallel striae, and their association with crescentic fractures (Figs. 3B–3D). Trails of crescentic gouges occur in association with slightly bent grooves (Figs. 3B and 3C), resulting from mechanic crushing and fracturing by rock fragments within a subglacial deforming layer (Benn and Evans, 2010). In addition to their parallel occurrence, some striae are associated with transverse crescentic fractures along the strike (Fig. 3D), a feature unique to a subglacial environment where mechanic grinding and fracturing occurs under the persistent overburden pressures from glaciers (Benn and Evans, 2010). (Additional images are available in the GSA Data Repository[1].)

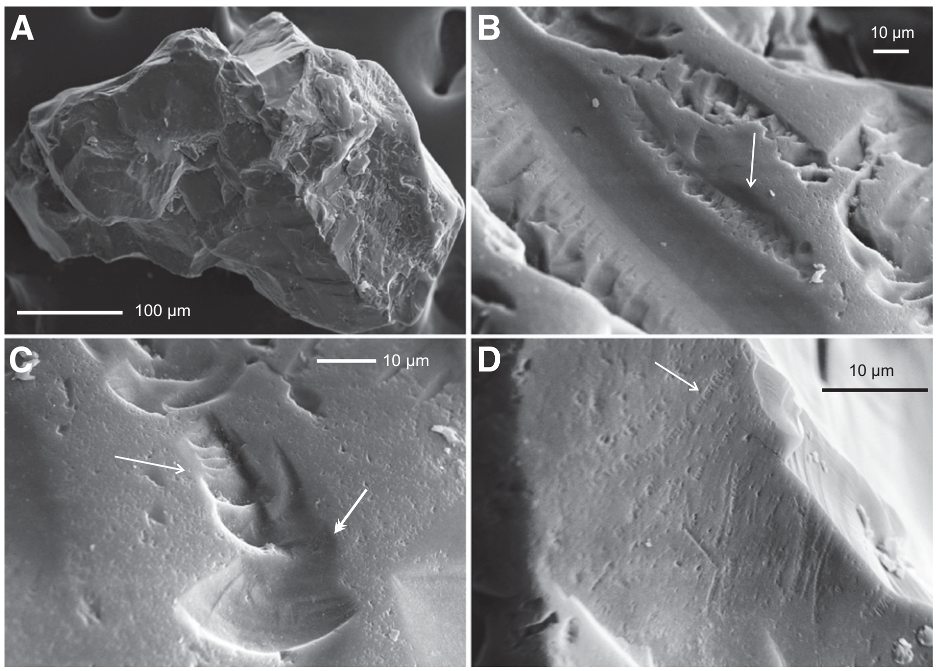

Figure 3. Microtextures of quartz grains under scanning electron microscopy, formed typically in a subglacial environment. A: Subangular grain with a deep trough. B: Coaxial crescentic gouges in a groove (arrow). C: Truncation of a trail of crescentic gouges in a groove (arrow) by another gouging feature (double-head arrow). D: Parallel striae and transverse crescentic fractures along striae (arrow).

[1]GSA Data Repository item 2012277, Figures DR1–DR5, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Thin sections of the Pliocene till were compared with those of the late Wisconsinan tills in the nearby area. All of the samples reveal the sediment to be glacial diamict of likely subglacial origin. Both tills were emplaced as sediments containing a large volume of entrained, scavenged sediments from a subglacial deforming layer. Some of these included sediments that were most likely frozen prior to emplacement. Evidence of porewater escape, clay translocation, and other deformation textures all suggest that, following emplacement, the overburden pressures from an ice sheet resulted in porewater transmission throughout these sediments (Menzies et al., 2006). The relatively few edge-to-edge grain crushing events may point to low stress levels under a thin lobe of the Pliocene ice sheet in the James Bay Lowland. It is further hypothesized that these tills may indicate sediments laid down under ice-lobe surging conditions.

