Absolute chronology for major Pleistocene advances of the Laurentide Ice Sheet

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ABSTRACT

We used a ^{26}Al-^{10}Be burial isochron method to date the glacial stratigraphic section in Missouri, USA, that records the largest advances of the Laurentide Ice Sheet. This permits an improved comparison of terrestrial and marine records of glaciation. The first recorded advance of the Laurentide Ice Sheet reached 39°N, near the extreme southern limit of North American glaciation, 2.4 Ma. The next advance to this latitude took place near the beginning of the mid-Pleistocene transition, 1.3 Ma, and three more took place from 0.75 to 0.2 Ma. There is no evidence that the Laurentide Ice Sheet advanced south of ~45°–47°N between 2.4 and 1.3 Ma. This chronology: (1) shows that North American continental glaciation postdated Cordilleran alpine glaciation; (2) is consistent with the hypothesis that both of these events were threshold responses to tropical cooling; (3) is consistent with the hypothesis that the first advance of the Laurentide Ice Sheet was glaciologically anomalous due to the presence of deformable preglacial regolith; (4) is not consistent with the hypothesis that this deformable regolith persisted until the mid-Pleistocene transition; and (5) indicates that the increase in global ice volume at the mid-Pleistocene transition was at least in part the result of a more extensive Laurentide Ice Sheet.

INTRODUCTION

The defining feature of Earth's climate during the past 2–3 m.y. is the presence of ice sheets on the northern continents. However, nearly all paleoclimate records for this period, that underpin models that seek to explain the initial growth and periodic advance of these ice sheets, are drawn from marine sediments. This reflects the contrast between the continuous and well-preserved nature of marine sediments and the discontinuous and difficult to date terrestrial glacial stratigraphic record. Global ice volume can be reconstructed from marine geochemical records, but, with the exception of the most recent glaciation, it is rarely possible to know where individual ice sheets were located. This in turn makes it difficult to understand processes responsible for Pliocene–Pleistocene climate and ice sheet change. For example, (1) the latitudinal extent of ice sheets controls their susceptibility to summer melting, but cannot be determined from marine geochemical records, and (2) one cannot distinguish, from marine records alone, whether variability in total ice volume reflects variability in the geographic extent of ice sheets, variability in their thickness, or simply which ice sheets existed during particular ice volume excursions (e.g., Raymo and Huybers, 2008). These issues could be resolved by absolute dating of the extensive glacial stratigraphic records on the polar continents. However, this has not been possible because Pliocene–Pleistocene glacial sedimentary sequences in North America and Eurasia are both difficult to date, because volcanic ashes are rare in cratonic areas, and difficult to correlate over large areas, because of the discontinuous nature of glacial deposition. Here we use cosmogenic-nuclide burial dating to date the sequence of glacial deposits that record the southernmost Pleistocene advances of the Laurentide Ice Sheet into the central United States. This clarifies the history of the Laurentide Ice Sheet and provides new constraints on ice extent that can help to guide Pliocene–Pleistocene climate–ice sheet models.

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MISSOURI TILL SEQUENCE

The glacial stratigraphic section in central Missouri, USA, includes five lithologically and magnetostratigraphically distinct tills that record advances of the Laurentide Ice Sheet to near its most southern extent at 39°N. These tills include: (1) the Atlanta Formation, a magnetically reversed till that overlies colluvium and bedrock residuum; (2) the magnetically reversed Moberly Formation; and (3) the normal polarity Fulton, Columbia, and Macon members of the McCredie Formation (Fig. 1; Rovey and Tandarich, 2006). Regional loess and soil stratigraphy indicates that all five predate marine isotope stage (MIS) 6 (ca. 0.15 Ma) (Rovey, 1997). Although glacial sequences typically contain unconformities, several features of the Missouri sequence indicate that all ice advances into this region are recorded by tills. First, a dense network of boreholes and extensive exposure due to active clay mining permits comprehensive access to the entire section. Second, although not all tills are observed at all sections, tills always occur in the same sequence. Third, paleosols are nearly always present between tills, indicating that tills were rarely significantly eroded by later ice advances.

