The First Glacial Maximum in North America

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The regular advance and retreat of continental ice sheets is a defining feature of the past several million years of Earth history. Despite widespread glacial sediments in Europe, Asia, and North America, however, most of what we know about the timing and extent of ice sheets before the most recent ones comes from marine oxygen-isotope ($\delta^{18}O$) records. This is because there are few methods for dating terrestrial glacial deposits that are too old for ^{14}C or luminescence dating techniques. Marine isotope records reflect global ice volume and rarely identify the location of the ice, so it is seldom possible to associate individual terrestrial glacial deposits with particular marine isotope stages. This presents a challenge to understanding long-term ice sheet and climate dynamics. Here we use an example from North America to describe a way to overcome this difficulty, by using the cosmic ray–produced radionuclides ^{26}Al and ^{10}Be to date sequences of intercalated paleosols and tills.

These two nuclides are produced at a fixed ratio in quartz that is exposed to cosmic rays, but they decay at different rates. If sedimentary quartz is exposed long enough that nuclide concentrations reach a balance between production and loss by decay and surface erosion and is then buried and removed from the cosmic ray flux, ^{26}Al and ^{10}Be measurements can yield the duration of burial and the erosion rate before burial. This technique has been used to date river sediment buried in caves (*1*); we adapted it to more complicated stratigraphic situations (*2*). It is most accurate when sediments are exposed for long periods of time (>10^5 years) and then buried rapidly to at least several meters' depth. This situation arises when soils develop during long periods of landscape stability and are then buried by till during ice sheet advances. In this case, the ^{26}Al and ^{10}Be concentrations in the buried soil tell us the age of the overlying till.

At the Musgrove clay pit in central Missouri (Fig. 1), two tills, the Atlanta and Moberly formations, overlie deeply weathered shale and limestone as well as locally derived colluvium of the Whippoorwill formation. Each till is capped by a paleosol; thus, the section records a long period of weathering and slow erosion before glaciation, followed by at least two ice sheet advances with an intervening period of soil formation (fig. S1) (*3*). We measured ^{26}Al and ^{10}Be in quartz from paleosols in the Whippoorwill and Atlanta formations (table S1) and found that the Atlanta till was deposited 2.41 ± 0.14 million years ago (Ma). The Whippoorwill paleosol has unusually high nuclide concentrations, which allows accurate measurements and ensures that any slow production of nuclides after burial is insignificant compared to the large nuclide inventory produced before burial. This minimizes the effect of uncertainties in the burial history and in the nuclide production rates on our inferred age for the Atlanta till. Samples from the Atlanta paleosol had lower nuclide concentrations, leading to larger uncertainties, and determining the age of the Moberly till from these samples required assumptions about the initial nuclide concentration in the Atlanta till. Given a conservative range of concentrations, the Moberly till is 1.6 to 1.8 million years old.

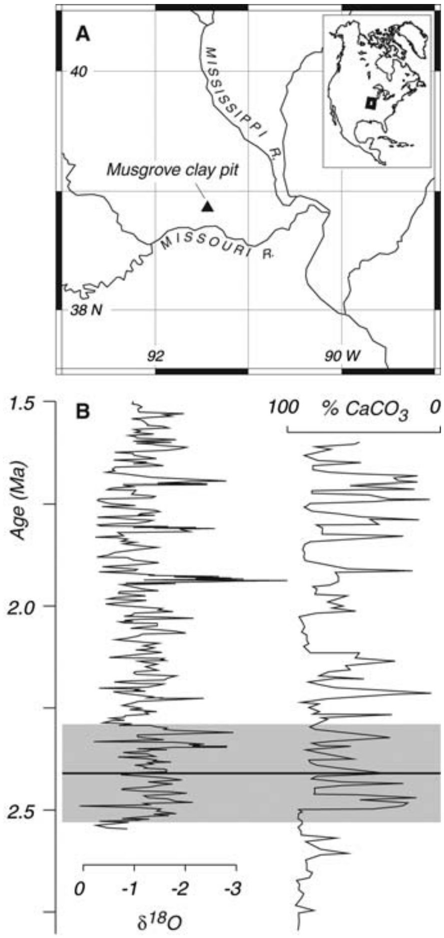

Fig. 1. (**A**) The location of Musgrove pit. (**B**) Marine records suggesting early advances of the Laurentide Ice Sheet: the $\delta^{18}O$ record from Ocean Drilling Program site 625A in the Gulf of Mexico (*4*) and the carbonate percentage at Deep-Sea Drilling Program site 552A in the North Atlantic, which is inversely related to the concentration of ice-rafted debris (*5*). The horizontal line and the shaded band denote our age estimate for the Atlanta till and ±1σ uncertainty. We have adjusted the time scales of the $\delta^{18}O$ (*4*) and $CaCO_3$ (*5*) records to account for revisions to the magnetic polarity time scale (*2*); however, the two time scales may differ in this age range.

The Atlanta till is thus the oldest direct evidence of continental glaciation in the Northern Hemisphere. It records the first, and nearly the most southerly, advance of the Laurentide Ice Sheet. Given our dating uncertainty, this is likely the same advance suggested by negative $\delta^{18}O$ excursions in Gulf of Mexico sediments of similar age (*4*), although the present uncertainties in the half-lives of ^{26}Al and ^{10}Be (*2*), as well as in the time scales for the marine records, make it difficult to correlate either event with the major increase in North Atlantic ice-rafted debris near 2.5 Ma (shown in Fig. 1 by the abrupt decrease in $CaCO_3$ percentage) (*5*). The idea that Northern Hemisphere continental ice sheets first formed 2.7 to 2.4 Ma has previously been based on inference from marine sediments. The Atlanta till is direct terrestrial evidence that the Laurentide Ice Sheet did in fact develop and advance to its full extent during this time interval.

References and Notes

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Supporting Online Material
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Materials and Methods
Fig. S1
Table S1
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