

Fate of the preglacial regolith beneath the Laurentide Ice Sheet

Greg Balco^{a,*} John O.H. Stone^a Carrie E. Jennings^b

^a *Quaternary Research Center and Department of Earth and Space Sciences
University of Washington, Mail Stop 351310, Seattle, WA 98195-1310 USA*

^b *Minnesota Geological Survey
2642 University Ave. W., St. Paul, MN 55114-1057 USA*

Abstract

Subglacial erosion and transport of deformable sediment influence the size, stability, and sensitivity to climate of large ice sheets. These processes may cause or sustain ice-sheet instabilities [1], and may have dictated the periodicity of the Cenozoic ice ages, in particular the enigmatic mid-Pleistocene transition from small and frequent to large and infrequent glaciations [2,3]. Subglacial erosion, however, is difficult to study. Where active at present, it is hard to observe, and, like other erosional processes, it continuously removes the evidence of its previous actions. Here we use the cosmic-ray-produced radionuclide ^{10}Be , which is abundant in deeply weathered soils but absent in fresh bedrock, to investigate the sources of subglacial sediment eroded from the Canadian Shield by the Laurentide Ice Sheet (LIS) and deposited as till in the north-central U.S. Some tills have extraordinarily high ^{10}Be concentrations, as high as those in deeply weathered regolith in unglaciated areas that has accumulated ^{10}Be over millions of years. In general, the lowermost tills have high ^{10}Be concentrations, tills directly overlying them have ^{10}Be concentrations that are lower by an order of magnitude, and Wisconsinan tills have the lowest ^{10}Be concentrations. There are exceptions to this general picture in two boreholes, where intermediate-age tills have higher ^{10}Be concentrations than the oldest tills. These results, combined with a box model for ^{10}Be and sediment transport during a series of glaciations that we use to interpret the results, show the following: First, some tills cannot be the result of deep subglacial erosion of unweathered rock, but must have originated by mobilization of a relatively thin layer of deeply weathered surface sediment. This source can only have been the preglacial regolith and saprolite, the legacy of millions of years of Tertiary weathering, that was present on the Canadian Shield before the onset of Northern Hemisphere glaciation. Second, the preglacial regolith formed a source for early tills, but was rapidly removed from the core area of the ice sheet by the first few Plio-Pleistocene ice sheet advances. Third, renewed export of ^{10}Be -rich till sometime after 1 Ma appears to reflect an increase in the area exposed to subglacial erosion. It was likely a consequence, and not a cause, of a change in ice sheet dynamics at the mid-Pleistocene transition.

Key words: cosmogenic nuclides, beryllium-10, glacial erosion, Minnesota, South Dakota, till, Quaternary

1 Introduction

Once geologists of the 19th century recognized that the northern continents had been covered by massive ice sheets in the relatively recent geologic past, they and their successors looked at the streamlined and polished landscapes of these glaciated regions, and came to the intuitively reasonable conclusion that ice sheets were uniquely effective agents of erosion, and that these landscapes had been formed by the subglacial scouring off of perhaps hundreds of meters of crystalline bedrock. Flint [4] made one of the first efforts to evaluate this idea quantitatively by mapping and determining the volume of all the terrestrial glacial sediment in North America, and came to the apparently contrary conclusion that all of the Plio-Pleistocene advances of the Laurentide Ice Sheet (LIS) had accomplished only a few tens of feet of erosion of the Canadian Shield. White [5] pointed out that this ignored the much larger quantity of sediment deposited in the oceans, and revised the estimate upward once again; since then a large array of evidence has been marshaled to support one or the other of these positions [6–14]. From the perspective of this paper, the most interesting pieces of evidence that have arisen from this controversy are: 1) the similarity in shape between glacially polished landscapes and the chemical weathering front beneath regolith- and saprolite-mantled terrain in unglaciated regions; and 2) the numerous examples of surviving pre-glacial regolith in glaciated regions. These suggest that Plio-Pleistocene ice sheets may have done no more than remove a pre-existing blanket of deeply weathered regolith — the legacy of a temperate Tertiary climate acting on stable, low-relief cratonic surfaces over millions of years – and lightly buff the surface of the underlying unweathered bedrock [15–17].

This idea is important because of its relationship to paleoclimate research through the connections between subglacial sediment, ice-sheet dynamics, and climate change. The basic idea is that ice sheets bedded in soft, easily deformable sediment and ice sheets that sit on undeformable beds of competent rock have fundamentally different dynamics. This idea can explain otherwise enigmatic features of present and former ice sheets, in particular ice streams and ice sheet collapses. Both glaciological principles [18] and observations from the West Antarctic Ice Sheet (WAIS) [19,20] suggest that deformable subglacial sediment is necessary to initiate and maintain fast, low-gradient stream flow within ice sheets: this type of flow is in

* Corresponding author. Tel. 206-221-6383

Email addresses: balcs@u.washington.edu (Greg Balco),
stone@geology.washington.edu (John O.H. Stone), carrie@umn.edu
(Carrie E. Jennings).

turn required to support the physical instabilities believed to be responsible for quasi-periodic “collapses” of the WAIS [1] and the LIS [21]. A further suggestive idea is that the supply of deformable subglacial sediment appears to be finite: physical arguments [18] indicate that the export of deformable sediment should greatly exceed the rate at which it is produced from fresh bedrock. Thus, ice streams and large-scale ice sheet instabilities must rely on a pre-existing reservoir of deformable subglacial sediment, and would cease with the exhaustion of this reservoir. Clark and others [3,2] combined these ideas with an effort to explain another enigmatic feature of the Plio-Pleistocene ice ages, that is, the middle Pleistocene transition between 40,000-yr and 100,000-yr frequencies in climate and ice sheet variability, and proposed that the preglacial regolith on the Canadian Shield served as a finite reservoir of deformable subglacial sediment beneath the LIS. In this hypothesis, early instances of the LIS were fast-flowing, low-gradient, and therefore thin, and could grow and melt rapidly in response to the dominant 41,000-yr insolation cycle. Subglacial erosion eventually exhausted the deformable regolith in the core areas of the LIS, and later instances of the ice sheet were thus hard-bedded, steeper in slope, and therefore thicker. By the middle Pleistocene, the LIS was too thick to grow and decay entirely within a single obliquity cycle, which forced the global ice-climate system into the longer-period, larger-amplitude oscillation characteristic of the last million years.

In this paper, we are motivated by the question of how the initial supply and eventual fate of deformable subglacial sediment is related to the long-term evolution of ice sheets, and, in particular, whether gradual erosion of the preglacial regolith beneath the LIS could have triggered the mid-Pleistocene climate transition. Subglacial erosion and sediment transport, however, are inherently difficult to study. First, where these processes are active at present, that is, at the bottom of ice sheets, they are difficult to observe; second, where the beds of former ice sheets are exposed, we face the problem common to all eroding landscapes that the record of past events is effaced as the surface erodes. Here we seek to work around these difficulties by using the cosmic-ray-produced radionuclide ^{10}Be , which is abundant in deeply weathered soils but absent in fresh bedrock, to characterize the source of subglacial sediment eroded from the Canadian Shield, and deposited in Minnesota and South Dakota, by the Laurentide Ice Sheet (LIS). We describe ^{10}Be concentrations in Minnesota tills and related glacial and preglacial sediments, and show: a), that ^{10}Be concentrations in some LIS tills are so high that they can only be derived from a ^{10}Be -enriched preglacial regolith; and b), that we can distinguish tills derived mostly from this regolith from those formed mostly from erosion of unweathered bedrock by their ^{10}Be concentrations. We then seek to explain the variation in ^{10}Be concentrations within Plio-Pleistocene till sequences by use of a simple box model that accounts for erosion of regolith and rock in the core area of the LIS, recycling of previously deposited tills during subsequent ice sheet advances, and continuing deposition and radioactive decay of ^{10}Be . We conclude eventually that the preglacial regolith was rapidly removed from the core area of the LIS and likely did not survive long enough to provide a trigger for the mid-Pleistocene climate

transition.

2 Atmospherically-produced ^{10}Be

In this study, we are concerned with atmospherically-produced ^{10}Be in soil and sediment. This “meteoric” or “garden-variety” ^{10}Be is produced in the atmosphere by spallation of N and O nuclei and delivered to the soil surface by precipitation. This source of environmental ^{10}Be is distinct from ^{10}Be produced by spallation of O nuclei within quartz grains (“*in-situ*”-produced ^{10}Be ”), which is commonly used for exposure-age dating of rock surfaces. The global average deposition rate of atmospherically-produced ^{10}Be is $\sim 1.3 \times 10^6 \text{ atoms} \cdot \text{cm}^{-2} \cdot \text{yr}^{-1}$ [22], which is large relative to typical (depth-integrated) *in-situ* ^{10}Be production rates at low elevations of $\sim 1.5 \times 10^3 \text{ atoms} \cdot \text{cm}^{-2} \cdot \text{yr}^{-1}$; thus the *in-situ*-produced contribution to the bulk ^{10}Be concentration in soil and sediment can be disregarded for our purposes. The half-life of ^{10}Be is $1.5 \times 10^6 \text{ yr}$.

^{10}Be produced in the atmosphere adheres to aerosols and arrives at the Earth’s surface mostly in precipitation, and to a lesser extent by dry deposition. It then adheres to soil and sediment particles. Under most natural conditions Be is nearly irreversibly bound to sediment [23]. At neutral to alkaline pH, soil-water partition coefficients for Be are $> 10^5$ [24], and there is also evidence that ^{10}Be can substitute for Al in weathering reactions and become immobilized in silicate and oxyhydroxide minerals [25,26]. Thus, regolith and saprolite that result from prolonged weathering become highly enriched in ^{10}Be (Figure 1). Eventually, the soil ^{10}Be inventory (‘inventory’ here denoting the depth-integrated ^{10}Be concentration per unit area, and having units of $\text{atoms} \cdot \text{cm}^{-2}$) reaches equilibrium between ^{10}Be addition by fallout, and loss by radioactive decay and surface erosion of soil particles [27]. Deep weathering profiles on stable cratonic landscapes south of the glacial limit in North America have total ^{10}Be inventories near $10^{12} \text{ atoms} \cdot \text{cm}^{-2}$ ([28,29]), and the regolith that covered the Canadian Shield prior to glaciation must have had similar characteristics. Pleistocene and Holocene soils that developed in glaciated regions during interglaciations of 10,000 – 60,000 yr may have high ^{10}Be concentrations in the uppermost few centimeters, but have much smaller total ^{10}Be inventories of $2 - 8 \times 10^{10} \text{ atoms} \cdot \text{cm}^{-2}$ (Figure 1 and references cited therein). Unweathered bedrock that is more than a few million years old contains no ^{10}Be . The order-of-magnitude contrasts between the ^{10}Be inventories in the preglacial regolith, interglacial soils, and unweathered rock means that the bulk ^{10}Be concentration of till should mainly reflect the extent to which the till was derived from remobilization of deeply weathered regolith rather than erosion of unweathered rock.