^{26}AL-^{10}BE BURIAL DATING

We used two different methods of cosmogenic-nuclide burial dating. These rely on pairs of trace nuclides that are produced at a fixed ratio by cosmic-ray bombardment of minerals exposed at the Earth's surface, but have different half-lives. Here we use ^{26}Al and ^{10}Be, which are produced in quartz at ^{26}Al:^{10}Be = 6.75:1 and have half-lives of 0.705 Ma and 1.39 Ma, respectively. When quartz undergoes surface exposure, its ^{26}Al and ^{10}Be concentrations conform to the production ratio. If it is then buried deeply enough to halt the cosmic-ray flux,

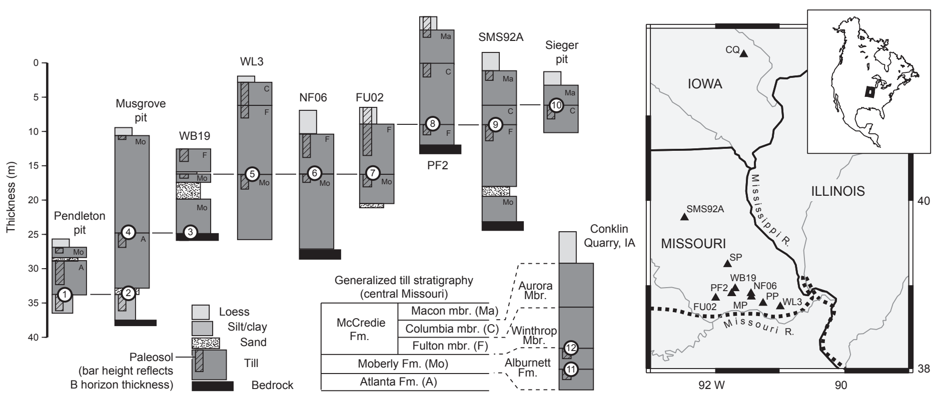

Figure 1. Stratigraphic nomenclature for glacial sediments in Missouri, site locations, and stratigraphy of clay pits and boreholes investigated in this work (mbr.—member; Fm.—formation]]. Correlation of Missouri stratigraphy to that at Conklin Quarry, Iowa (IA), is also shown. Numbers correspond to site numbers in Table 1. Dotted line on map shows southern limit of glacial deposits.

^{26}Al and ^{10}Be decay and the ^{26}Al/^{10}Be ratio diverges from the production ratio. Till-paleosol sequences imply that quartz in paleosols underwent surface exposure during soil formation, and then was buried by emplacement of the overlying till. Thus, ^{26}Al and ^{10}Be concentrations in paleosol quartz can be used to date overlying tills.

The simplest approach to ^{26}Al-^{10}Be burial dating applies when a sample has undergone a two-stage history including a single period of surface exposure and subsequent burial. In this case, ^{26}Al and ^{10}Be measurements on a single sample yield a unique burial age (Granger, 2006). We refer to an age thus determined as a "simple" burial age. This situation applies at several of our sites where a paleosol formed in place from underlying bedrock is overlain by till. However, the parent material of most paleosols in this study is till. Simple burial dating fails in this case because quartz in till is commonly recycled from older sediment that underwent previous episodes of exposure and burial (Balco et al., 2005b). At these sites, inherited ^{26}Al and ^{10}Be were present in an unknown ratio at the time that soil formation began. In order to deal with this situation, we developed an isochron method of burial dating in which one measures ^{26}Al and ^{10}Be concentrations at several depths in the paleosol. These concentrations form a line in ^{26}Al-^{10}Be space, the slope of which reflects the burial age of the paleosol regardless of the inherited nuclide concentrations (Balco and Rovey, 2008).

