A. PROJECT SUMMARY.

EROSION BENEATH THE LAURENTIDE ICE SHEET, AND ITS ROLE IN PLEISTOCENE ICE AGE DYNAMICS

Subglacial erosion and sediment dynamics influence the size, stability, and climatic sensitivity of large ice sheets. These processes may regulate large-scale surging behavior, initiating rapid shifts in climate and sea level (MacAyeal, 1993a,b), and perhaps dictate the periodicity of the Quaternary ice ages (Clark and Pollard, 1998). We intuitivly associate the scoured landscapes of the northern continents with subglacial erosion, yet estimates of the rates, timing and spatial pattern of erosion by the Pleistocene ice sheets are conflicting or ambiguous. Subglacial erosion is difficult to study because: (i) The processes involved take place beneath large ice sheets. (ii) As in all eroding landscapes, the record of change is continually effaced as the surface is removed, and (iii) Although thick deposits of Pleistocene glacial sediment, which contain information about erosional conditions, survive around the margins of former ice sheets, they are patchily preserved and difficult to date.

We propose to study the history of erosion by the Laurentide ice sheet, using the cosmogenic isotopes ^{10}Be and ^{26}Al. First, we will date glacial sedimentary sequences at the southern margin of the former ice sheet using the technique of "burial dating" (Granger et al., 1997). Cosmogenic ^{10}Be and ^{26}Al are produced within the crystal structure of sedimentary quartz grains while the sediment is exposed to cosmic radiation near the Earth's surface. Once the sediment is buried, these isotopes decay at different rates and their ratio provides a measure of the burial time. We have used this technique in trial measurements on glaciofluvial sands interbedded with till, providing stratigraphically consistent mid-Pleistocene bracketing ages on previously undated glacial deposits. Second, we will use atmospherically-produced ^{10}Be, which accumulates in soils and is highly concentrated near the surface of deeply weathered terrains, to investigate the contribution of pre-glacial regolith to Laurentide tills. We presume the deep regolith that covered the Canadian Shield prior to the Quaternary must have contained an enormous inventory of ^{10}Be, far exceeding what could have accumulated on the craton during Quaternary interglacial periods. By measuring the ^{10}Be content of sediments eroded and deposited by the Laurentide ice sheet throughout the Pleistocene, we will track the removal of pre-glacial regolith and evaluate the ice sheet's response to the onset of hard-bed conditions. Our initial measurements show that mid-Pleistocene tills contain enormous concentrations of 'meteoric' ^{10}Be. Concentrations in Wisconsin till are two orders of magnitude lower. It appears that the Laurentide ice sheet was 'mining' a cover of heavily-weathered surficial material in the middle Pleistocene, but that this source has now been largely exhausted.

We will apply these methods to well-studied sequences of till and interbedded glaciofluvial sediments in southwestern Minnesota, and early Pleistocene tills bracketed by well-dated ash layers in drill cores from South Dakota and Nebraska. This combination will provide samples of material eroded by the Laurentide Ice Sheet throughout the Pleistocene. The field area in southwestern Minnesota provides access to at least nine separate till units in outcrop and drill core. Extensive prior work in the area, and easy access to both surface and subsurface samples make it ideal for this study.

EROSION BENEATH THE LAURENTIDE ICE SHEET, AND ITS ROLE IN PLEISTOCENE ICE AGE DYNAMICS

Principal investigator:
John Stone, University of Washington

Graduate student participant:
Greg Balco, University of Washington

Collaborating investigator:
Carrie Patterson, Minnesota Geological Survey

C. PROJECT DESCRIPTION

C1. Results from prior NSF support

We propose to use cosmogenic nuclide methods to date glacial sedimentary sequences and track erosion beneath the Laurentide Ice Sheet. This project will build on past work at UW using cosmogenic nuclides to date glacial deposits and study geomorphic processes. It will also draw on laboratory methods and calibration studies of cosmogenic nuclide production by the PI and his students at the ANU and UW. The following section describes this work, and its relevance to the proposed project:

1. Low-level ^{10}Be- and ^{26}Al analyses: We have discovered through trial measurements (described in Section C4) that dating buried glacial sediments will require precise ^{26}Al and ^{10}Be measurements at very low isotopic concentrations. Work on two prior NSF-funded projects has allowed us to develop the necessary lab techniques. In connection with a study of *Land surface stability in the Dry Valleys, Antarctica* (OPP-9725542; PIs: Hallet, Sletten McKay and Mellon; 7/98-6/02; Stone is a co-investigator; $414,200), we have analysed small (1.5-4 g), heavily-shielded samples of quartz recovered from cores into an enigmatic body of ancient ice in the floor of Beacon Valley, Antarctica. The ice was discovered by Sugden et al. (1995) beneath 8.1 Myr old volcanic ash, suggesting a Miocene age, but its survival since the Miocene seems to defy current understanding of sublimation rates and processes (Hindmarsh et al., 1998). Our ^{10}Be measurements (Fig. 1) show that the ice body is subliming at a rate of ~50 m/Myr, and that it is at least 500,000 years old, directly demonstrating that this is the oldest ice known on Earth (Stone et al., 2000, 2001; Smith et al., 2001).

A second project, to study the *Retreat history of the West Antarctic Ice Sheet, Marie Byrd Land* (OPP 9909778; PI: Stone; 7/2000-6/2002; $119,814), has revealed evidence of very recent deglaciation in West Antarctica. Figure 2 shows exposure ages of erratics from peaks in Ford Ranges, Marie Byrd Land, plotted *vs.* their height above adjacent glaciers. The data show that: (i) all but the highest peaks in the Ford Ranges were overrun by the West Antarctic ice sheet during the last glacial maximum, (ii) deglaciation mostly occurred in the late Holocene, and is ongoing, and (iii) ice-sheet downwasting rates have averaged 5-10 cm/yr since ~ 7 kyr BP. The project has required extremely low-level ^{10}Be/^{9}Be measurements (down to 8×10^{-15}) to date low-altitude samples as young as 590 ± 70 years (Stone et al., 2001b, c).