POLLEN ANALYSIS

Pollen analysis of over 100 samples from the lacustrine deposit indicates an assemblage from the North Carolina–like mixed deciduous forest to a boreal evergreen forest (Fig. 4). The Carolinian forest is dominated by *Quercus* (oak) and *Pinus* (pine), followed by *Carya* (hickory), *Liquidambar* (sweetgum), and other hardwood trees, as well as *Taxodium* (cypress). *Taxodium*-like leaf stomata were found in the deposit, confirming the presence of a local cypress swamp. Fossil wood that lacks resin canals also suggests local trees of Taxodiaceae (redwood family) (J.F. Basinger, 2011, personal commun.). The boreal forest consists of *Picea* (spruce), *Abies* (fir), and *Betula* (birch). Although it remains undetermined whether *Pinus* came primarily from Carolinian or boreal species, this pollen type trends opposite to oak, suggesting that it responds to changing climate (Fig. 4). By analogy with the modern floras (Whitehead and Tan, 1969; Wolfe, 1980), the Carolinian and boreal forests suggest a mean annual temperature of 8–12 °C and 0–3 °C, respectively, i.e., 13 to 1 °C higher than present (−1 °C) in this area.

Pollen analysis of detrital peat from a till sample indicates a flora like the Carolinian forest from the overlying lacustrine deposit, suggesting no significant composition gaps between the two floras (Fig. 4). The peat predated the glaciation and was later incorporated into the till during the advance of the ice sheet. This floral similarity suggests the emplacement of the till and overlying lacustrine deposits within a constrained time frame (e.g., the middle Pliocene) consistent with the sedimentological evidence above that indicates infill of the bedrock trench following the retreat of the ice sheet.

The Carolinian forest differs from the *Picea*- and *Larix* (larch)–dominated modern vegetation in this area, but resembles the late Tertiary mixed deciduous forests in middle- to high-latitude North America (Wolfe, 1980; McAndrews et al., 1982; Graham, 2010). The Tertiary floras of North America evolved over time with extinction and extirpation of species, becoming modernized or similar to present ones in the late Pliocene to early Pleistocene (Graham, 2010). Although virtually all of the trees in the pollen flora can be found in present-day eastern North America, most of them do not grow in the study area, which include *Quercus*, *Carya*, *Liquidambar*, *Nyssa* (tupelo), and *Taxodium*. Furthermore, *Pterocarya* (wingnut), now native to southeastern Asia, became extinct in North America by late Pliocene to early Pleistocene (Groot, 1991; Pazzaglia et al., 1997). The pollen flora suggests Pliocene age, consistent with the magnetostratigraphy. It differs from the Miocene floras of eastern North America that contain, in addition to *Pterocarya*, other trees relict to this region (e.g., *Engelhardia*, *Melia,* and *Podocarpus*) (McCartan et al., 1990; Pazzaglia et al., 1997). In the early Pliocene at 5–4 Ma, boreal forests grew in the Canadian Arctic, and in the early Pleistocene at ca. 2 Ma, forest tundra grew in northern Greenland (Salzmann et al., 2008; Csank et al., 2011). A correlation to the Pliocene of this pollen flora agrees well with this geographic trend and the projected regional vegetation of middle Pliocene (Salzmann et al., 2008).

DISCUSSION AND CONCLUSIONS

The till in the bedrock trench is direct evidence for glaciation of North America in the midlatitude James Bay Lowland at ca. 3.5 Ma. An advancing ice sheet likely excavated this trench along some structurally weakened zones resulting from the Jurassic kimberlitic volcanic eruptions that fractured the adjacent limestone bedrock and perhaps also resulting from karst processes. The alignment of the trench suggests an ice flow probably to the west-southwest. Like the late Wisconsinan Laurentide ice sheet (Shilts, 1980), an ice dome ~500 km northeast of the study site in northern Quebec and Labrador would have caused ice to flow west-southwestward across the James Bay Lowland. With the retreat of the ice sheet, the trench hosted a lake that was slowly silted up.

After glaciation, rapid warming permitted Carolinian forest to expand into this region (Fig. 4). The gradual rise of *Picea*, *Pinus*, and *Betula* and decline of *Taxodium* and *Quercus* suggest cooling during a prolonged postglacial period from 3.5 to 3.0 Ma. Within the cooling trend, the climate oscillated. During warm periods, Carolinian forest grew, whereas during cool intervals, boreal forest predominated (Fig. 4). The number of climate oscillations visible in the pollen succession should be treated as the minimum because of the large sampling intervals (>1 m) in pollen analysis. The cooling at the top of the lacustrine sequence coincides with coarse-grained debris in the laminated silt and clay (Fig. 2D), which suggests icebergs in the lake. Although the present data do not permit distinguishing seasonal ice from glacier ice, the disappearance of thermophilic trees