AGES

We dated the lowest till, the Atlanta Formation, at two sites where it overlies bedrock residuum. Four simple burial ages from one site agree with two from another and yield a mean age of 2.42 ± 0.14 Ma (Table 1). This till and underlying sediment are magnetically reversed (Rovey et al., 2006), so must postdate the 2.6 Ma Matuyama-Gauss reversal. The till was most likely emplaced during MIS 96–100 (2.43–2.54 Ma). We dated the second-lowest till, the Moberly Formation, at two sites. Four simple burial ages from a site where it overlies bedrock residuum agree with an isochron age at a site where it overlies the Atlanta till, yielding a mean age of 1.307 ± 0.089 Ma (Table 1; Fig. 2). At some sites the Moberly displays a parting or weak weathering zone separating tills of identical composition, suggesting the possibility of deposition by two closely spaced ice sheet advances. However, we have not observed a paleosol at this horizon. We dated the third till, the Fulton till, at three sites where it overlies the Moberly till. Three isochron ages agree, yielding a mean age of 0.798 ± 0.056 Ma. This till is magnetically normal, so must postdate the 0.78 Ma Brunhes-Matuyama reversal (Rovey and Kean, 1996). It was most likely emplaced during MIS 18 (0.76–0.72 Ma). These results show that the burial ages are (1) consistent with magnetostratigraphic age constraints, and (2) reproducible both between sites and between simple and isochron burial ages. Two isochron ages on the second-youngest Columbia till have a mean age of 0.22 ± 0.16 Ma, and one on the uppermost Macon till yields an age of 0.21 ± 0.18 Ma. The large uncertainties in these youngest ages reflect the growth of relative uncertainties with decreasing burial age, at a rate controlled by the production rates and half-lives of the nuclide pair (Balco and Shuster, 2009). The ^{26}Al/^{10}Be pair is not well suited to dating sediments younger than 0.4 Ma. These two tills were most likely emplaced during MIS 8–12 (0.25–0.5 Ma).

Rovey and Kean (1996) proposed correlations between the Missouri till sequence and a sequence of at least five widely recognized tills to the north in Nebraska and Iowa (Fig. 1) on the basis of paleomagnetism, till composition, and stratigraphic order. The Atlanta till resembles reversed tills called C by Boellstorff (1978) or R2 by Roy et al. (2004). At one site a C till underlies a 2 Ma volcanic ash. The Moberly till resembles reversed tills variously called B, A4 (Boellstorff, 1978), R1 (Roy et al., 2004), or the Alburnett Formation (Hallberg, 1980). At one site, a B till overlies a 1.3 Ma ash. The Fulton, Columbia, and Macon tills in Missouri resemble normal polarity tills called A Boellstorff (1978), N (Roy et al., 2004), or the Wolf Creek (Hallberg, 1980). To evaluate these correlations, we dated Alburnett and Wolf Creek tills at Conklin Quarry, Iowa. Like the Moberly in Missouri, the Alburnett displays a weathering zone between two otherwise indistinguishable tills. However, at this site a weak paleosol (A horizon directly overlying C) is present. Quartz in this paleosol

TABLE 1. ^{26}AL-^{10}BE BURIAL AGES

Site	Paleosol	Till dated	Site name	Type of burial date	Age (Ma)	Internal uncertainty* (Ma)	External uncertainty† (Ma)
1	Whippoorwill	Atlanta	Pendleton pit§	Simple (n = 4)	2.281	0.089	
2	Whippoorwill	Atlanta	Musgrove pit**	Simple (n = 2)	2.482	0.059	
		Atlanta	**Error-weighted mean:**		**2.421**	**0.049**	**0.143**
3	Residuum	Moberly	WB19	Simple (n = 4)	1.307	0.055	
4	Atlanta	Moberly	Musgrove pit††	Isochron	1.31	0.13	
		Moberly	**Error-weighted mean:**		**1.307**	**0.051**	**0.089**
5	Moberly	Fulton	WL3††	Isochron	0.798	0.044	
6	Moberly	Fulton	NF06	Isochron	0.74	0.12	
7	Moberly	Fulton	FU02	Isochron	0.839	0.096	
		Fulton	**Error-weighted mean:**		**0.798**	**0.038**	**0.056**
8	Fulton	Columbia	PF2††	Isochron	0.21	0.16	
9	Fulton	Columbia	SMS92A	Isochron	0.31	0.50	
		Columbia	**Error-weighted mean:**		**0.22**	**0.15**	**0.16**
10	Columbia	Macon	Sieger pit††	Isochron	0.21	0.17	0.18
11	Alburnett lower	Alburnett upper	Conklin Quarry	Isochron	0.87	0.43	0.43
12	Westburg	Winthrop	Conklin Quarry	Isochron	0.72	0.37	0.37

Note: For cosmogenic-nuclide concentrations and age calculation methods, see text footnote 1.