2. Sub-surface production of ^{10}Be and ^{26}Al and their use in modeling surface processes: Low-yield cosmic-ray muon reactions produce ^{10}Be, ^{26}Al and ^{36}Cl at depths of tens to hundreds of meters (Kubik et al., 1984; Lal, 1988, 1991; Brown et al., 1995; Stone et al., 1994, 1998; Heisinger et al., 2000). The muon-produced component of a cosmogenic isotope accumulates

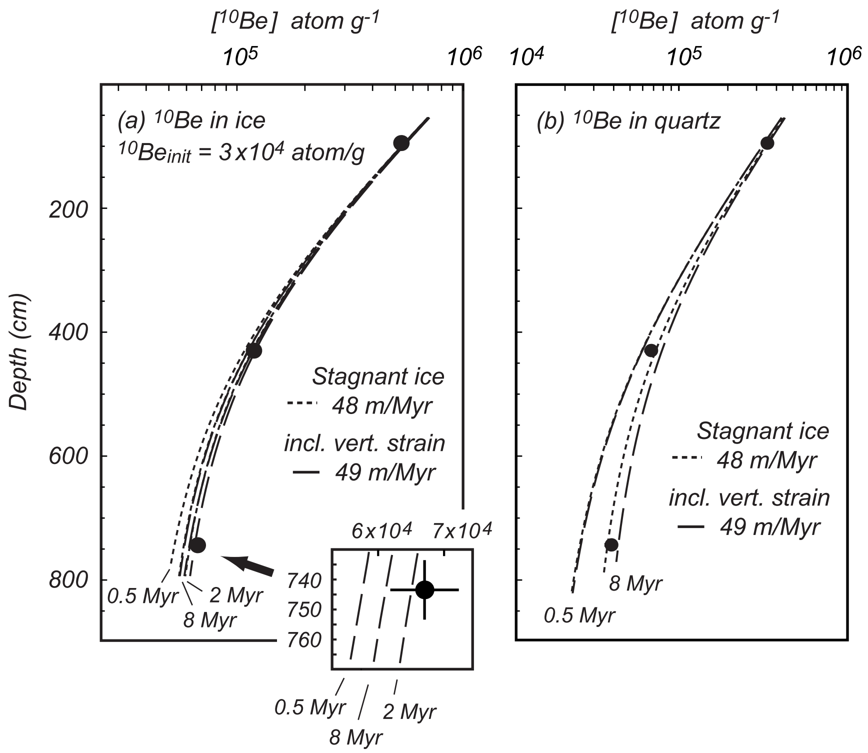


Fig. 1: Be-10 profiles in Beacon Valley ice (a), and embedded quartz grains (b), compared to calculated profiles for sublimation rates of ~50 m/Myr and ages between 0.5 Myr and 8 Myr. The ablation rate of the ice is tightly constrained by the data. The profiles require an age > 0.5 Myr, and do not rule out the "stratigraphic" age of > 8 Myr.

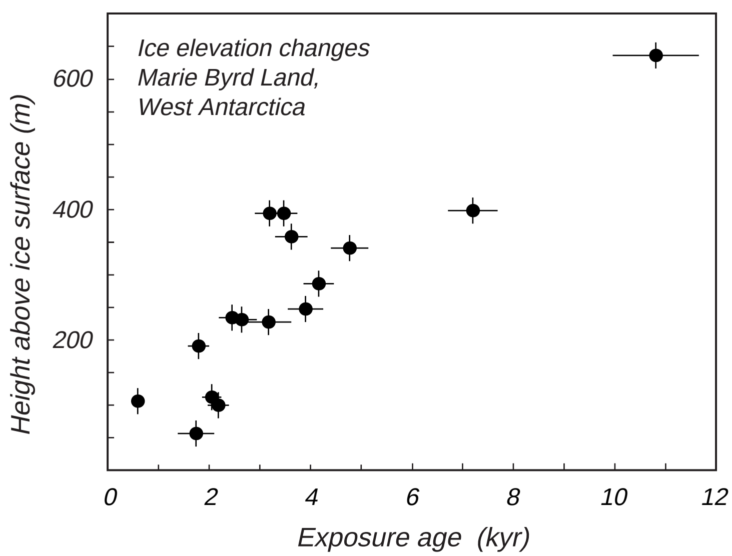


Fig. 2: Cosmogenic Be-10 exposure ages of erratics from peaks in the Ford Ranges, West Antarctica. Erratics were stranded on mountain summits and slopes as glacier margins receded, reaching their present levels less than 650 years ago. The highest sample in the elevation transect, with an exposure age of 110 kyr (not plotted), either lay above the LGM ice limit, or remained undisturbed beneath thin, cold-based ice capping the peak.

more slowly beneath an eroding surface than the component produced at shallow depths by nuclear spallation, and can be exploited to resolve multi-stage exposure, burial and erosion histories (e.g. Stone et al., 1994, 1998; Granger and Smith, 2000; Heisinger and Nolte, 2000). Sub-surface ^{10}Be and ^{26}Al production sets limits on the "burial dating" technique we will use to date glacial sedimentary sequences (Granger et al., 2001; see Section C4) and must be included in burial dating calulations. Depth profile measurements from a calibration study of ^{10}Be, ^{26}Al and ^{36}Cl production by muons (*Development of a comprehensive cosmogenic $^{10}Be - ^{26}Al$ production model for quartz*; EAR-9910209; PI: Stone; 2/2000-7/2001; $41,098) constrain the sub-surface production rates required for these calculations (Fig. 3) and provide a test for cross-sections measured in muon irradiation experiments (Heisinger et al., 2000). Note that the precise ^{10}Be measurements made in the study fall systematically below the curve predicted by experimental cross-sections, which may indicate a more complex erosion history than assumed, or a complication in the muon irradiation experiments. The sub-surface production rates derived from this calibration study are required for modeling ice dynamics in Beacon Valley (Fig. 1, described above), and also bear on surface production rates of ^{10}Be and ^{26}Al (Stone, 2000).