A number of previous studies (e.g., [30,31]) have sought similar information about till sources by looking for clay minerals characteristic of deeply weathered regolith in Laurentide tills. Atmospherically-produced ^{10}Be should be a better re-

regolith tracer than clay mineralogy for two reasons: first, the large concentration contrast between regolith and fresh bedrock; and second, the likely persistence of ^{10}Be through mineralogical changes that might otherwise disguise the contribution of a weathered source. Ratios of clay minerals such as expansible clays, illite/mica, and kaolinite in tills may record weathering history, but are more likely to reflect till provenance, especially from distinctive clay-rich sources such as the Cretaceous shales which are common in our study area. Weathering of such rock types is not necessarily reflected in clay mineralogy unless extreme silica loss occurs, but would be recorded by ^{10}Be uptake. For example, mineral indicators of intense weathering such as gibbsite have rarely been reported from Laurentide tills ([30] reports one case). This may be due to gibbsite breakdown under silica-rich conditions during erosion, transport, or diagenesis to produce clay minerals like illite or kaolinite that suggest less-intense weathering. ^{10}Be should be conserved during such mineralogical transformations, and may in fact become more tightly bound [26,32]. Conversely, although weathering of till after deposition could produce mineral assemblages that mimic the preglacial regolith, relatively low ^{10}Be inventories would remain a reliable indicator that weathering postdated rather than predated glaciation.

Finally, ^{10}Be should be conserved during the erosion, deposition, and postdepositional weathering of till if its pH remains neutral or alkaline. One of the advantages of our field area in Minnesota and South Dakota is that nearly all tills in this region contain limestone clasts and/or secondary carbonate cement, indicating neutral to slightly alkaline pH since till emplacement, and precluding significant postdepositional ^{10}Be loss to groundwater.

3 Till stratigraphy in southwest Minnesota and adjacent South Dakota

The regions of the north-central U.S. closest to the core area of the LIS, in northern Minnesota and the upper Great Lakes region, have experienced long-term glacial erosion and are largely bedrock with patchy Wisconsinan glacial sediment. The sedimentary section becomes thicker and more complete to the south. The thickest glacial sediments, which also record the greatest number of ice sheet advances, are located in southwest Minnesota and adjacent South Dakota. The stratigraphic section here consists mostly of till with few paleosols or other evidence of long interglaciations, suggesting that ice sheet advances were frequent and that most ice sheet advances deposited tills. Even farther to the south, in Iowa, Nebraska, and Missouri, the glacial section is thinner, there are fewer tills, and paleosols and loess are more common, reflecting the fact that fewer ice advances reached this latitude and ice-free periods were longer ([31,33–42]).

In this paper we focus on the ^{10}Be concentrations of tills from a set of boreholes in southwest Minnesota and adjacent South Dakota (Figures 2,3; Table 2). This area

is underlain by 100-300 m of Plio-Pleistocene glacial sediment, including at least 12 distinct tills that predate the most recent glaciation. All of these tills contain fragments of Canadian Shield rock types found north-northeast to northwest of the study area ([33–35]). We chose this area for three reasons: First, the greatest number of tills are present here, suggesting that this is the longest and most complete record of Plio-Pleistocene ice sheet advances available. Second, this area is near the northernmost extent of significant till accumulation, which means that the tills here are less likely than tills further south to include remobilized and recycled older glacial sediment. This makes it more likely that the primary source of these tills was subglacial erosion in the core area of the LIS to the north. Third, the stratigraphy consists primarily of till, with little evidence of soil development or prolonged interglacial exposure. This increases the likelihood that the ^{10}Be concentration in our samples reflects the source material for the till rather than postdepositional ^{10}Be accumulation during long periods between ice sheet advances.

One disadvantage of this region is that the chronology of the till sequence is not as well established as it is in areas further south. The stratigraphically lowest tills in our study area were deposited approximately 2 Ma, the uppermost tills are middle and late Wisconsinan in age, an intermediate till in one of the boreholes was deposited 1-1.2 Ma, and cosmogenic-nuclide analyses of interglacial fluvial sediments in some of the boreholes limit the ages of some other parts of the till section to 0.5-1.5 Ma ([43], summarized in Figure 4). In contrast, the till sequences farther south in Nebraska and Iowa are associated with three dateable volcanic ashes, so even though individual tills there cannot be directly dated, their ages can be bracketed with more confidence([31]). Roy and others ([44]), who also sought to learn about the fate of the preglacial regolith by looking for geochemical and mineralogical weathering indicators in LIS tills, chose the Nebraska-Iowa till sequence because of its better-established chronology. We chose not to use these tills for two reasons. First, the ice sheet advances that delivered tills to southern Iowa advanced over hundreds of kilometers of previously deposited glacial sediment, providing the maximum opportunity to dilute the portion of the till that originated in the core area of the ice sheet with recycled older tills, interglacial paleosols, or nonglacial deposits. Second, and more importantly, the long ice-free periods in Iowa and Nebraska mean that tills there were subjected to pervasive weathering and pedogenesis after they were emplaced, which makes it likely that the ^{10}Be concentration of the till source has been obscured by postdepositional ^{10}Be accumulation. We investigated this possibility with a set of trial measurements of ^{10}Be in Nebraska and Iowa tills (described in detail in [45]), and found that: a) tills believed to be the same on the basis of lithologic and stratigraphic correlations had ^{10}Be concentrations that scattered widely, in some cases by an order of magnitude; and b) higher ^{10}Be concentrations were associated with samples collected closer to the surface of a till (where the sample would have been closer to the surface during weathering and soil formation between ice sheet advances), and lower ^{10}Be concentrations with samples farther below the till surface, regardless of age. These observations suggested that, despite our efforts to obtain unweathered samples of till for our

analyses, the ^{10}Be concentration of these tills was seriously affected by postdepositional ^{10}Be addition during soil formation. Although these measurements do not entirely preclude the possibility that ^{10}Be analyses of southern-region tills might provide useful information about till sources, we conclude that the ^{10}Be concentrations in tills in Minnesota/South Dakota sequence are most likely to accurately reflect the ^{10}Be concentrations in sediment eroded from the core area of the LIS, and are thus more suitable for this study.

4 Analytical methods

We collected till samples from a total of nine drill cores (Tables 1,2) . We sought to obtain representative samples of unweathered and unoxidized till matrix by selecting samples well away from weathered zones at the surface of till units, avoiding oxidized joint surfaces, and excluding clasts larger than 0.5 cm. This resulted in 100-400 g samples of dry till matrix. We ground each sample to powder using a closed shatterbox-type mill, subsampled a 1-g aliquot, added 400 μg commercial reagent Be as carrier, and extracted Be by fusion with KHF_2 [46]. We measured Be isotope ratios at the Lawrence Livermore National Laboratory, Center for Accelerator Mass Spectrometry (LLNL-CAMS) and at the Purdue Rare Isotope Measurement Laboratory (PRIME Lab), and renormalized measurements from PRIME Lab to LLNL internal ^{10}Be standards. Our Be carrier solution had $^{10}\text{Be}/^9\text{Be} = 1.5 \pm 0.2 \times 10^{-14}$, and our process blanks contained an additional $8 \pm 5 \times 10^4$ atoms ^{10}Be .

5 Results: ^{10}Be concentrations in Minnesota and South Dakota tills

5.1 *How consistent is the ^{10}Be concentration in a particular till?*

In an effort to establish the extent to which the tills in our study area are well-mixed with regard to their ^{10}Be concentrations, we measured ^{10}Be concentrations in multiple samples from ten tills (these results are included in Table 1 and Figure 4, and are described in more detail in [45]). For nine of these tills, we collected several samples at different depths in the same borehole. In eight cases we found that the scatter in multiple measurements from the same till was 5-15 % of the average concentration. This degree of scatter exceeds the measurement uncertainty (~ 3 %) but is much smaller than the order-of-magnitude differences in ^{10}Be concentration between tills. The ninth case was the till between 51-59 m depth in borehole UMRB-3. This till appeared poorly mixed in core, being generally gray in color but containing seams and enclaves of red till, and, in fact, ^{10}Be concentrations in multiple samples from this till varied by a factor of five. We use the average of four measurements

for the ^{10}Be concentration of this till in later discussion. Finally, ^{10}Be concentrations in a till with distinctive lithology that can be correlated between boreholes (till unit 7 of [34]) were indistinguishable in two separate boreholes. We conclude that tills which appear lithologically well-mixed, that is, all the tills we analyzed in this study with the exception of the one poorly mixed till just discussed, do in fact have uniform ^{10}Be concentrations. Given that the ^{10}Be concentrations in tills in this study span two orders of magnitude, the fact that multiple analyses from individual tills agree within 5-15 % suggests that a single measurement is, for all practical purposes, sufficient to characterize the overall ^{10}Be concentration of a particular till.

5.2 ^{10}Be concentrations in Minnesota-South Dakota tills

The stratigraphically lowest units in boreholes UMRB-3 and SD-CO are nonglacial fluvial fine sands and silts. These underlie the entire glacial section and thus appear to represent the Pliocene surface sediment prior to the onset of glaciation. They have high ^{10}Be concentrations ($10^8 - 10^9$ atoms \cdot g $^{-1}$), as expected for surface sediment in an unglaciated, low-relief, cratonic landscape (Figure 4). The oldest tills in these boreholes, that directly overlie these sands and silts, have similar ^{10}Be concentrations. With two exceptions, progressively younger tills have progressively lower ^{10}Be concentrations. The exceptions occur in boreholes UMRB-1 and SD-CO, where we found intermediate tills with high ^{10}Be concentrations approaching 10^9 atoms \cdot g $^{-1}$. Finally, nearly all Wisconsinan tills have much lower ^{10}Be concentrations near 10^7 atoms \cdot g $^{-1}$. The one exception to this final observation is the uppermost till in borehole SD-CO, which is believed to be middle Wisconsinan in age but has a ^{10}Be concentration near 10^8 atoms \cdot g $^{-1}$; however, the age of this till is not well established, so we are hesitant to make too much of this exception.

The important features of these results, which we seek to explain in the rest of this paper, are as follows:

- (1) Some tills have extraordinarily high ^{10}Be concentrations.
- (2) In boreholes that penetrate the base of the glacial section (UMRB-3, SD-CO, and possibly SWRA-3), the lowermost tills have high ^{10}Be concentrations, and tills immediately overlying them have ^{10}Be concentrations that are lower by an order of magnitude or more. In general, younger tills contain less ^{10}Be and Wisconsinan tills have the lowest ^{10}Be concentrations of all.
- (3) There are exceptions to this overall trend where intermediate high- ^{10}Be tills occur in two boreholes.
- (4) There are order-of-magnitude differences in the ^{10}Be concentration of adjacent tills.

6 Discussion I: First-order implications for the origin of Minnesota-South Dakota tills.

These results lead directly to several basic conclusions about the origin of the Minnesota-South Dakota tills. First, some tills have extraordinarily high ^{10}Be concentrations, as high as those observed in deeply weathered cratonic regolith that has been accumulating ^{10}Be for millions of years, and much higher than observed in all but the upper few centimeters of interglacial soils (Figure 1). These ^{10}Be -enriched tills can not be derived from deep subglacial erosion of unweathered bedrock. They can only have originated from mobilization of a relatively thin layer of deeply weathered surface material, presumably the preglacial regolith.

Second, the overall decrease in ^{10}Be concentrations between the stratigraphically lowest tills and Wisconsinan tills means that the ^{10}Be concentration of whatever source the tills were derived from must have decreased over time. If no initial reservoir of ^{10}Be were present, and the sources supplying ^{10}Be to glacial sediment were the same during all glacial cycles – that is, for example, if the ^{10}Be concentration of tills reflected only the ^{10}Be inventory deposited during interglaciations – older tills would now have lower ^{10}Be concentrations than younger tills due to radioactive decay. Lower ^{10}Be concentrations in younger tills require either depletion of a preglacial ^{10}Be -enriched source, or an increase in dilution of that source by sediment with a low ^{10}Be concentration. The oldest tills in these boreholes must have been drawn from a ^{10}Be -enriched source, presumably the preglacial regolith, that is not present in most younger tills.