*Includes ^{26}Al and ^{10}Be measurement uncertainties as well as site-specific uncertainties in the thicknesses, densities, ages, and estimated erosion rates of overburden units. Should be used when comparing burial ages to each other.

†Also includes production rate and decay constant uncertainties. Should be used when comparing burial ages to ages determined by other methods.

§Some data from this site are also in Rovey and Balco (2010).

**Some data from this site are also in Balco et al. (2005a).

††Some data from this site are also in Balco and Rovey (2008).

yielded an isochron age of 0.87 ± 0.43 Ma for the upper Alburnett. Low ^{26}Al and ^{10}Be concentrations in these samples (Table DR1; see the GSA Data Repository[1]) decrease precision in the burial age and also indicate, in agreement with the weak soil development, that this paleosol was exposed for <10 k.y. The two Moberly and/or Alburnett tills most likely record ice-marginal fluctuations during a single glaciation, rather than multiple glaciations. The paleosol overlying the Alburnett yielded 0.72 ± 0.37 Ma for the lowest Wolf Creek till. These ages are consistent with the proposed Alburnett-B/A4-Moberly and Fulton-A-Wolf Creek correlations.

CONCLUSIONS

The ages for the Missouri till sequence, and the likely correlation between the Missouri and Iowa-Nebraska tills, lead to three important conclusions. First, the time of the first Laurentide Ice Sheet advance into central North America is indistinguishable from the sustained appearance of ice-rafted debris (IRD) in North Atlantic marine sediments at 2.5–2.6 Ma (Raymo et al., 1989; Fig. 3). With the exception of a till of possible Gauss age in the western Canadian Arctic (Barendregt and Duk-Rodkin, 2004), there is no evidence for continental glaciation in North America before emplacement of the Atlanta till. Thus, the development of the Laurentide Ice Sheet postdates the sustained appearance of significant IRD in North Pacific marine sediments at 2.7 Ma (Prueher and Rea, 1998), as well as Gauss-age mountain glaciations in the Canadian Rockies (Barendregt and Duk-Rodkin, 2004), showing that the initiations of North American montane and continental glaciation were temporally distinct. This sequence of events is consistent with hypotheses that successive initiations of montane and continental glaciation in North America were threshold responses to gradual changes in tropical temperature, tropical ocean stratification, and/or atmospheric CO_2 after ca. 3 Ma (e.g., Huybers and Molnar, 2007, and references therein; Fig. 3). It also provides an opportunity to test these hypotheses by comparing the climatological requirements for glaciation in these regions with the corresponding climate changes implied by these processes.

Second, all evidence indicates that a single ice sheet advance to 39°N took place at 2.4 Ma, and no similarly extensive advance occurred until 1.3 Ma. Boellstorff (1978) suggested, on the basis of silt partings and a weak oxidation zone at two sites in eastern Nebraska near the extreme southwestern limit of glaciation, that the C tills

[1]GSA Data Repository item 2010224, materials and methods, Figs DR1–DR2, and Tables DR1–DR2, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