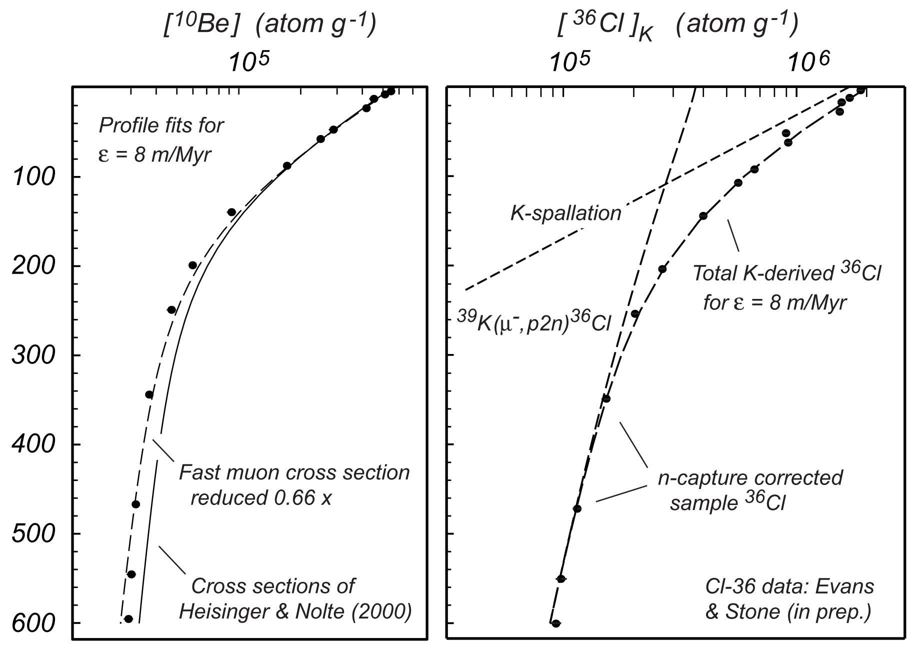


Fig. 3: Depth profiles for Be-10 (quartz) and Cl-36 (K-feldspar). Near-surface samples constrain the erosion rate, allowing muon production parameters to be calculated from the deep samples. The discrepancy between data and measured Be-10 cross-sections may imply a complex exposure history (recent decrease in erosion rate) or unaccounted-for effects in the muon irradiation study.

3. Cosmogenic isotope systematics of deeply weathered terrains: Our trial measurements of atmospherically-produced ("meteoric") ^{10}Be in mid-Pleistocene Laurentide till show astonishingly high levels, comparable to what is found in the regolith cover of deeply weathered cratonic terrains (Section C5). The basis for this comparison, shown in Fig. 5, comes in part from data collected in a study of the *Antiquity and evolution of cratonic surfaces* (EAR-9805132; PI: Stone; 7/1998-6/2002; $249,676), a joint research project with Dr Paulo Vasconcelos of the University of Queensland, Australia. This project has produced weathering chronologies for cratonic planation surfaces in Australia and Brazil using cosmogenic-nuclide analyses and ^{40}Ar/^{39}Ar dates on K-bearing Mn oxides formed by weathering. The study has shown that ancient weathered profiles (^{40}Ar/^{39}Ar ages ranging back to 55-70 Myr) are confined to high-level remnant surfaces, where erosion rates are < 2 m/Myr. Lower-lying surfaces have younger weathering ages and higher erosion rates. The results indicate that (i) relief and geomorphic heterogeneity have increased through time in these landscapes, and (ii) the topography of these regions can be largely accounted for by differential downwearing throughout the Tertiary (Vasconcelos and Stone, 2001). The geomorphic evolution of these landscapes on the 10^7-10^8

year timescale differs dramatically from the classical Davisian concept of steady reduction of relief.

4. Laboratory methods for cosmogenic nuclide extraction: The proposed project will rely on low-blank, high-sensitivity analyses of *in-situ*-produced ^{10}Be and ^{26}Al, as well as efficient methods for extraction of meteoric ^{10}Be from bulk till samples. Stone (1998) described a rapid method for extraction and purification of Be from sediments, which we have applied successfully in trial ^{10}Be analyses on till (Section C5). We have adapted the method to make low-level Be carrier from deep-mined beryl. Procedural blanks using this carrier, prepared in the recently completed cosmogenic isotope labs at UW have returned ^{10}Be/^{9}Be ratios of ~ 3-8x10^{-16}, minimising uncertainties associated with blank corrections in low-level analyses.

C2. <u>Collaboration with Dr Carrie Patterson, Minnesota Geological Survey</u>

The proposed project will involve close collaboration with Dr Carrie Patterson of the Minnesota Geological Survey. Patterson has mapped approximately 10,000 sq. miles in western Minnesota, including the study area (Section C6; Patterson, 1995; Patterson et al.1999a, b, Patterson, ed., 1999), and is familiar with all aspects of the stratigraphy and sedimentology of the glacial sediments we intend to sample. Her detailed work on the Wisconsinan glacial deposits in this region (Patterson, 1997a; 1998) developed previous indications of rapid motion of the Des Moines lobe of the Laurentide Ice Sheet into a clear pattern of evidence indicating multiple rapid advances of this lobe at a time when the Laurentide ice sheet was in overall retreat. This in turn indicates that these lobes were the marginal expressions of streaming ice originating deep within the Laurentide ice sheet in Canada, and shows that the record of ice sheet fluctuations in this area must be interpreted in the light of ice dynamics as well as climate changes. In addition, Patterson has involved undergraduate students in her research on the area, through an NSF-funded project: *Origin and history of glacial deposits in west-central Minnesota - an REU program to encourage women in Geology* (EAR 9820249; PI: Patterson; 1998-2001) This grant supported an undergraduate research experience for ten women students who spent seven weeks of training in glacial processes and sedimentology. After training in field and lab methods they worked on independent research projects in western Minnesota and studied modern glacial environments in the Canadian Rockies. They presented their findings to a gathering of professional geologists and submitted abstracts for the North Central GSA section meeting.

C3. <u>Introduction: Erosion by continental ice sheets</u>

Large ice sheets are the defining feature of the Quaternary Earth. We know from the oxygen isotopic composition of marine sediments (Emiliani, 1955; Shackleton and Opdyke, 1973) that large ice sheets have advanced regularly and repeatedly throughout the Pleistocene. We infer from this, from physical arguments, and from the barren and streamlined terrain they leave behind, that ice sheets are a critical part of the global climate system as well as the primary geomorphic agent responsible for arctic and northern-temperate landscapes.