Third, the high- ^{10}Be tills in the middle of the stratigraphic section in boreholes UMRB-1 and SD-CO have higher ^{10}Be concentrations than any tills below them, which means they cannot be the result of recycling of stratigraphically lower tills by later ice sheet advances. The ^{10}Be -enriched tills at the bottom of the stratigraphic section and those in the middle of the stratigraphic section must record two separate influxes of high- ^{10}Be source material. It seems most likely that the ^{10}Be -enriched tills at the bottom of the section record erosion of the preglacial regolith from the core area of the LIS at the onset of North American glaciation in the late Pliocene. The ^{10}Be -enriched tills in the middle of the section record some later expansion of either the entire ice sheet or the erosive part of its bed, which exposed previously undisturbed regolith to erosion and transport.

To summarize, the unexpectedly high ^{10}Be concentrations of some tills, and the overall up-section decrease in till ^{10}Be concentrations, support the basic idea that the regolith existing in the core area of the LIS before the onset of North American glaciation was mobilized by early ice sheet advances and eventually exhausted. The oldest tills in the Minnesota-South Dakota sequence were derived mostly from mobilization of the preglacial regolith, and the youngest tills mostly from the erosion of relatively unweathered bedrock.

7 Discussion II: Plio-Pleistocene ^{10}Be balance and the total amount of glacial erosion of the Canadian Shield.

As we discuss above, the first-order features of our results support the idea of a ^{10}Be -enriched preglacial regolith that was exhausted by subglacial erosion. Here we explore this in a somewhat more quantitative way, by looking at whether this idea and our measurements are consistent with the expected Plio-Pleistocene ^{10}Be balance for the glaciated part of North America.

The sediment eroded from the core area of the LIS during all its Plio-Pleistocene advances, and eventually delivered either to terrestrial glacial deposits or to the oceans, must contain the total ^{10}Be inventory that was present in the preglacial regolith at the onset of glaciation, as well as the total amount of ^{10}Be deposited in the glaciated area since then. Taking the existing measurements of ^{10}Be inventories in the unglaciated part of North America as a guide (Figure 1), the preglacial inventory I_{pre} was approximately 1×10^{12} atoms \cdot cm $^{-2}$. During the 2.5 million years since the onset of Northern Hemisphere glaciation, this would have been reduced by radioactive decay to 3.2×10^{11} atoms \cdot cm $^{-2}$. The total ^{10}Be inventory deposited in the glaciated part of North America (or anywhere else) since the onset of glaciation I_{dep} , taking account of radioactive decay, is approximately:

$$I_{dep} = \frac{D}{\lambda} (1 - e^{-\lambda t}) \quad (1)$$

where D is the deposition rate of ^{10}Be (1.3×10^6 atoms \cdot cm $^{-2}$ \cdot yr $^{-1}$ [22]), λ is the decay constant for ^{10}Be (4.62×10^{-7} yr $^{-1}$), and t is 2.5 Myr. This yields $I_{dep} = 1.9 \times 10^{12}$ atoms \cdot cm $^{-2}$. Thus, at present a total ^{10}Be inventory $I_{total} = I_{pre} + I_{dep}$ equivalent to $\sim 2.2 \times 10^{12}$ atoms \cdot cm $^{-2}$ must be found somewhere in Plio-Pleistocene glacial sediment derived from the LIS.

If the average depth of Plio-Pleistocene glacial erosion, in the parts of North America that were eroded by the LIS, is E_{total} , the average ^{10}Be concentration in the resulting glacial sediment is $C_{avg} = I_{total}/E_{total}\rho_T$, where ρ_T is the sediment density. The average ^{10}Be concentration in all the Minnesota and South Dakota tills we analysed is 8×10^7 atoms \cdot g $^{-1}$. Taking this as representative of all glacial sediment of LIS origin, and using a sediment density of 2 g \cdot cm $^{-3}$ (a typical dry bulk density for till; see [45]), yields an average erosion depth of 135 m. This is close to the estimate of 120 m derived from marine sediment volumes by [6]. Given the gross assumptions required for our calculation, it is difficult to take this agreement too seriously, but the important point is that the ^{10}Be concentrations we observe in glacial sediment are consistent with other information about Plio-Pleistocene glacial erosion and with the idea that ^{10}Be in till is derived only from the preglacial regolith and from Plio-Pleistocene deposition. No additional first-order sources or sinks of ^{10}Be are needed.

8 Discussion III: box model for ^{10}Be transport from source to sink.

In this section we seek to use not only the average ^{10}Be concentration in all of our tills, but the changes in ^{10}Be concentrations in stratigraphically ordered tills as well, to learn something about the processes that control till ^{10}Be concentrations. We seek to explain three important characteristics of our results: 1) the high ^{10}Be concentration ($\sim 10^9$ atoms \cdot g $^{-1}$) in the oldest tills in our boreholes; 2) the order-of-magnitude differences in ^{10}Be concentration between the stratigraphically lowest tills and those immediately overlying them; and 3) the low ^{10}Be concentration ($\sim 10^7$ atoms \cdot g $^{-1}$) in the youngest tills. In order to do this, we use a simple box model that predicts the ^{10}Be concentration of successive tills formed by erosion of a source region that is initially mantled by a ^{10}Be -rich regolith (Figure 5).

The rules of the model are as follows. The erosional history spans 2.5 Myr, divided into a sequence of n glaciations, each of which has duration $D = 2.5 \times 10^6/n$. Here we take the length of each glaciation to be 0.1 Myr, for a total of 25 glaciations. Prior to the first Pliocene glaciation, the till source region in the Canadian Shield is covered by both areas of unweathered bedrock and areas of deeply weathered regolith, both of which erode during each glaciation. At the beginning of the model run, regolith-mantled parts of the source region have ^{10}Be concentration-depth profiles $N(z)$ (atoms \cdot g $^{-1}$) like those measured at regolith- and saprolite-mantled sites south of the glacial limit in Virginia by [28] and [29] (Figure 1). Unweathered bedrock has a ^{10}Be concentration of zero. Erosion of unweathered rock contributes a fraction f_K of the total amount of material eroded during each glaciation; the rest is composed of regolith.

During each glaciation, the ice sheet erodes a thickness E (cm) from the source region and deposits it in the sink region as a till. The ^{10}Be concentration in the first till deposited depends on the depth of erosion, the amount of ^{10}Be present in the part of the initial regolith profile that is eroded, and the amount of unweathered bedrock on the landscape that is also eroded and serves to dilute the regolith with ^{10}Be -free sediment.

The ^{10}Be concentration in the second till, and all subsequent tills, depends on the three factors above and two additional ones: the amount of ^{10}Be deposited on the landscape during interglaciations (an inventory I_d , with units of atoms \cdot cm $^{-2}$), and the extent to which previously deposited tills are remobilized and recycled into the present till (a fraction f_R which describes the proportion of each till that is composed of recycled older tills). We assume that recycling of older tills is nonselective, that is, the quantity of recycled older till that is incorporated into the present till blends all previously deposited tills equally. Finally, we have to account for radioactive decay of ^{10}Be to predict the ^{10}Be concentrations actually observed at the present time. Figure 5 gives an idea of the processes in the model, and we provide a full mathematical description in Appendix A.

To summarize, the model predicts the ^{10}Be concentration in a stratigraphic sequence of tills and depends on the following input parameters: 1) the initial ^{10}Be concentration-depth profile in regolith in the source area; 2) the degree to which regolith is diluted by unweathered bedrock during erosion in the source area; 3) the depth of erosion in each glaciation; 4) the ^{10}Be inventory deposited on the landscape during each interglaciation; and 5) the fraction of each till which is composed of recycled older tills. Of the features of the data that we seek to duplicate, 1) the ^{10}Be concentration in the stratigraphically lowest tills is primarily a function of the erosion depth in each glaciation and the degree of dilution of the eroded regolith by unweathered rock; 2) the drop in ^{10}Be concentration between the first and subsequent tills is mainly controlled by the erosion depth and the recycling fraction; and 3) the ^{10}Be concentration in the youngest tills is a balance between the erosion depth and the interglacial ^{10}Be deposition.

This model framework has two significant weaknesses. First, the processes represented in the model (that is, gradual depletion of a preglacial regolith whose ^{10}Be concentration decreases with depth, and non-selective recycling of previously deposited till) can never produce the intermediate high- ^{10}Be tills that we observe in two boreholes. These tills can only be the result of a new supply of ^{10}Be -enriched sediment that is not accounted for by the single source area in the model. We could arbitrarily impose such a new ^{10}Be source on the model to produce intermediate high- ^{10}Be tills, but in the absence of any independent information about where or when it might have originated, this would provide no new insight into the processes represented in the model. Thus, we ignore the intermediate high- ^{10}Be tills in this part of the discussion. The second key weakness is that, in order to compare the till ^{10}Be concentrations in our boreholes with those predicted by this model, we must take the till sequences in our boreholes, in particular near the bottom of the stratigraphy, to be essentially complete sequences of all tills exported by the LIS. This is a more serious problem, as the number of tills in any given borehole (~ 10) is smaller than the total number of Plio-Pleistocene ice sheet advances into the north-central U.S. inferred from the marine sedimentary record (~ 30 ?), so it is very likely that our stratigraphic sections contain unconformities where ice sheet advances that reached Minnesota are not represented by tills. This possibility affects some of our conclusions and we discuss it in more detail where it becomes important below.

Leaving these weaknesses aside for the moment, we can duplicate many of the main features of our observations with reasonable choices of model parameters (Figure 6), and we can use the model to somewhat restrict the possible values of some of the parameters.

First, one can trade off the erosion depth with the degree of dilution of eroded regolith by unweathered rock to produce any desired ^{10}Be concentration in the first till. Given a particular ^{10}Be concentration-depth profile in the preglacial regolith, however, the decrease in concentration between the first and subsequent tills is in-

dependent of the fraction of fresh rock and depends primarily on the erosion depth and the recycling fraction. With the measured ^{10}Be concentration-depth profiles available to us, it is only possible to produce both the correct ^{10}Be concentration in the first till and the observed order-of-magnitude decrease in the concentration between the first and successive tills if the erosion depth is at least 5-10 m, and the recycling fraction is relatively small, less than $\sim 10\%$. In other words, the fact that we find much more ^{10}Be in the lowest than in the next-to-lowest tills tells us that: a) most of the initial ^{10}Be inventory is exported in the first ice sheet advance, and b) there is little recycling of the first, high- ^{10}Be till into subsequent tills. More generally, the fact that adjacent tills throughout our boreholes have ^{10}Be concentrations that differ by an order of magnitude or more requires that there be very little recycling of older into younger tills. If we relax the assumption that the lowest tills in our boreholes belong to consecutive glaciations and are not separated by major unconformities, our constraint on the depth of erosion in the first few glaciations is weakened, but the more general conclusion that till recycling is very limited remains unaffected. The large amount of ^{10}Be in the lowest tills was entirely removed from the till source area by the first ice sheet advances, and was not available to be remobilized and retransported by later ice sheet advances.

Second, the ^{10}Be concentration in Wisconsinan tills reflects a balance between the depth of erosion in the till source area (which, at the end of the entire sequence of glaciations, supplies only ^{10}Be -free bedrock – the initial ^{10}Be inventory in the preglacial regolith has been long since exhausted) and the amount of ^{10}Be deposited during interglaciations. Measured ^{10}Be inventories in Holocene soils suggest that the interglacial ^{10}Be inventory (I_d) should be near 2×10^{10} atoms $\cdot \text{cm}^{-2}$ (see Appendix A for further discussion). The observed ^{10}Be concentration in Wisconsinan tills of $\sim 1 \times 10^7$ atoms $\cdot \text{g}^{-1}$ then suggests E on the order of 10 m, which is in broad agreement with the erosion depth inferred above from the ^{10}Be concentrations in the lowermost tills.