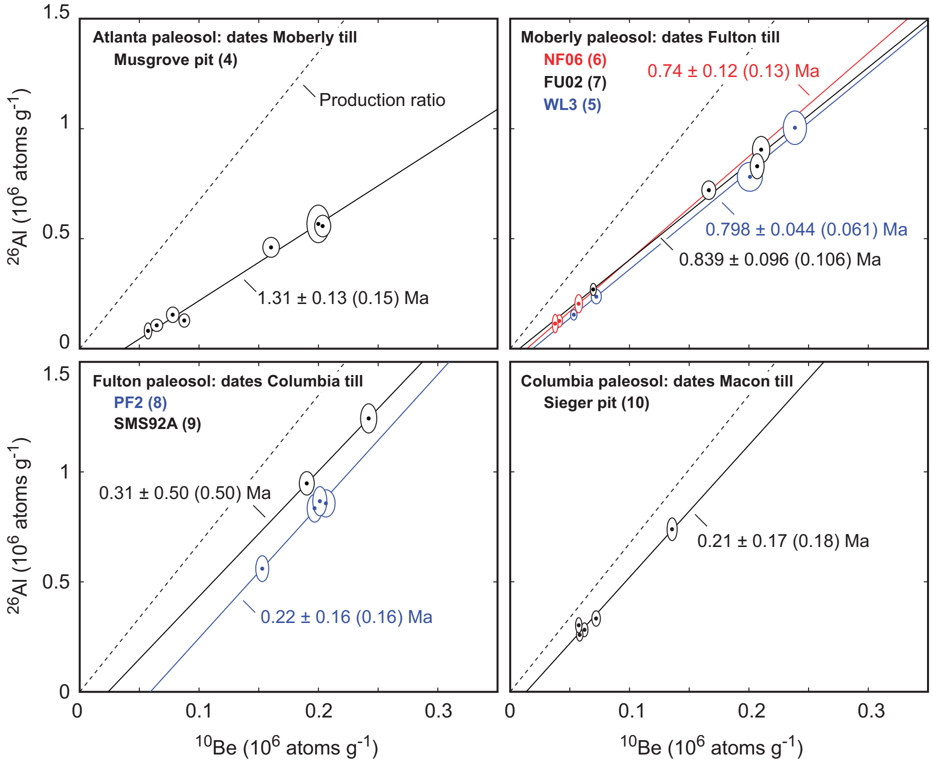

Figure 2. ^{26}Al-^{10}Be burial isochrons for Missouri tills. Where several isochrons are shown together, isochron of particular color is drawn through data shown in same color. Ellipses are 68% confidence regions reflecting measurement uncertainty. ^{26}Al and ^{10}Be concentrations have been corrected for post-burial nuclide production as described in Balco and Rovey (2008). Numbers in parentheses correspond to Table 1. Nuclide concentrations and age calculation methods appear in Data Repository (see footnote 1).