In actual fact, most of what we know about Pleistocene ice sheets prior to the last glacial maximum (LGM) comes from marine records. This is because the pre-LGM glacial record, although extensive, is fragmentary and older than the range of radiocarbon dating. In most regions we are forced to rely on long-distance correlations, widely-spaced volcanic ashes and magnetostratigraphic boundaries to bracket the ages of glacial deposits. What we do know about the terrestrial record of Pleistocene glaciation has led to two important inconsistencies which we intend to investigate in this proposal.

First, the role of ice sheets in Pleistocene climate is confused by an inconsistency between the size and cyclicity of marine $\delta^{18}O$ excursions and the size of terrestrial ice sheets. The most southerly deposits of the Laurentide Ice Sheet (LIS) are known from intercalated volcanic ashes to be 1-2 Myr old (Boellstorff, 1978). These large excursions of the ice sheet occurred at a time when marine $\delta^{18}O$ excursions were small and followed a pattern of 41,000 year cyclicity. In contrast, the largest marine $\delta^{18}O$ excursions occurred after the mid-Pleistocene transition at 0.9 Ma from 41,000 to 100,000-year ice-age cyclicity. This is difficult to explain with models of long-term Pleistocene climate variability (e.g, Saltzman and Verbitsky, 1992, Deblonde and Peltier, 1996) which assume that ice sheet dynamics were much the same throughout the Pleistocene, and thus that marine $\delta^{18}O$ should be a proxy for both the volume and the geographic extent of large ice sheets. It suggests fundamental variability either in the dynamics of individual ice sheets or in the apportioning of ice among different ice sheets.

A second controversy concerns the origin of the streamlined and polished landscapes that we intuitively attribute to deep glacial erosion of resistant bedrock. Flint (1947) calculated from the volume of terrestrial glacial sediments around the margin of the LIS that subglacial erosion had been minimal. White (1972) realized that vastly more glacial sediment was deposited in the ocean and argued that the Precambrian rocks of Canada and Fennoscandia were exhumed by hundreds of meters of glacial abrasion. This disagreement persists. Estimates of marine sediment volumes suggest that total erosion by the Pleistocene LIS was on the order of 100 m (Bell and Laine, 1985). This conflicts with geomorphic evidence for the survival of pre-glacial landscapes and rock surfaces (Sugden, 1976, 1978, 1989; Hall and Sugden, 1987; Kleman, 1994; Briner and Swanson, 1998; Bierman et al., 1999; Harbor et al.,1999), the persistence of Tertiary planation surfaces across glacial boundaries (Sugden, 1976), the morphologic similarity between glacially eroded surfaces and the chemical weathering front beneath deeply weathered terrains (Feininger, 1971; Lidmar-Bergstrom, 1988, 1987; Patterson and Boerboom, 1999), and numerous examples of surviving pre-glacial regolith in glaciated regions. These all indicate that Pleistocene ice sheets may have accomplished little more than removing a pre-existing blanket of deeply weathered regolith, the legacy of a temperate Tertiary climate acting on the low-relief interiors of continental shields for millions of years.

Recent work showing the importance of subglacial sediment to ice sheet dynamics has drawn these geomorphic and paleoclimatic questions together. Both theory (Cuffey and Alley, 1996), and observations from the West Antarctic ice sheet (reviewed by Blankenship, 2001, and Bindschadler, 2001) suggest that a supply of deformable subglacial sediment is essential for initiating and maintaining fast, low-gradient flow within ice sheets. MacAyeal (1993a,b; MacAyeal and Dupont, 1994) explained Heinrich events — massive discharges of ice-rafted debris into the North Atlantic, accompanied by global climate changes (Heinrich, 1988) — as a physical instability of the LIS in which coupled changes in thickness and basal temperature alternately froze and thawed basal sediments. This showed that it was possible for subglacial conditions to directly affect the stability of global climate. Clark and Pollard (1998) coupled these ideas and suggested that the early Pleistocene LIS, riding on a thick layer of weak pre-glacial regolith, was thin, fast-flowing, and could advance and retreat rapidly in response to the 41,000-year inclination cycle. As repeated ice advances removed the lubricating regolith and left resistant bedrock, increased basal shear stress produced thicker, less responsive ice sheets. This hypothesis may explain the apparent mismatch between the large geographic extent and small inferred ice volume of the early Pleistocene LIS. It may also explain the mid-Pleistocene climate transition: the thick late Pleistocene ice sheet responded to temperature change slowly enough to force the global climate system into longer-period variability.

This theory relies upon the idea that the supply of deformable material beneath ice sheets is limited. Cuffey and Alley (1996) show this theoretically as well, pointing out that subglacial bedrock erosion is too slow to replace subglacial sediment evacuated by streaming flow. Therefore Antarctic ice streams (at present exporting marine sediments from Cenozoic basins beneath the West Antarctic ice sheet), and possibly unstable ice sheets in general, rely on a pre-existing supply of unconsolidated material. Exhausting this supply would cause a fundamental change in ice sheet dynamics. Clark and Pollard's hypothesis suggests that this happened to the LIS. The focus of this proposal will be to investigate this idea by studying the erosion and removal of pre-Pleistocene regolith from beneath the Laurentide ice sheet.

This poses two challenges. First, we must date the early and middle Pleistocene glacial sediments that surround the former ice sheet. Second, we must develop a means to identify pre-glacial regolith in subglacial sediments, differentiate it from the products of bedrock erosion, and determine the rate and timing of its removal. We propose to address both using cosmogenic isotope geochemistry. First, we will use the technique of "burial dating," based on the different decay rates of *in-situ*-produced cosmogenic ^{10}Be and ^{26}Al (Granger et al., 1997), to date pre-Wisconsinan glacial deposits near the southern margin of the LIS. Second, we will measure atmospherically-produced ^{10}Be in glacial tills to determine whether they are derived from deeply weathered pre-Pleistocene sediment or from freshly-eroded bedrock, and thus determine the rate and timing of export of the preglacial regolith.