To summarize, the box model reinforces the conclusion that the ^{10}Be enriched sediment source, presumably the preglacial regolith, which is present in the lowermost tills in our boreholes, was depleted by the first few ice sheet advances and is not present in most younger tills. Given the available information about what the ^{10}Be concentration-depth profile may have been in the preglacial regolith, it suggests erosion depths of at least 5-10 meters in each glaciation. This is consistent with the idea that the total amount of Plio-Pleistocene glacial erosion of the Canadian Shield was 120-150 m ([6] and foregoing discussion in Section 7), as well as with independent measurements of the depth of subglacial erosion on the Canadian Shield during the last glaciation (6-20 m) by [9]. This amount of subglacial erosion implies that the entire ^{10}Be -enriched portion of the preglacial regolith (~ 20 m by analogy to modern regolith and saprolite profiles) would have been removed from the core area of the LIS by the first few Plio-Pleistocene ice sheet advances.

We can also try to evaluate this conclusion, that the ^{10}Be -enriched preglacial re-

regolith was exhausted in the source area of our tills after the first few Plio-Pleistocene ice sheet advances, by comparing till ^{10}Be concentrations to the few direct dates on the tills (which are described in detail in [43]). A till near 75 m depth in borehole SD-CO (Figure 4) has low ^{10}Be concentrations (10^7 atoms \cdot g $^{-1}$), must therefore postdate the exhaustion of the preglacial regolith, and was deposited 0.9-1.2 Ma. The lowest tills in boreholes SD-CO and SWRA-3 have high ^{10}Be concentrations ($\sim 2 \times 10^8$ atoms \cdot g $^{-1}$) and were deposited > 1.25 Ma and 1.5-2 Ma respectively. These require that the ^{10}Be -enriched preglacial regolith be exhausted before ca. 1 Ma, and are consistent with it being exhausted as early as 1.5-2 Ma.

9 Discussion IV: Relation to other studies of weathering proxies in till.

Our conclusion, that the preglacial regolith was removed from the core area of the ice sheet by the first few ice sheet advances, perhaps in the late Pliocene, is at odds with the conclusions of Roy et al. ([44]). They measured a variety of geochemical and mineralogical proxies for weathering intensity in tills from the Nebraska-Iowa till sequence, and interpreted them to indicate that the preglacial regolith in the core area of the LIS survived until ca. 1 Ma, and its exhaustion could therefore have served as a trigger for the mid-Pleistocene transition. However, we argue that our conclusions – that the regolith was entirely removed by the first few ice sheet advances and could not have provided such a trigger – are consistent with their measurements. They found that pre-2 Ma tills (their ‘R2’ tills) were highly enriched in a variety of weathering indicators, and that 1.3-0.76 Ma tills (‘R1’ tills) and < 0.76 Ma tills (‘N’ tills) contained lower, but indistinguishable, concentrations of these weathering proxies. They were not able to distinguish between 1.3-0.76 Ma tills and < 0.76 Ma tills on the basis of any weathering indicator, suggesting that there was no detectable change in till source material near 1 Ma. In our opinion, the major differences they observed between pre- and post-2 Ma tills, and the relatively low variability in post-2 Ma tills, is consistent with our conclusion that the preglacial regolith in the core area of the LIS was entirely removed by the first few Plio-Pleistocene ice sheet advances.

10 Summary and conclusions.

Rapid regolith removal and restricted recycling. The ^{10}Be concentrations in the lowest tills in our boreholes, the ^{10}Be concentrations in Wisconsinan tills, and the order-of-magnitude contrasts in ^{10}Be concentration between the lowest tills and those immediately overlying them, all suggest that: 1) the LIS accomplished at least several meters of erosion in the till source area during each glaciation, and 2) early tills were not recycled into stratigraphically higher ones. This in turn suggests

that the ^{10}Be -enriched preglacial regolith was entirely removed from the core area of the LIS by the first few Plio-Pleistocene ice sheet advances.

Middle Pleistocene ^{10}Be injection. The high ^{10}Be concentrations in intermediate tills in the UMRB-1 and SD-CO boreholes, but not in tills immediately above or below them, cannot be explained by gradual depletion of a single area of preglacial regolith, by recycling of older tills into younger ones, or by ^{10}Be deposition during interglaciations. These tills suggest that erosion of regolith beneath the LIS took place in two stages: the area of regolith that could be eroded by early ice sheet advances was rapidly exhausted, but at some point a new source of regolith became available for subglacial erosion. This could be the result of an increase in the area of the ice sheet, the thawing of a region of the ice sheet bed that had previously been frozen and thus protected from subglacial erosion, or by a large-scale change in ice-flow direction that mobilized regolith that had previously been protected by the bed topography. Although we know only that these high- ^{10}Be intermediate tills are younger than ca. 1 Ma (Figure 4), these possibilities are all likely consequences of the growth of a larger ice sheet at the mid-Pleistocene transition.

Regolith depletion not a likely cause of the middle Pleistocene climate transition. The idea that the mid-Pleistocene climate transition could be caused by depletion of a stock of deformable preglacial regolith requires one of two scenarios. First, some thickness of undisturbed regolith could persist in place until 0.9 Ma; second, the regolith could be entirely mobilized by early ice sheet advances, but continually recycled by subglacial transport, so that the sediment reservoir thinned as it gradually moved away from the core of the ice sheet. The ice sheet models of [3] that simulate the middle Pleistocene transition rely on both of these possibilities. The ^{10}Be concentrations in Minnesota and South Dakota tills do validate the idea that the preglacial regolith was the source of early tills and was eventually removed by subglacial erosion, but they do not support the idea that regolith depletion could have served as a trigger for the mid-Pleistocene transition. The low ^{10}Be concentrations in most intermediate-age tills show that the preglacial ^{10}Be inventory that was available at the onset of glaciation was depleted by the first few ice sheet advances. The abrupt differences in the ^{10}Be concentration of adjacent tills indicate that older tills did not serve as a source for younger tills, which is not consistent with the idea of continual sediment recycling. As the entire regolith down to the bedrock weathering front in unglaciated areas is enriched in ^{10}Be (Figure 1, [28,29]), our argument that the preglacial ^{10}Be inventory was exhausted well before 1 Ma implies that all the regolith that could have served as a reservoir of deformable subglacial sediment was exhausted at the same time. This does not rule out the possibility that a different source of ^{10}Be -free deformable sediment could have affected ice-sheet dynamics. However, we conclude that the preglacial regolith was removed from the core area of the LIS well before the middle Pleistocene climate transition, and could not have provided an internal trigger for ice sheet growth at that time. We suggest instead that renewed export of ^{10}Be -rich till, derived from a previously undisturbed source of regolith sometime after ca. 1 Ma, was a consequence, and not a cause, of

a change in ice dynamics.

11 Acknowledgements

Greg Balco was supported by a graduate fellowship from the Fannie and John Hertz Foundation, by a graduate fellowship from DOSECC, and by the J. Hoover Mackin Award of the Geological Society of America. Travel and analytical work were supported by National Science Foundation grant EAR-0207844. Derrick Johnson and Pat Jaybush assisted with sample preparation. We thank Kelli McCormick of the South Dakota Geological Survey for providing access to archived drill cores.

References

- [1] D. MacAyeal, Irregular oscillations of the West Antarctic Ice Sheet, *Nature* 359 (1992) 29–32.
- [2] P. Clark, R. Alley, D. Pollard, Northern hemisphere ice-sheet influences on global climate change, *Science* 286 (1999) 1104–1111.
- [3] P. Clark, D. Pollard, Origin of the middle Pleistocene transition by ice sheet erosion of regolith, *Paleoceanography* 13 (1998) 1–9.
- [4] R. Flint, *Glacial Geology and the Pleistocene Epoch*, J. Wiley and Sons, New York, 1947.
- [5] W. White, Deep erosion by continental ice sheets, *Geological Society of America Bulletin* 83 (1972) 1037–1056.
- [6] M. Bell, E. Laine, Erosion of the Laurentide region of North America by glacial and glaciifluvial processes., *Quaternary Research* 23 (1985) 154–174.
- [7] D. Sugden, A case against deep erosion of shields by ice sheets, *Geology* 4 (1976) 580–582.
- [8] D. Sugden, Glacial erosion by the Laurentide Ice Sheet, *Journal of Glaciology* 20 (1978) 367–391.
- [9] C. Kaszycki, W. Shilts, Glacial erosion of the Canadian Shield — calculation of average depths. Atomic Energy of Canada Technical Report TR-106., Atomic Energy of Canada Ltd., 1980.
- [10] D. Sugden, Modification of old land surfaces by ice sheets, *Zeitschrift fur Geomorphologie* 72 (1989) 163–172.
- [11] A. Hall, D. Sugden, Limited modification of mid-latitude landscapes by ice sheets: the case of northwest Scotland, *Earth Surf. Processes Landf.* 12 (1987) 531–542.

- [12] J. Kleman, Preservation of landforms under ice sheets and ice caps, *Geomorphology* 9 (1994) 19–32.
- [13] J. P. Briner, T. W. Swanson, Using inherited cosmogenic ^{36}Cl to constrain glacial erosion rates of the Cordilleran ice sheet, *Geology* 26 (1) (1998) 3–6.
- [14] D. Hildes, G. Clarke, G. Flowers, S. Marshall, Subglacial erosion and englacial sediment transport modelled for North American ice sheets, *Quaternary Science Reviews* 23 (2004) 409–430.
- [15] T. Feininger, Chemical weathering and glacial erosion of crystalline rocks and the origin of till, Tech. rep., U.S. Geological Survey Professional Paper 750-C, pp. C65–C81 (1971).
- [16] K. Lidmar-Bergstrom, A long-term perspective on glacial erosion, *Earth Surface Processes and Landforms* 22 (1997) 297–306.
- [17] C. Patterson, T. Boerboom, The significance of pre-existing, deeply weathered crystalline rock in interpreting the effects of glaciation in the Minnesota River Valley, U.S.A., *Annals of Glaciology* 28 (1999) 53–58.
- [18] K. Cuffey, R. Alley, Is erosion by deforming subglacial sediments significant? (Toward till continuity), *Annals of Glaciology* 22 (1996) 17–24.
- [19] D. Blankenship, D. Morse, C. Finn, R. Bell, M. Peters, S. Kempf, S. Hodge, M. Studinger, J. Behrendt, J. Brozena, Geologic controls on the initiation of rapid basal motion for West Antarctic ice streams: a geophysical perspective including new airborne radar sounding and laser altimetry results, in: R. Bindschadler, R. Alley (Eds.), *The West Antarctic Ice Sheet: Behavior and Environment*, American Geophysical Union, Washington, DC, 2001, p. 105.
- [20] R. Bindschadler, J. Bamber, S. Anandkrishnan, Onset of streaming flow in the Siple Coast region, West Antarctica, in: R. Bindschadler, R. Alley (Eds.), *The West Antarctic Ice Sheet: Behavior and Environment*, American Geophysical Union, Washington, DC, 2001, p. 123.
- [21] D. MacAyeal, Binge/purge oscillations of the Laurentide Ice Sheet as a cause of the North Atlantic's Heinrich Events., *Paleoceanography* 8 (1993) 775–784.
- [22] M. Monaghan, S. Krishnaswami, K. Turekian, The global average deposition rate of ^{10}Be , *Earth and Planetary Science Letters* 76 (1986) 279–287.
- [23] L. Brown, ^{10}Be as a tracer of erosion and sediment transport, *Chemical Geology* 65 (1987) 189–196.
- [24] C. You, T. Lee, Y. Li, The partition of Be between soil and water, *Chemical Geology* 77 (1989) 105–118.
- [25] R. Middleton, J. Klein, B. Dezfouly-Arjomandy, A. Albrecht, S. Xue, G. Herzog, J. Gregory, Be-10 in bauxite and commercial aluminum, *Nuclear Instruments and Methods in Physics Research B* 92 (1994) 362–366.