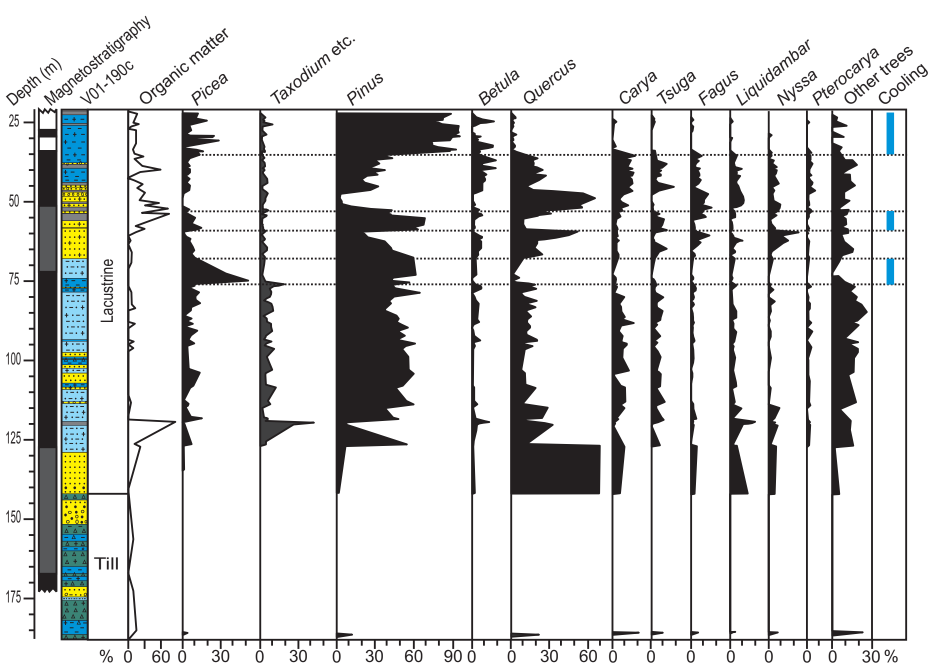

Figure 4. Major fossil pollen types and inferred climate oscillations. "Other trees" include *Ulmus* (elm), *Acer* (maple), *Ostrya* (hop-hornbeam), *Ilex* (holly), *Tilia* (lime/linden), *Abies* (fir), and *Castanea* (chestnut). Herbs are insignificant, including Cyperaceae, Ericaceae, and Poaceae. For simplification, they are not included. Blue bars indicate cooling intervals. Pollen data expressed as percentages of 200 or more tree pollen. Refer to Figure 2 for lithology.

attests to significant cooling during this period (Fig. 4). A gradually cooled, oscillated climate is consistent with marine benthic $\delta^{18}O$ records (Lisiecki and Raymo, 2005).

The glaciation of the James Bay Lowland coincides with the intensification of glaciation in the northwest Pacific region during Marine Isotope Stage MG6 at ca. 3.45 Ma (Maslin et al., 1995; Lisiecki and Raymo, 2005). For the middle Pliocene, this is the only time when a major flux of icebergs occurred in the North Pacific Ocean, thus providing a reliable marine record for correlation. In contrast to the benthic $\delta^{18}O$ record that shows an increase in global ice then (Jansen and Sjøholm, 1991), no major ice-rafted detritus accumulated in the North Atlantic to indicate significant ice expansion in Greenland and Fennoscandia (Kleiven et al., 2002). This implies significant contribution from the glaciation in North America to the elevated benthic $\delta^{18}O$ value recorded. On the other hand, the lack of major ice-rafted detritus in the North Atlantic does not exclude the possibility that ice sheets developed in the continental interior but did not reach the coast.

ACKNOWLEDGMENTS

We thank De Beers Canada for granting access to their drill cores and Victor diamond mine, and three anonymous reviewers for their comments and suggestions. James Basinger and David McNeil undertook wood and foraminifer analyses, respectively. Discussions were had with Derek Armstrong on Paleozoic geology; Andy Bajc, Peter Barnett, Ross Kelly, Julie Kong, Nicole Januszczak, Stephan Kurszlaukis, and Stew Hamilton on glacial geology; and Phil Gibbard and Sylvia Peglar on Tertiary floras. John Hechler and Sandra Clarke assisted in SEM analysis, and Zhenyu Yang and Jusong Shi in paleomagnetism work. This paper is published with the permission of the Director of the Ontario Geological Survey.

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Manuscript received 5 December 2011
Revised manuscript received 11 April 2012
Manuscript accepted 3 May 2012

Printed in USA