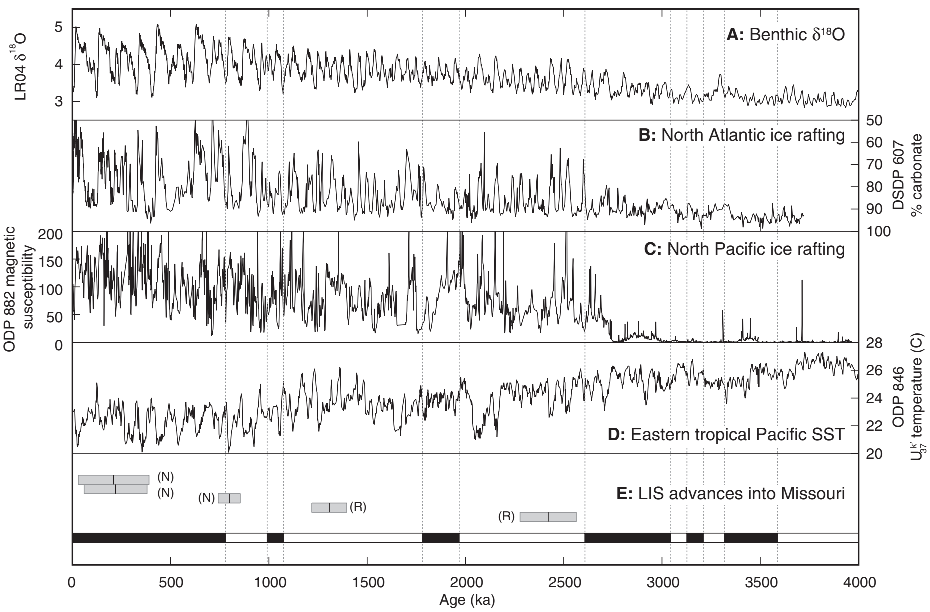

Figure 3. Laurentide Ice Sheet advances into central Missouri compared with Pliocene–Pleistocene climate records. A: LR04 benthic δ^{18}O stack (Lisiecki and Raymo, 2005). B: Percent carbonate at Deep Sea Drilling Project (DSDP) Site 607, central North Atlantic (Raymo et al., 1989). Inverted scale reflects inverse proportionality of carbonate to ice-rafted debris (IRD). C: Magnetic susceptibility, which is proportional to IRD concentration, at Ocean Drilling Program (ODP) Site 882, central North Pacific (Rea et al., 1995). D: $U^{k'}_{37}$ alkenone sea-surface temperature (SST) at ODP Site 846, eastern equatorial Pacific (Lawrence et al., 2006). E: Ages for central Missouri tills (gray boxes; width reflects 1σ uncertainty) and geomagnetic polarity time scale (black, normal; white, reversed). Magnetic polarity (N—normal; R—reversed) of tills is noted in parentheses.

represented two distinct ice sheet advances. We examined these sites and found no evidence that these features represent a detectable period of exposure or soil formation. We conclude that they record local ice-marginal fluctuations and the C–R2–Atlanta till records a single major ice sheet advance. This is important because marine oxygen isotope records show lower amplitude ice volume changes before, and higher amplitude after, the 0.8–1.25 Ma mid-Pleistocene transition from 41 k.y. to 100 k.y. periodicity evident in numerous paleoclimate records. In contrast, the longstanding observation that there is least one till older than 2 Ma in Iowa and Nebraska has suggested that the geographic extent of the Laurentide Ice Sheet must have been similar both before and after the mid-Pleistocene transition (Clark and Pollard, 1998, and references therein). There is indirect evidence that ice sheets were present somewhere in North America 2.4–1.3 Ma from (1) sustained IRD deposition in the North Atlantic (Fig. 3), and (2) negative $\delta^{18}O$ excursions in Gulf of Mexico surface waters 1.9–1.6 Ma that suggest the presence of ice within the Mississippi watershed (Joyce et al., 1993). Thus, we propose that following a single anomalous advance to 39°N at 2.4 Ma, the southern margin of the Laurentide Ice Sheet was no further south than ~45°–47°N, the northern boundary of the Mississippi drainage, between 2.4 and 1.3 Ma. The anomalous geographic extent of the first advance is consistent with the hypothesis that the mobilization of deformable preglacial regolith at initial Laurentide Ice Sheet development forced shallower ice surface slopes, and a greater geographic extent for the same ice volume, for the first ice sheet advance than for later advances (Clark and Pollard, 1998). However, it is not consistent with the further hypothesis of Clark and Pollard (1998) that this deformable regolith survived until the mid-Pleistocene transition.

Third, the presence throughout central North America of tills that are correlative with the 1.3 Ma Moberly till in Missouri shows that a significant expansion of the Laurentide Ice Sheet was temporally indistinguishable from the beginning of the mid-Pleistocene transition. Clark et al. (2006) showed that 100 k.y. periodicity in climate and ice volume records was strong 1.25–1.1 Ma, weak 1.1–0.9 Ma, and strong after 0.9 Ma. As expected from the observation that the size of global ice volume changes increased with the emergence of 100 k.y. periodicity at the mid-Pleistocene transition, major advances of the Laurentide Ice Sheet into central North America correspond with the strength of the 100 k.y. period: large advances of the Laurentide Ice Sheet to near its extreme southern limit occurred near 1.3 Ma and were common after 0.8 Ma. Overall, the stratigraphy and chronology of glacial deposits in central North America show that, with the exception of a single geographically anomalous advance 2.4 Ma that may be explained by the unique subglacial sediment dynamics and consequent area-volume relationship of the first ice sheet to form, Laurentide Ice Sheet advances were more extensive after the mid-Pleistocene transition than before. Although the location of the southern margin of the Laurentide Ice Sheet is not necessarily an accurate proxy for its volume, it is most likely that the increase in global ice volume observed at the mid-Pleistocene transition is at least in part explained by an increase in the size of the Laurentide Ice Sheet.

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