This study will address the specific hypothesis of Clark and Pollard about the role of preglacial regolith in the evolution of Pleistocene climate, which may prove important to the evolution of large ice sheets in general. It also has broader applications to improving correlations between marine and terrestrial glacial records, providing new information about the source of subglacial sediment, demonstrating a widely applicable new tool for chronostratigraphic correlation of glacial sediments, and perhaps shedding new light on the role of ice sheets in landscape evolution.

C4. "Burial dating" of glacial sediments using cosmogenic ^{10}Be and ^{26}Al in quartz.

Our first task is to establish the chronology of glacial deposits in the proposed field area in southern Minnesota. This will provide the age framework for our study of glacial erosion and sediment export and allow us to correct meteoric ^{10}Be measurements to the time of till deposition.

We will do this using the technique of "burial dating". This relies on the cosmogenic isotopes ^{26}Al and ^{10}Be, with half-lives of 0.7 Myr and 1.5 Myr respectively, which are produced in quartz grains during cosmic ray bombardment of surface rocks and sediments. If quartz is buried after exposure to cosmic rays, production rates of the isotopes are reduced, and both decay to levels supported by much lower production rates at depth. Because the decay rates of the isotopes differ, their ratio R changes progressively from a value characteristic of surface exposure, R_0, to the steady-state value $(P_{Al\text{-}26}\ \lambda_{Be\text{-}10}) / (P_{Be\text{-}10}\ \lambda_{Al\text{-}26})$, where P_i is the deep production rate and λ_i the decay constant for isotope *i*. If the initial period of surface exposure is less than a few tens of thousands of years, R_0 is close to the production ratio of the isotopes, ~6.1 (Nishiizumi et al., 1989). In the simplest case of a single exposure period followed by uninterrupted deep burial, both the original exposure age and the duration of burial can be calculated from ^{26}Al and ^{10}Be abundances (Figure 4). This is the "burial dating" concept discussed by Klein et al. (1986) and described in detail by Granger et al. (1997, 2001). In this case, the burial age is given by:

$$t = -\ln(R/R_0) / (\lambda_{Al\text{-}26} - \lambda_{Be\text{-}10}) \quad (1).$$

The abundance and durability of quartz, and the fact that the production profiles of ^{10}Be and ^{26}Al have now been well calibrated (Heisinger et al., 1997; Heisinger and Nolte, 2000; Granger and Smith, 2000), make burial dating applicable to wide range of sedimentary systems (Klein et al., 1986; Granger et. al, 1997). However, sediments must meet certain criteria for burial dating to yield meaningful depositional ages:

<u>Sediment must have been exposed to cosmic rays in the past</u>. The longer the initial exposure, the greater the initial and present day concentrations of ^{26}Al and ^{10}Be, and the more precise and accurate the burial age that can be obtained. We have made trial measurements on eight samples of fluvial or glaciofluvial sand intercalated with deeply buried till deposits in our proposed field area in southern Minnesota. All of these samples contain measurable quantities of ^{10}Be and ^{26}Al (Table 1), which indicate initial surface exposure ages of ~10,000-25,000 yr. Since similar fluvial units are intercalated with tills throughout our field area, we anticipate that we will be able to obtain bracketing ages for nearly all glacial advances represented. In the course of the project, we will also analyze quartz from till units, especially those exposed at the surface during interglacial periods (recognizable by oxidation and soil formation). Quartz in some of these tills may have sufficient prior exposure to be useful for burial dating — in the only existing measurements we are aware of, Nishiizumi et al. (1989) observed both inherited and postdepositional ^{26}Al and ^{10}Be in the Sherwin Till from the Sierra Nevada. Concentrations of ^{10}Be and ^{26}Al in quartz from till will also yield information about subglacial erosion. Quartz with low initial concentrations of ^{26}Al and ^{10}Be is likely to be the product of deep erosion. Conversely, quartz with high cosmogenic isotope concentrations in till would indicate glacial erosion of near-surface material, or entrainment and remobilization of surficial sediment.

<u>Burial dating requires sediment with a predictable initial $^{26}Al/^{10}Be$ ratio</u>. If deposits to be dated contain recycled quartz, the $^{26}Al/^{10}Be$ ratio at the time of burial may have been lower than the assumed value of R_0, and the burial age deduced will be too old. Granger et al (2001) consider assumptions regarding the initial $^{26}Al/^{10}Be$ ratio in detail. We will address them in three ways: (i) We will measure $^{26}Al/^{10}Be$ ratios in modern fluvial sediments, as well as Wisconsinan glaciofluvial sediments that are analogous to the Pleistocene sediments we intend to date. (ii) We will analyse sediments from different depositional environments at the same stratigraphic level to determine whether quartz in certain types of sediment (i.e. glaciolacustrine *vs.* fluvial *vs.* till) gives consistent offsets. (iii) We will analyse glacial sediments associated with volcanic ash beds of known age. We have obtained samples from drill core in South Dakota for this purpose.

Table 1. Burial dating results for trial samples of fluvial/glaciofluvial sediments intercalated with glacial tills.

Sample name	[^{10}Be] (10^5 atoms/g quartz)	[^{26}Al] (10^5 atoms/g quartz)	^{26}Al/^{10}Be	Burial age[1] (Myr)	Initial exposure[1] (yr)
Sand units intercalated with tills 6-8 of Patterson et al (1995) -- upper pre-Wisconsinan sediment package					
UMRB-1-62	0.731 ± 0.023	2.77 ± 0.17	3.8 ± 0.3	0.92 ± 0.13	16500
UMRB-1-75	0.969 ± 0.022	3.96 ± 0.31	4.1 ± 0.3	0.77 ± 0.15	20400
UMRB-2-149	0.531 ± 0.016	1.82 ± 0.22	3.4 ± 0.4	1.10 ± 0.24	13000
UMRB-2-185	0.616 ± 0.024	2.44 ± 0.17	4.0 ± 0.3	0.83 ± 0.15	13400
UMRB-2-207	0.482 ± 0.018	1.88 ± 0.57	3.9 ± 1.2	0.86 ± 0.59	10600
UMRB-2-209	0.439 ± 0.023	1.75 ± 0.13	4.0 ± 0.4	0.82 ± 0.18	9400
		Error-weighted mean of the above:		0.86 ± 0.07	
Sand units intercalated with tills 9-10 of Patterson et al (1995) -- lower pre-Wisconsinan sediment package					
UMRB-1-192	1.161 ± 0.055	3.86 ± 0.17	3.3 ± 0.2	1.17 ± 0.13	29500
UMRB-1-216	1.057 ± 0.031	3.41 ± 0.21	3.2 ± 0.2	1.22 ± 0.13	27500
		Error-weighted mean of the above:		1.19 ± 0.09	

1. Simple burial and initial exposure ages are calculated assuming R_0 = 6.1 and a single period of exposure followed by burial at infinite depth.