- [26] D. Lal, E. Barg, A. J. T. Jull, M. J. Pavich, J. R. Southon, M. Caffee, R. C. Finkel, Cosmogenic nuclear methods for determining soil erosion and formation rates, in: Isotope techniques in the study of past and current environmental changes in the hydrosphere and atmosphere., International Atomic Energy Agency, Vienna, 1993.
- [27] M. Pavich, L. Brown, J. Klein, R. Middleton, ^{10}Be accumulation in a soil chronosequence, *Earth Planet. Sci. Lett.* 68 (1984) 198–204.
- [28] M. J. Pavich, L. Brown, J. Vallette-Silver, J. Klein, R. Middleton, ^{10}Be analysis of a Quaternary weathering profile in the Virginia Piedmont, *Geology* 13 (1985) 39–41.
- [29] L. Brown, M. Pavich, R. Hickman, J. Klein, R. Middleton, Erosion of the eastern United States observed with ^{10}Be , *Earth Surface Processes and Landforms* 13 (1988) 441–457.
- [30] C. Gravenor, Erosion by continental ice sheets, *American Journal of Science* 275 (1975) 594–604.
- [31] M. Roy, P. Clark, R. Barendregt, J. Glasmann, R. Enkin, Glacial stratigraphy and paleomagnetism of late Cenozoic deposits of the north-central United States, *Geological Society of America Bulletin* 116 (1/2) (2004) 30–41.
- [32] E. Barg, D. Lal, M. J. Pavich, M. W. Caffee, J. R. Southon, Beryllium geochemistry in soils: evaluation of $^{10}\text{Be}/^9\text{Be}$ ratios in authigenic minerals as a basis for age models, *Chemical Geology* 140 (3-4) (1997) 237–258.
- [33] C. Patterson, Surficial geology of southwestern Minnesota, in: C. Patterson (Ed.), Contributions to the Quaternary Geology of Southwestern Minnesota. Minnesota Geological Survey Report of Investigations No. 47, University of Minnesota, St. Paul, MN, 1997.
- [34] C. Patterson, Quaternary geology - upper Minnesota River basin, Minnesota. Minnesota Geological Survey Regional Hydrologic Assessment RHA-4 (1999).
- [35] D. Setterholm, Quaternary geology – southwestern Minnesota. Minnesota Geological Survey Regional Hydrologic Assessment Series RHA-2 (1995).
- [36] J. Lineburg, Sedimentology and stratigraphy of pre-Wisconsin drifts, Coteau des Prairies, eastern South Dakota, M.S. thesis, University of Minnesota (1993).
- [37] G. Hallberg, Pre-Wisconsinan glacial stratigraphy of the central Plains region in Iowa, Nebraska, Kansas, and Missouri, in: V. Sibrava, D. Bowen, G. Richmond (Eds.), Quaternary Glaciations of the Northern Hemisphere, Pergamon Press, Oxford, 1986, pp. 11–15.
- [38] G. Hallberg, T. Kemmis, Stratigraphy and correlation of the glacial deposits of the Des Moines and James lobes and adjacent areas in North Dakota, South Dakota, Minnesota, and Iowa, in: V. Sibrava, D. Bowen, G. Richmond (Eds.), Quaternary Glaciations of the Northern Hemisphere, Pergamon Press, Oxford, 1986, pp. 65–68.
- [39] J. Boellstorff, North American Pleistocene stages reconsidered in light of probable Pliocene-Pleistocene continental glaciation, *Science* 202 (1978) 305.

- [40] J. Boellstorff, Chronology of some late Cenozoic deposits from the central United States and the ice ages, *Transactions of the Nebraska Academy of Sciences* VI (1978) 35–48.
- [41] J. Boellstorff, A need for redefinition of North American Pleistocene stages, *Transactions of the Gulf Coast Association of Geological Societies* XXVIII (1978) 65–74.
- [42] I. Rovey, C.W., W. Kean, Pre-Illinoian glacial stratigraphy in east-central Missouri, *Quaternary Research* 45 (1996) 17–29.
- [43] G. Balco, J. Stone, C. Jennings, Dating Plio-Pleistocene glacial sediments using the cosmic-ray-produced radionuclides ^{10}Be and ^{26}Al , *American Journal of Science* 305 (2005) 1–41.
- [44] M. Roy, P. Clark, G. Raisbeck, F. Yiou, Geochemical constraints on the regolith hypothesis for the middle Pleistocene transition, *Earth and Planetary Science Letters* 227 (2004) 281–296.
- [45] G. Balco, The sedimentary record of subglacial erosion beneath the Laurentide Ice Sheet, Unpublished Ph.D. thesis, University of Washington (2004).
- [46] J. Stone, A rapid fusion method for separation of beryllium-10 from soils and silicates, *Geochimica Et Cosmochimica Acta* 62 (3) (1998) 555–561.
- [47] D. Soller, P. Packard, Digital representation of a map showing the thickness and character of Quaternary sediments in the glaciated United States east of the Rocky Mountains. USGS Digital Data Series DDS-38 (1998).

Table 1

^{10}Be measurements. The ‘Average’ column contains error-weighted mean concentrations in till units where we analyzed samples from multiple depths.

Sample name	Borehole	Till number and reference	Sample depth (m)	^{10}Be (10^6 atoms \cdot g $^{-1}$)	Average
UMRB-1-8	UMRB-1	Unnamed till	2.4	7.73 ± 0.22	
UMRB-1-14	UMRB-1	Till 4 of [34]	4.3	3.01 ± 0.1	
UMRB-1-41	UMRB-1	Unnamed till	12.5	15.05 ± 0.38	
UMRB-1-63	UMRB-1	Till 7 of [34]	19.2	15.17 ± 0.42	14.41 ± 0.21
UMRB-1-64	UMRB-1	(same unit)	19.5	15.15 ± 0.45	
UMRB-1-65	UMRB-1	(same unit)	19.8	14.64 ± 0.42	
UMRB-1-68	UMRB-1	(same unit)	20.7	13.08 ± 0.38	
UMRB-1-69	UMRB-1	Unnamed till	21.0	14.2 ± 0.5	17.79 ± 0.31
UMRB-1-70	UMRB-1	(same unit)	21.3	16.67 ± 0.46	
UMRB-1-72	UMRB-1	(same unit)	22.0	28.91 ± 0.76	
UMRB-1-73	UMRB-1	Unnamed till	22.3	381.22 ± 5	352.55 ± 2.66
UMRB-1-74	UMRB-1	(same unit)	22.6	425.63 ± 5.46	
UMRB-1-75U	UMRB-1	(same unit)	22.9	299.21 ± 3.85	
UMRB-1-94	UMRB-1	Unnamed till	28.7	712.61 ± 8.96	
UMRB-1-116B	UMRB-1	Till 8 of [34]	35.4	78.1 ± 1.72	
UMRB-1-146B	UMRB-1	Unnamed till	44.5	98.82 ± 1.68	91.18 ± 1.37
UMRB-1-153	UMRB-1	(same unit)	46.6	75.64 ± 2.39	
UMRB-1-201	UMRB-1	Unnamed till	61.3	88.98 ± 2.82	
UMRB-1-218	UMRB-1	Unnamed till	66.5	46.24 ± 1.47	
UMRB-2-19	UMRB-2	Till 1 of [34]	5.8	13.8 ± 0.36	
UMRB-2-39	UMRB-2	Till 2 of [34]	11.9	14.32 ± 0.38	
UMRB-2-111	UMRB-2	Till 4 of [34] ?	33.8	9.92 ± 0.27	
UMRB-2-133	UMRB-2	Till 5 of [34]	40.5	9.12 ± 0.25	
UMRB-2-140	UMRB-2	Till 5 of [34]	42.7	9.73 ± 0.27	
UMRB-2-146	UMRB-2	Till 5 of [34]	44.5	9.46 ± 0.26	
UMRB-2-164	UMRB-2	Till 6 of [34]	50.0	8.99 ± 0.25	
UMRB-2-182	UMRB-2	Unnamed till	55.5	12.32 ± 0.35	
UMRB-2-194	UMRB-2	Till 8 of [34] ?	59.1	4.61 ± 0.15	
UMRB-3-42	UMRB-3	Till 7 of [34]	12.8	13.58 ± 0.35	
UMRB-3-70	UMRB-3	Unnamed till	21.3	17.03 ± 0.44	
UMRB-3-92	UMRB-3	Unnamed till	28.0	23.72 ± 0.6	
UMRB-3-95	UMRB-3	Unnamed till	29.0	13.69 ± 0.36	14.58 ± 0.18
UMRB-3-97	UMRB-3	(same unit)	29.6	12.94 ± 0.34	
UMRB-3-99	UMRB-3	(same unit)	30.2	14.64 ± 0.38	
UMRB-3-102	UMRB-3	(same unit)	31.1	16.2 ± 0.55	
UMRB-3-110	UMRB-3	(same unit)	33.5	17.86 ± 0.46	

continued on next page

Table 1 (continued)

Sample name	Borehole	Till number and reference	Sample depth (m)	[¹⁰ Be] (10 ⁶ atoms · g ⁻¹)	Average
UMRB-3-169	UMRB-3	Unnamed till	51.5	20.87 ± 0.54	28.36 ± 0.36
UMRB-3-170	UMRB-3	(same unit)	51.8	22.79 ± 0.58	
UMRB-3-174	UMRB-3	(same unit)	53.0	93.82 ± 1.51	
UMRB-3-188	UMRB-3	(same unit)	57.3	49.87 ± 1.25	
UMRB-3-195	UMRB-3	Nonglacial fluvial silt	59.5	264.24 ± 4.14	16.32 ± 0.3
UMRB-3-196	UMRB-3	Nonglacial fluvial silt	59.8	121.94 ± 2.15	
SWRA-3-188	SWRA-3	Till 4 of [35]	57.3	18.53 ± 0.48	16.32 ± 0.3
SWRA-3-193	SWRA-3	(same unit)	58.8	14.86 ± 0.39	
SWRA-3-228	SWRA-3	Unnamed till	69.5	28.6 / <i>pm</i> 0.72	12.29 ± 0.31
SWRA-3-258	SWRA-3	Till 5 of [35]	78.7	121.09 ± 1.67	
SD-CO-10	SD-CO	Unnamed till	3.0	82.24 ± 2.68	
SD-CO-44	SD-CO	Unnamed till	13.4	125.75 ± 4.08	
SD-CO-65	SD-CO	Unnamed till	19.8	181.23 ± 5.7	
SD-CO-151	SD-CO	Unnamed till	46.0	325.19 ± 9.85	
SD-CO-219	SD-CO	Unnamed till	66.8	20.17 ± 0.65	
SD-CO-258	SD-CO	Unnamed till	78.7	10.72 ± 0.36	
SD-CO-293	SD-CO	Unnamed till	89.3	11.47 ± 0.42	
SD-CO-320	SD-CO	(same unit)	97.6	13.27 ± 0.46	
SD-CO-367	SD-CO	Unnamed till	111.9	11.08 ± 0.39	12.29 ± 0.31
SD-CO-390	SD-CO	Unnamed till	118.9	188.41 ± 5.84	
SD-CO-401	SD-CO	Nonglacial fluvial silt	122.3	112.66 ± 3.72	
SD-CO-402	SD-CO	Nonglacial fluvial silt	122.6	111.35 ± 3.66	