Pending these tests, our initial results show no evidence of variation in R_0. Five samples from one sequence of glacial sediments, which are independently correlated and believed to be similar in age (Patterson et al., 1995; Fig. 6), yield indistinguishable ages of approximately 0.85 Myr (Table 1). A sixth sample (UMRB-2-149) from this sequence appears anomalously old (although statistically indistinguishable from the others) but this may be the result of a poor ^{26}Al analysis on a difficult sample. Two samples from a second sequence of glacial sediments give indistinguishable ages near 1.2 Myr. The consistency of these results suggests that fluvial sands in the field area do not contain significant amounts of previously buried quartz. Moreover, these ages agree (within large error bounds) with other dates on major advances of the Laurentide ice sheet, from fluvial sediments in the Ohio River system and marine sediments in the Gulf of Mexico (Granger et al. 2001; Joyce et al., 1993).

Re-exposure of the topmost few meters of sediment during interglacial periods could overwrite the former burial history of the sediment and lead to underestimated ages. We can avoid this by sampling the lower portions of tills and sand deposits shielded by thick tills. The presence of thick till above a sampled layer indicates that it was rapidly buried by ice and has remained shielded by (at least) the overlying thickness of till until the present time. The majority of the tills in our field area are thicker than 5m (which provides sufficient shielding; Figure 4b). The ice sheet itself would have provided effective shielding at times when it overrode the section.

Finally, burial dating can also present ambiguities when dating material many millions of years old, because the paths followed by samples re-equilibrating to production by muons at depth converge (Figure 4a). The fact that the deposits we are dating are (presumably) Pleistocene, i.e. < 2.5 Myr old, largely eliminates this potential problem. As shown in Figure 4a, burial paths between zero and 2.5 Myr are distinct functions of the initial exposure time and burial age.

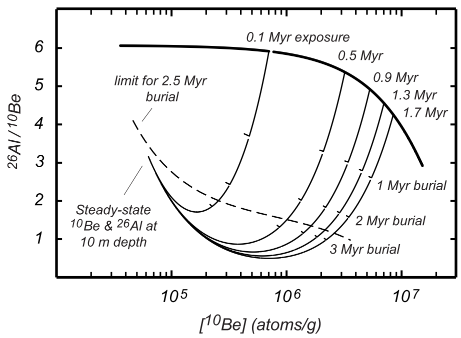


Fig. 4a: Evolution of ^{10}Be and ^{26}Al in an exposed sample (upper dark line), and after burial at 10m depth (lower curves). The $^{26}Al/^{10}Be$ ratio decreases initially after burial, before increasing to a steady-state ratio supported by the isotope production rates at 10m depth. The lower, dashed curve is a 2.5 Myr isochron for burial at this depth. Burial curves converge as steady-state is approached, resulting in large uncertainties in age and initial exposure time. This should not be a significant problem for Pleistocene-age samples.

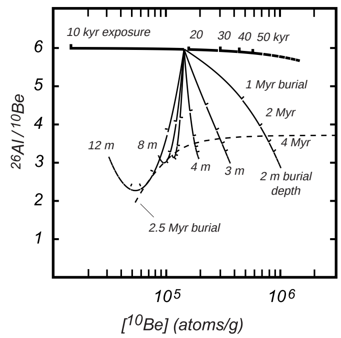


Fig. 4b: Evolution of ^{10}Be and ^{26}Al in material exposed for 20 kyr and then buried at various depths from 2m - 12m. Isotope production rates are high enough at shallow depths to cause continued growth of ^{10}Be. Prolonged residence at shallow depths can cause errors in burial age estimates for samples with multi-stage burial histories. The problem is minimised by sampling at the base of thick sedimentary units.

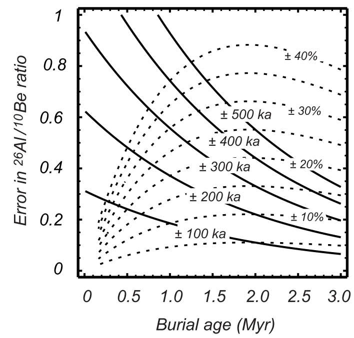


Fig. 4c: Error estimates for burial dating. Solid curves are absolute errors, dashed curves give percentage errors. AMS analytical errors scale roughly with the square root of the number of atoms analysed, so the age error can be reduced by inccreasing sample size relative to amount of Be carrier (^{10}Be), decreasing the Al concentration in quartz samples and duplicating analyses (^{26}Al), and by analysing quartz with long initial exposure.

Overall, difficulties in burial dating are minimized when samples are less than a few million years old, and have remained continuously and deeply buried. We believe these criteria can be met in glacial sedimentary sequences in our field area.

The major challenge of this part of the project will be making sufficiently precise ^{26}Al and ^{10}Be analyses. Because burial ages are calculated from an isotope ratio, their errors reflect the amalgamated error from two AMS measurements. In addition, the effective half-life of the $^{26}Al/^{10}Be$ ratio is long, ~1.3 Myr, meaning that long periods of time produce only small changes in the ratio (Figure 4c). At present, we generally obtain 1σ uncertainties of about ± 3% for ^{10}Be analyses and ± 5% for ^{26}Al, unless the initial exposure time of the sample is exceptionally short or the ^{27}Al concentration in the quartz is unusually high. With these individual errors, the compounded error in the isotope ratio is ± 6%. Error in the burial age, $\Delta t/t$, scales as $\Delta R/R \times 1/(\ln R_0 - \ln R)$, producing an age error of ~ ± 110,000 yrs for a single age determination on a 1 Myr old sample. Although this will preclude detailed correlation with the marine ^{18}O timescale, our results will improve on existing methods for dating and correlating glacial sedimentary sequences, provide the age framework for the study of regolith erosion and export described in section C5, and suffice for correcting meteoric ^{10}Be concentrations to the time of burial. In addition, obtaining multiple dates from the same stratigraphic section should allow us to reduce uncertainties (*cf.* Table 1), more so if it contains fixed points such as a dated volcanic ash or magnetic reversal. We also intend to pursue the highest possible levels of analytical accuracy by using large quartz samples, leaching the quartz thoroughly to reduce Al concentrations, and duplicating analyses if necessary, and we expect that we can improve on our initial results.

C5. Meteoric ^{10}Be in till as a tracer of long-term ice-sheet erosion.

The second aim of this project is to use meteoric ^{10}Be as a tracer to identify ancient pre-Pleistocene regolith in the source material of Laurentide tills. Cosmogenic ^{10}Be is produced in much greater quantities in the Earth's atmosphere than in surficial rocks. This "meteoric" ^{10}Be is stripped from the atmosphere by precipitation and transferred to the Earth's surface, where it adheres to soil particles (L. Brown, 1984, 1987; Lal et al., 1993; Barg et. al, 1997). Distribution coefficients between Be and clay minerals are typically $\sim 10^5$ or higher, increasing with increasing pH (You et al., 1989), hence under neutral to alkaline conditions Be becomes almost irreversibly bound to sediment particles. There is also evidence that ^{10}Be can substitute for Al in weathering reactions and become immobilized in silicate and oxy-hydroxide minerals (Middleton et al., 1994; Lal et.al, 1993). Thus, soils, saprolite and regolith resulting from prolonged weathering under suitable pH conditions become highly enriched in ^{10}Be. Many deeply weathered soils have ^{10}Be concentrations exceeding 10^9 atoms/g (Pavich et, al, 1985, 1986; Brown et al., 1988; Figure 5). Clay-particle illuviation, desorption-adsorption processes and bioturbation mix ^{10}Be downwards, and high concentrations can persist to depths of a few tens of meters (Figure 5 and refs. cited above).

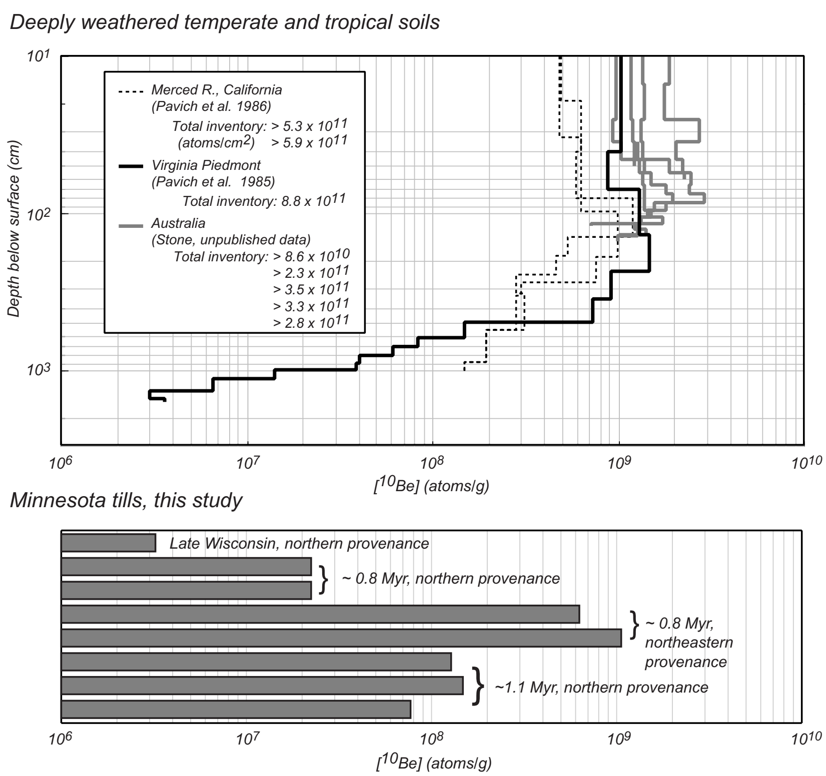


Fig. 5: Meteoric ^{10}Be concentrations in southern Minnesota tills, compared to concentrations in soils and saprolite from outside the limits of Pleistocene glaciation. Examples of deeply weathered profiles from Australia have developed over limestone and basalt, those from Virginia over metapelite. Examples from California have developed on river terraces estimated at 1.6-3 Myr old (Pavich et al., 1986). Be-10 is tightly retained in these soils, judging from total inventories of 10^{11}-10^{12} atoms/cm^2, which require accumulation times of $\sim 10^6$ yr at zero erosion.

Remnants of deep weathering profiles exist throughout glaciated shield regions, indicating that these areas were blanketed by thick regolith prior to glaciation (e.g. Feininger, 1971; Bouchard, 1985; Hall, 1985; Lidmar-Bergstrom, 1988, 1997; Patterson and Boerboom, 1998). Since the deeply-weathered mantle would have required low erosion rates over millions of years to accumulate, its ^{10}Be inventory almost certainly approached values on the order of 10^{11}-10^{12} atom/cm^2 (*cf*. Figure 5). This is much larger than the amount of ^{10}Be that can accumulate in a soil formed during an interglacial period, which will be on the order of ~10^{10} atom/cm^2 in the complete absence of erosion, and likely much less. (This assumes a ^{10}Be delivery rate of 10^6 atom/cm^2/yr for a period of 10^4 years. If the soil accumulates a surface concentration of 2×10^8 atom/g and erodes at 10 mm/kyr, the inventory is reduced by ~ 40%). Based on these estimates we expect meteoric ^{10}Be concentrations to indicate the presence of deeply-weathered material in Laurentide till, and provide us with a means of tracking the removal of weathered surficial cover from beneath the ice sheet.