Table 2
Location of boreholes

Borehole	Latitude	Longitude	Wellhead elevation (m)	Reference
UMRB-1	44.8970 N	96.4125 W	358	[34]
UMRB-2	45.3823 N	96.3467 W	335	[34]
UMRB-3	45.3012 N	95.7066 W	334	[34]
SWRA-3	44.0821 N	96.3888 W	529	[35]
SD-CO	45.0186 N	97.1847 W	547	South Dakota Geological Survey, unpublished reports

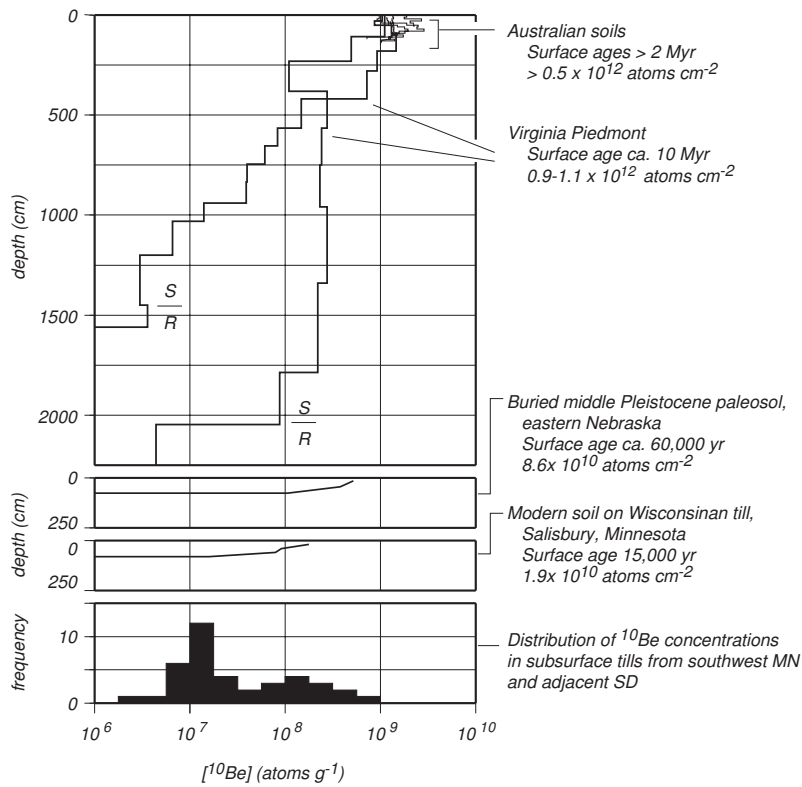


Fig. 1. ^{10}Be concentrations in ancient regolith and saprolite from unglaciated regions, interglacial soils from the north-central U.S., and Minnesota-South Dakota tills. There are no data below the upper 1-2 m of the Australian soils, so total inventories inferred from these measurements are minimum values. The boundary between saprolite (S) and unweathered rock (R) is shown for the two deep cores from the Virginia Piedmont. Data sources are as follows: Virginia Piedmont, [28] and [29]; Australian soils, J. Stone, unpublished measurements; interglacial soils, [45].

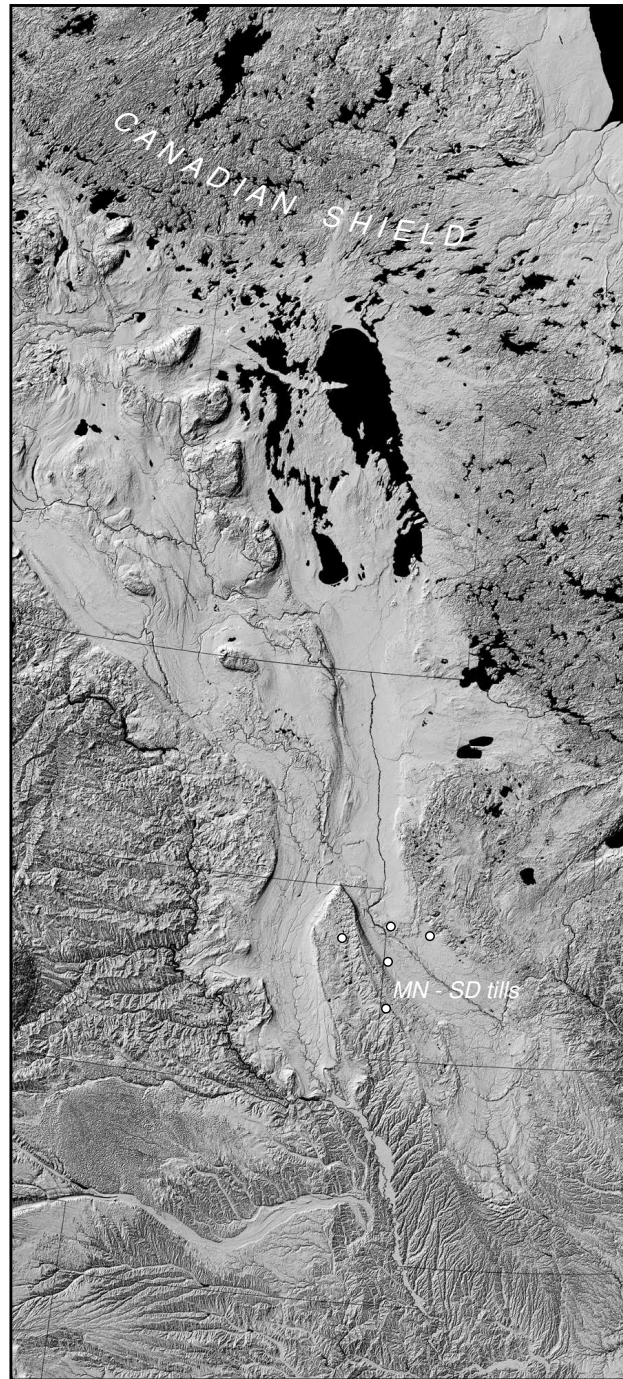


Fig. 2. Shaded-relief map of north-central North America, showing the location of Minnesota-South Dakota till sequences and their likely source areas on the Canadian Shield. Open circles show the locations of boreholes used in this study.

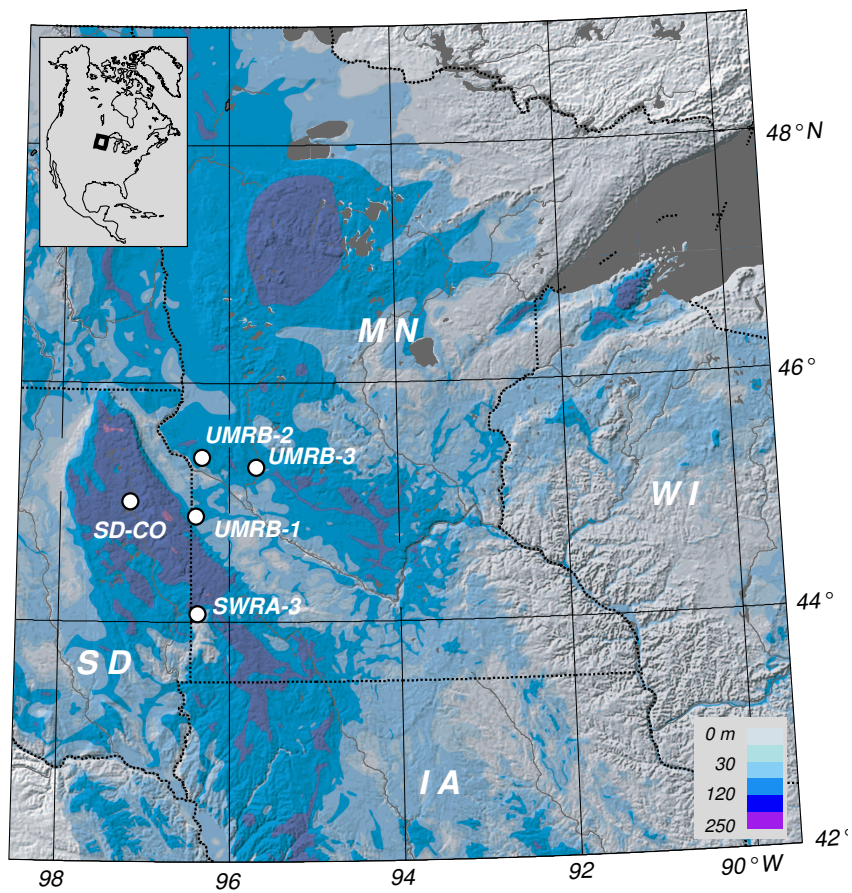


Fig. 3. Location of boreholes and thickness of Plio-Pleistocene glacial sediment thickness in Minnesota and adjacent states. Sediment thicknesses are from [47]. The thickness data stop at the Canadian border.

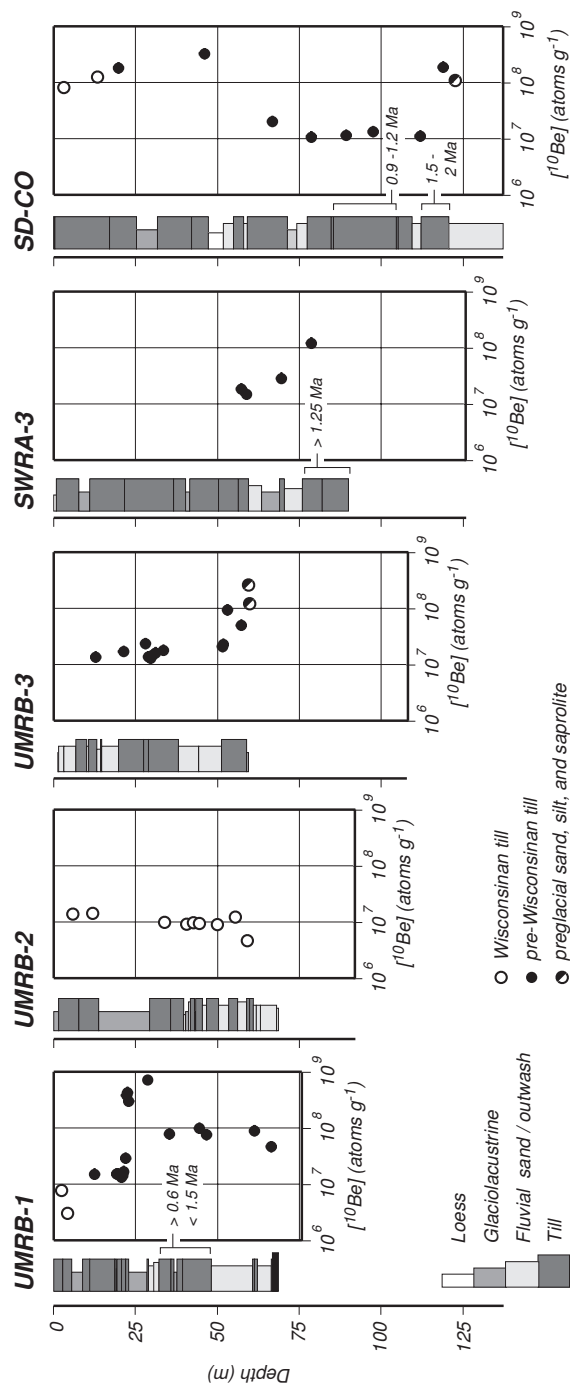


Fig. 4. Stratigraphy of Minnesota-South Dakota boreholes and ^{10}Be concentrations in tills. Age constraints for some tills are from [43].

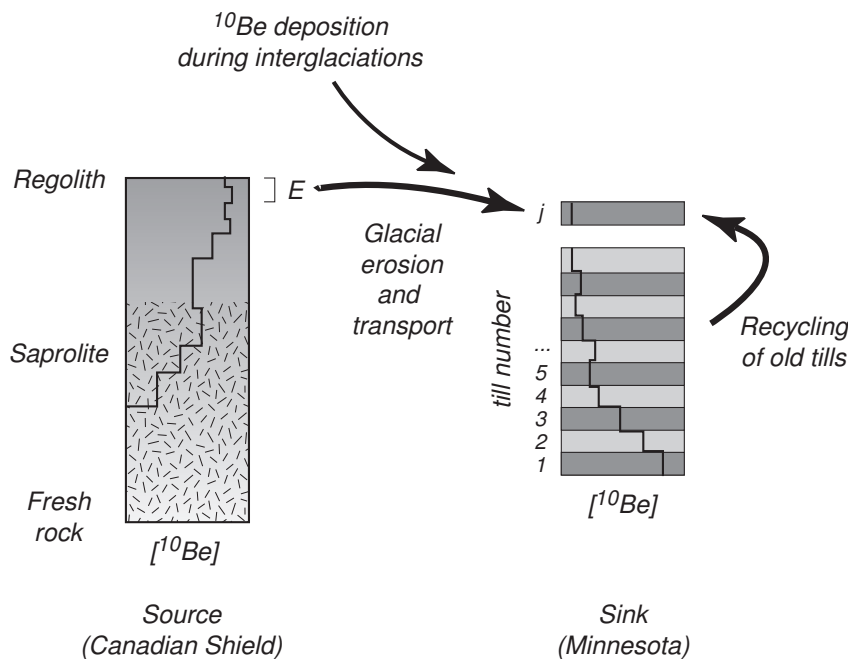


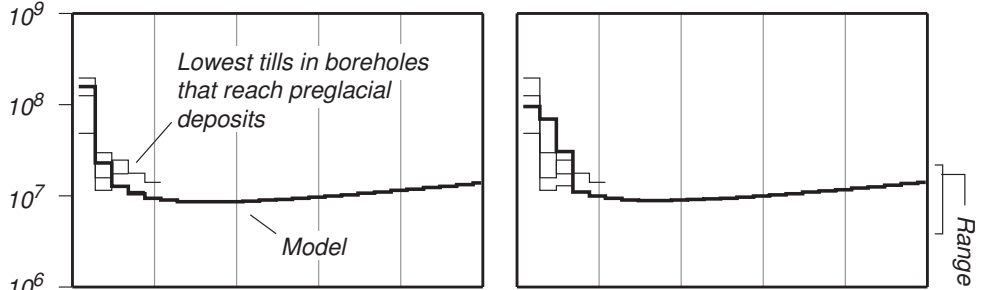
Fig. 5. Cartoon of box model describing ^{10}Be and till transport from source to sink.

Fig. 6. (on following page) ^{10}Be concentrations in till sequences simulated by the box model. The left and right panels differ only in the ^{10}Be concentration-depth profile assumed for the regolith mantle in the source area prior to the first glaciation. In all the panels, the dark line shows the ^{10}Be concentrations predicted by a reference model run with the following parameters: the ^{10}Be inventory deposited during interglaciations I_d is 2×10^{10} atoms $\cdot \text{cm}^{-2}$; the erosion depth in each glaciation E is 800 cm; the fraction of fresh rock in the source area f_K is 0.1; and the recycling fraction f_R is 0.1. In the top panels, the light lines show the measured sequence of ^{10}Be concentrations in the lowest 3-5 tills from boreholes where we most likely reached the bottom of the glacial sediment sequence (UMRB-3, SWRA-3, and SD-CO), and the range of ^{10}Be concentrations in Wisconsin till is indicated on the right side of the figure. The parameters used in the reference model run are selected to give a good match to these measurements. In the lower panels, the light lines show predicted ^{10}Be concentrations for different values of the model parameters.

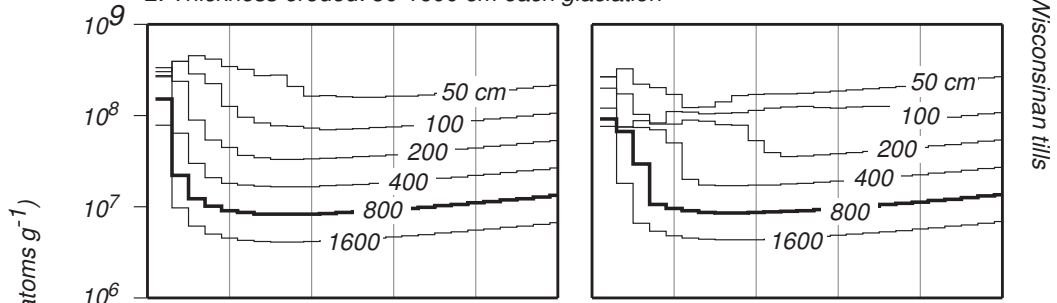
Inventory from Pavich et al. (1985)

Inventory from Brown et al. (1988)

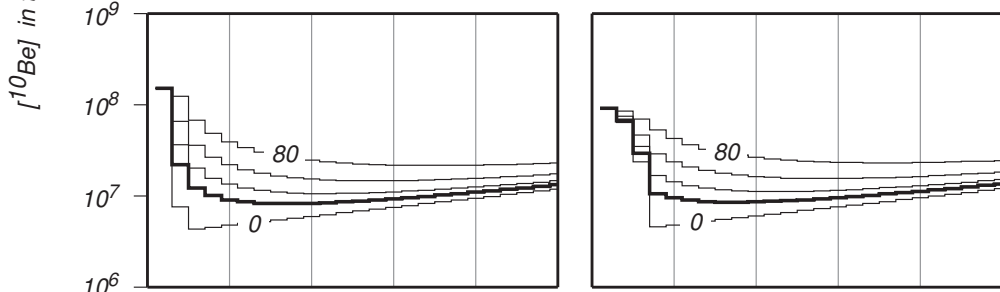
1. Reference model with measured concentrations



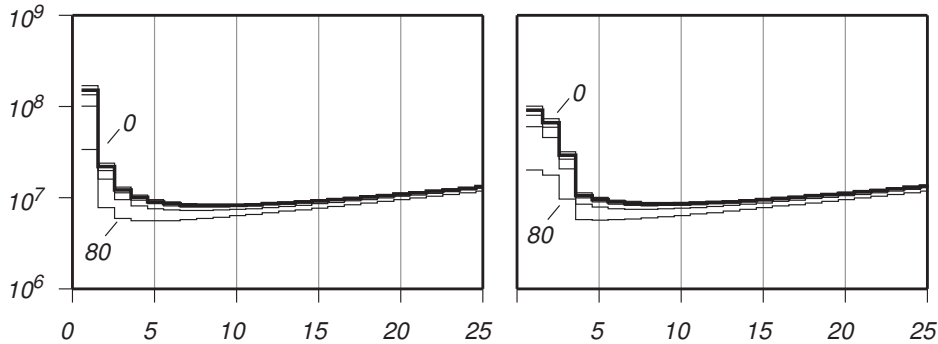
2. Thickness eroded: 50-1600 cm each glaciation



3. Fraction recycled older tills: 0-10-20-40-80 %



4. Fraction unweathered rock: 0-10-20-40-80 %



Glaciation number

A Appendix: Box model for ^{10}Be transport from source to sink.

This section describes a simple two-box model for the transport of ^{10}Be from some source area in the erosional portion of the Laurentide Ice Sheet to a sink area where the ice sheet deposits till. In the model we consider two stocks of rock and sediment: first, a source which represents material on the Canadian Shield that is available to be eroded by the Laurentide Ice Sheet; and second, a sink which represents the sequence of tills deposited by advances of the Laurentide Ice Sheet into the north-central U.S. During each glaciation, the ice sheet accomplishes a certain amount of erosion in the source area, and deposits the same amount of sediment in the sink area. The model is 1-dimensional, so both the source and sink are represented by a vertical column of sediment, and the areas of the source and sink are assumed equal. Thus, the amount of erosion in the source area during an ice sheet advance E is equal to the amount of deposition in the sink area, and both have units of cm. For simplicity, rock and sediment are both assumed to have a dry bulk density $\rho_T = 2 \text{ g} \cdot \text{cm}^{-3}$, which is typical of till: given that we seek to explain order-of-magnitude differences in ^{10}Be concentration among tills, the actual density difference between till, regolith, and various types of rock are of secondary importance.

For clarity, we first describe the entire model without taking account of radioactive decay of ^{10}Be . We then modify it so that ^{10}Be concentrations are corrected to the time of measurement (the present day) at the end.

A.1 Initial ^{10}Be inventory in the source area prior to glaciation.

We represent the initial ^{10}Be inventory in the source area prior to the first glaciation by the function $I(z)$, which yields the cumulative ^{10}Be inventory in the regolith above the depth z . I has units of $\text{atoms} \cdot \text{cm}^{-2}$ and z has units of cm. Figure A.1 and Tables A.1 and A.2 show the concentration-depth profiles and corresponding inventory functions from a pair of 20-m cores through regolith and saprolite and into unweathered rock from the Virginia Piedmont, south of the limit of North American glaciation ([28,29]). These cores are the only available measurements of the complete ^{10}Be inventory in a deep regolith-saprolite-bedrock column. The ^{10}Be inventory in the preglacial regolith that covered the Canadian Shield was likely similar in order of magnitude to that in the Virginia Piedmont, but would have varied locally according to rates of sediment erosion and deposition. However, as there are no other data available, we take these as the best available approximation of the initial inventory prior to glaciation.

A.2 Erosion and transport of the initial ^{10}Be inventory.

There are n ice sheet advances, and the total amount of erosion in the source area for the entire series of glaciations is thus En (cm). We also allow for a fraction f_K of the material eroded from the source area that consists of ‘bedrock’ whose ^{10}Be concentration is zero. One can think of this in two ways: either as a situation where f_K is an area fraction and the depth of erosion is the same throughout the source area, or as a situation where deep erosion in some parts of the source area contributes ^{10}Be -free sediment that serves to dilute ^{10}Be -rich sediment derived from shallow erosion of the regolith in other parts of the source area. These two situations would imply different choices of f_K but would not change the model formulation.

The inventory of ^{10}Be (atoms $\cdot \text{cm}^{-2}$) derived from erosion in the source area that is transported during ice sheet advance j , denoted $I_{E,j}$, is therefore the inventory of ^{10}Be contained in the regolith between the depth to which it was eroded in the previous glaciation, and the depth to which it is eroded in the present glaciation, diluted by the contribution of ^{10}Be -free bedrock that is also eroded:

$$I_{E,j} = [I(jE) - I(jE - E)] (1 - f_K) \quad (\text{A.1})$$

A.3 ^{10}Be deposited during interglaciations.

The ^{10}Be deposited in the source area, during the interglaciation prior to ice sheet advance j , that must then be transported by that ice sheet advance, is $I_{d,j}$. This inventory is much smaller than the initial inventory in the preglacial regolith. In the absence of soil erosion and radioactive decay, the ^{10}Be inventory in a soil is approximately Pt , where P is the global average deposition rate of ^{10}Be (1.3×10^6 atoms $\cdot \text{cm}^{-1} \cdot \text{yr}^{-1}$; [22]) and t is time (yr). So, for an interglaciation that is 15,000 yr long, we expect a soil ^{10}Be inventory of approximately 2×10^{10} atoms $\cdot \text{cm}^{-2}$. We measured the ^{10}Be inventory of a soil profile on 15,000 yr old till in Minnesota ([45]) and found that it was 2×10^{10} atoms $\cdot \text{cm}^{-2}$, so this is probably a good starting value. Note that this leaves aside the question of whether or not ^{10}Be deposited on top of the ice sheet during interglaciations is incorporated in till; however, this could be accounted for by adjusting I_d without changing the model framework.

We do not apply f_K to the ^{10}Be inventory deposited during interglaciations because: a) one could obtain the same effect by adjusting I_d ; and b) I_d is a rather weakly constrained parameter in any case.

A.4 *Total ^{10}Be inventory transported away from the source area in a glaciation.*

The total inventory of ^{10}Be that must be transported from source to sink during an ice sheet advance is:

$$I_{E,j} + I_d = [I(jE) - I(jE - E)](1 - f_K) + I_d \quad (\text{A.2})$$

I_d is assumed to be zero for the first ice advance where $j = 1$.

A.5 *^{10}Be concentration in till without recycling.*

If there is no recycling of previously deposited till into till j (we consider this later), then the ^{10}Be concentration in till j , C_j (atoms $\cdot \text{g}^{-1}$), is the ^{10}Be inventory that was transported from the source area, distributed over the thickness of the deposited sediment:

$$C_j = \frac{[I(jE) - I(jE - E)](1 - f_K) + I_d}{E\rho_T} \quad (\text{A.3})$$

A.6 *^{10}Be concentration in till with recycling.*

If previously deposited glacial sediment is recycled into till j , then we need a fraction f_R that describes what proportion of till j is composed of mixed-in older tills. We assume that the recycled till has the average ^{10}Be concentration of all the previous tills. This average ^{10}Be concentration $C_{avg,j}$ (atoms $\cdot \text{g}^{-1}$) is the total inventory of ^{10}Be mobilized in advances $1 \dots (j-1)$, divided by the total thickness of sediment mobilized:

$$C_{avg,j} = \frac{I(jE - E)(1 - f_K) + (j - 2)I_d}{\rho_T(jE - E)} \quad (\text{A.4})$$

The factor of $(j - 2)$ on I_d reflects the fact that $I_d = 0$ for $j = 1$. Thus, the ^{10}Be concentration in till j when recycling is taken into account is:

$$C_j = \frac{(1 - f_R)}{E\rho_T} \left([I(Ej) - I(jE - E)](1 - f_K) + I_d \right) + \frac{f_R}{\rho_T E(j - 1)} \left[I(jE - E)(1 - f_K) + (j - 2)I_d \right] \quad (\text{A.5})$$

A.7 Accounting for radioactive decay.

Accounting for radioactive decay requires an additional parameter, that is, the duration D (yr) of each glacial-interglacial cycle.

First, we account for decay of the preglacial ^{10}Be inventory in the source area until the end of period j . This changes Equation A.1 to:

$$I_{E,j} = [I(jE) - I(jE - E)] (1 - f_K) e^{-\lambda j D} \quad (\text{A.6})$$

The decay constant λ is $4.62 \times 10^{-7} \text{ yr}^{-1}$ for ^{10}Be .

Second, we account for the decay of the interglacial inventory I_d until the end of period j by replacing I_d with $I_d e^{-\lambda D}$. In reality both accumulation and decay would take place during the entire period of accumulation, but this approximation has a negligible effect on the result.

This changes the ^{10}Be inventory that is removed from the source area in glaciation j (Equation A.2) to:

$$[I(jE) - I(jE - E)] (1 - f_K) e^{-\lambda j D} + I_d e^{-\lambda D} \quad (\text{A.7})$$

Third, the concentration C_j that we observe at the end of period n must account for decay between the end of period j and the time of measurement, that is, the end of period n . Thus, in the absence of recycling, the concentration C_j is given by: (replacing Equation A.3):

$$C_j = \frac{e^{-\lambda D(n-j)}}{E \rho^T} \left([I(jE) - I(jE - E)] (1 - f_K) e^{-\lambda j D} + I_d e^{-\lambda D} \right) \quad (\text{A.8})$$

Fourth, the expressions that account for recycling become rather more complicated. The total inventory transported prior to period j , allowed to decay until the end of period j , is:

$$I(jE - E) (1 - f_K) e^{-\lambda D j} + \sum_{i=2}^{j-1} I_d e^{-\lambda D i} \quad (\text{A.9})$$

Note the implicit assumption that all the mixing takes place at the end of period j . Then the average ^{10}Be concentration in all the tills deposited prior to period j , at the end of period j , is (updating Equation A.4):

$$\frac{I(jE - E)(1 - f_K)e^{-\lambda Dj} + \sum_{i=2}^{j-1} I_d e^{-\lambda Di}}{\rho_T(jE - E)} \quad (\text{A.10})$$

We can then mix this concentration with the concentration in till j in the correct proportions, leading to the final expression for C_j (updating Equation A.5), which gives the final expression for the ^{10}Be concentrations C_j (atoms \cdot g $^{-1}$) that are observed at the end of period n :

$$C_j = \frac{(1 - f_R)e^{-\lambda D(n-j)}}{E\rho_T} \left([I(jE) - I(jE - E)](1 - f_K)e^{-\lambda jD} + I_d e^{-\lambda D} \right) + \frac{f_R e^{-\lambda D(n-j)}}{\rho_T(jE - E)} \left(I(jE - E)(1 - f_K)e^{-\lambda Dj} + \sum_{i=2}^{j-1} I_d e^{-\lambda Di} \right) \quad (\text{A.11})$$

We use this equation to produce the model results in Figure 6.

Note that the sum in Equation A.11 can't strictly be evaluated when $j = 2$; this sum is zero for $j = 2$.

A.8 Simplifications for lowest and highest tills.

We can simplify Equation A.11 for two important cases: the first till deposited (where we can disregard recycling and interglacial ^{10}Be deposition), and the last few tills deposited (where the initial ^{10}Be inventory in the preglacial regolith has long been exhausted, and its importance in the recycled older tills is greatly reduced by dilution and radioactive decay).

The simplified expression for the ^{10}Be concentration in the lowest till C_1 is:

$$C_1 = \frac{I(E)(1 - f_K)e^{-\lambda Dn}}{E\rho_T} \quad (\text{A.12})$$

For large j , the initial ^{10}Be inventory has been entirely removed from the source area, has been greatly reduced by radioactive decay, and makes up only a small part of the entire stack of previously deposited tills that is available for recycling. Thus, the nuclide concentration in the last till deposited after many glaciations approximates a balance between the amount of erosion in each glaciation and the amount of interglacial ^{10}Be deposition:

$$C_j = \frac{I_d}{E\rho_T} \quad (\text{A.13})$$

A.9 Summary.

To summarize, the model predicts the ^{10}Be concentrations in a sequence of n tills when supplied with the following parameters:

- (1) The function $I(z)$ that describes the depth dependence of the initial ^{10}Be inventory in the source area. We have already specified this to be the ^{10}Be profile from one of the regolith cores of [28] and [29]. z has units of cm. $I(z)$ has units of atoms $\cdot \text{cm}^{-2}$.
- (2) The ^{10}Be inventory deposited during interglacials I_d . Units of atoms $\cdot \text{cm}^{-2}$.
- (3) The area fraction f_K of non- ^{10}Be -contributing bedrock in the source area. Dimensionless.
- (4) The fraction of each till f_R which is composed of recycled older till. Dimensionless.
- (5) The amount of erosion in each ice sheet advance E . Units of cm.
- (6) The duration of each glacial-interglacial cycle D . Units of yr.
- (7) The number of glaciations n . Positive integer.

Table A.1

Cumulative ^{10}Be inventory in a soil/saprolite core on weathered gneiss in Virginia, as a function of depth. Reproduced from [28].

Cumulative ^{10}Be inventory (atoms \cdot cm $^{-2}$) $I(z)$	Depth (cm) z
0	0
5.60E+10	30
9.40E+10	50
1.87E+11	90
4.37E+11	180
6.21E+11	280
7.92E+11	420
8.31E+11	565
8.45E+11	655
8.56E+11	745
8.63E+11	837.5
8.72E+11	942.5
8.75E+11	1032.5
8.78E+11	1202.5
8.80E+11	1450
8.81E+11	∞

Table A.2
 Cumulative ^{10}Be inventory in a soil/saprolite core on weathered granite from Virginia.
 Reproduced from [29].

Cumulative ^{10}Be inventory (atoms $\cdot \text{cm}^{-2}$) $I(z)$	Depth (cm) z
0	0
2.02E+11	107
3.05E+11	230
3.33E+11	380
4.20E+11	565
4.95E+11	750
5.77E+11	958
7.56E+11	1340
9.23E+11	1787
9.62E+11	2046
1.02E+12	∞

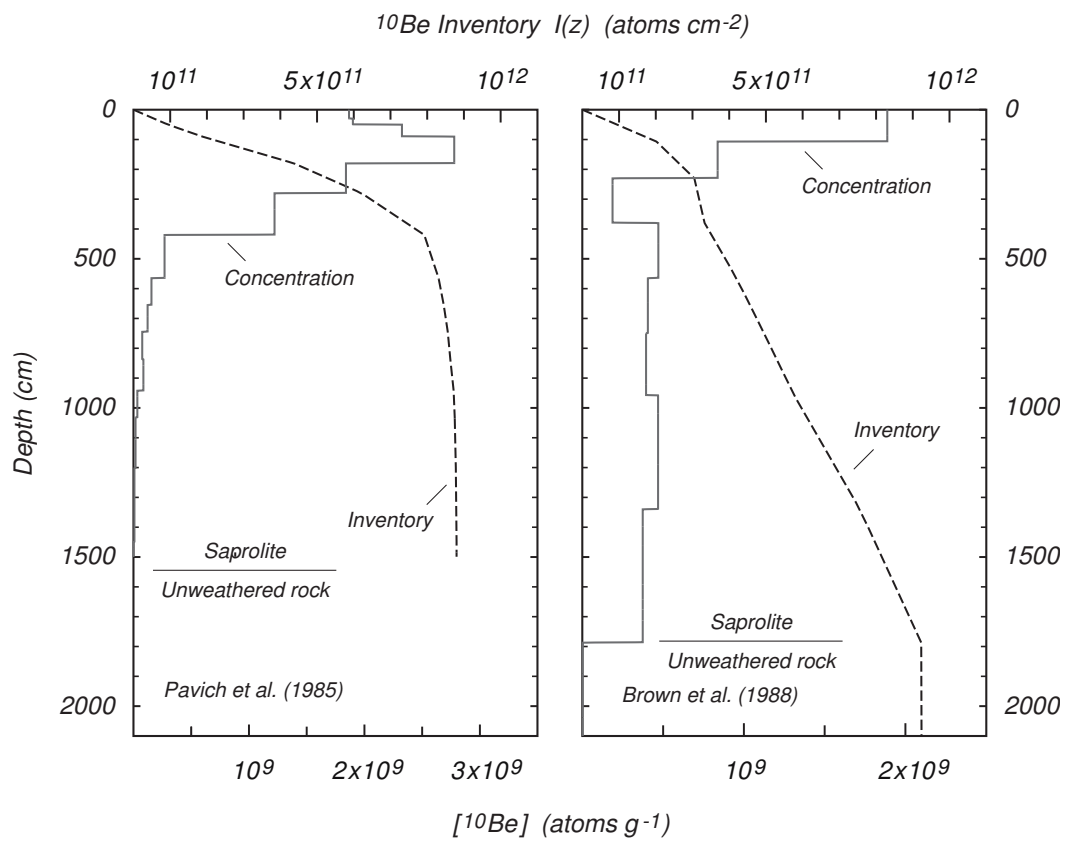


Fig. A.1. ^{10}Be concentration-depth profiles and corresponding inventory functions from regolith/saprolite cores in the Virginia Piedmont, described in [28] and [29].