In preparation for this proposal we measured meteoric ^{10}Be in a sequence of tills from one borehole (UMRB-1) in our proposed field area (Figures 5, 6). The results show that middle Pleistocene tills contain enormous concentrations (10^9 atoms/g) of meteoric ^{10}Be, which is characteristic of extremely old weathered surfaces and entirely excludes the possibility that these tills were formed by erosion of fresh bedrock. The ice sheet that deposited these tills must have mobilized only the upper few meters of a very old preglacial regolith. ^{10}Be abundance in these tills appears to be related to till provenance — the most ^{10}Be-enriched tills have a northeastern source while those from the north are less enriched. Among the northern-source tills, younger tills have lower ^{10}Be concentrations — in the case of the latest Wisconsinan till at the top of the section, by two orders of magnitude — in general agreement with the idea that more recent advances of the ice sheet entrained less pre-existing regolith and accomplished more erosion of fresh rock We propose to pursue these interesting initial results by expanding our geographical coverage and broadening our sampling of Pleistocene time (Section C6).

Three other aspects of meteoric ^{10}Be systematics are important to this study. First, we believe that ^{10}Be is the best available tracer of deeply weathered source materials because of (i) the strong concentration contrast between deeply-weathered regolith and fresh or lightly-weathered bedrock, and (ii) 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 sources such as Cretaceous shales. Weathering of such rock types is not necessarily reflected in their clay mineralogy unless extreme silica loss occurs, but would involve significant uptake of ^{10}Be. Mineral indicators of intense weathering such as gibbsite ($Al(OH)_3$) have rarely been reported from Laurentide till (Gravenor (1975) reports one case from Nebraska). However, 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 mineralogical transformations such as this, and may in fact become more tightly bound (Lal et al., 1993; Barg et al., 1997). Conversely, although weathering of till after deposition could produce mineral assemblages characteristic of pre-glacial regolith, low levels of ^{10}Be would remain a reliable indicator that weathering post-dated rather than pre-dated deposition -- the amount of meteoric ^{10}Be likely to accumulate during a period of weathering between glaciations is small compared to expected pre-glacial concentrations.

Second, ^{10}Be should be conserved during the erosion and deposition of till if its pH remains neutral or alkaline. Nearly all of the sediments in the proposed field area contain secondary carbonate cement and/or limestone clasts, which should ensure alkaline conditions and preclude postdepositional loss of ^{10}Be.

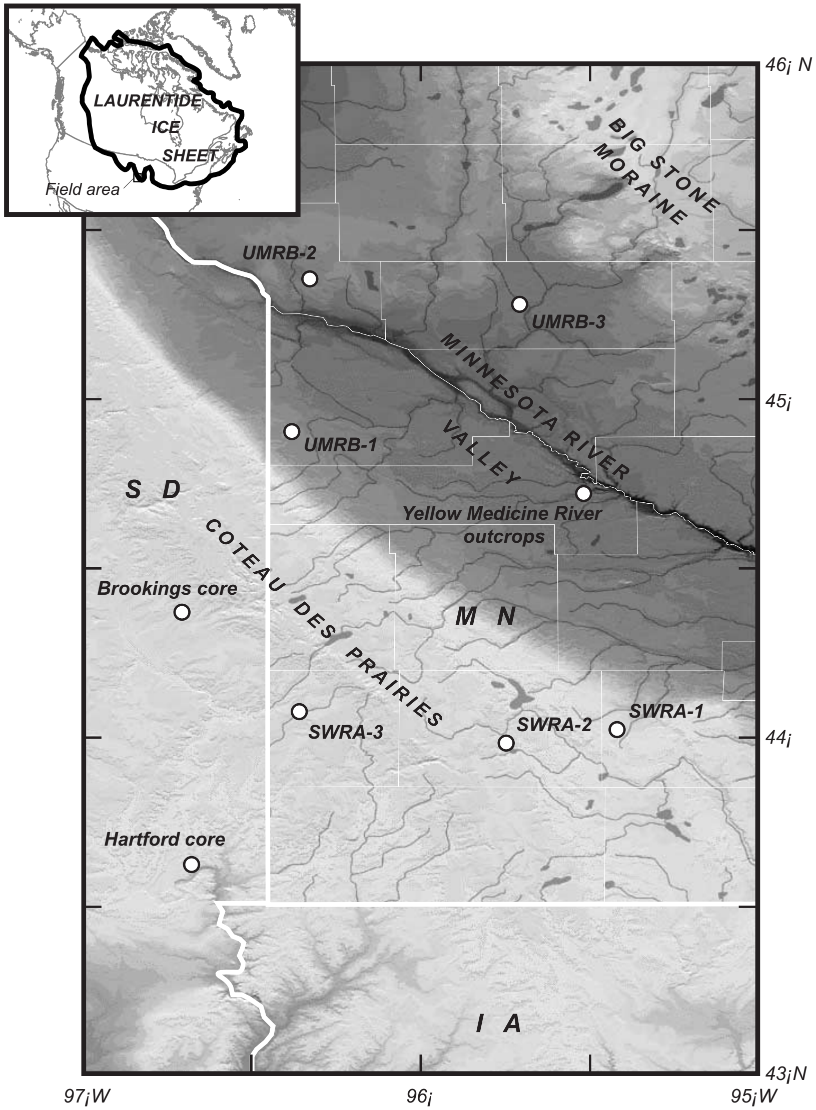
Third, ^{10}Be concentrations decrease by radioactive decay ($t_{1/2}$ = 1.5 Myr) and will have to be corrected to the time of till deposition. This is a second motivation for the burial dating discussed in section C.4 above. The decrease in ^{10}Be concentrations over the Pleistocene (less than twice the ^{10}Be half-life) is less than the expected contrast in ^{10}Be between pre-glacial regolith and interglacial soils. Consequently, errors in our corrections resulting from uncertainty in burial dating will not significantly affect our conclusions.

C6. Field area in southern Minnesota.

Nearly all areas around the margins of the LIS are covered by thick sequences of till interbedded with glaciolacustrine and glaciofluvial sediments. With few exceptions, only the uppermost units in these sequences, deposited within the range of radiocarbon dating, have been dated. In rare cases, identifiable volcanic ashes (Lineburg, 1993; Boellstorff, 1978) or magnetostratigraphic boundaries (Patterson, 1997 b; Hallberg, 1986) provide age constraints on older units. Thus the techniques of burial dating and bulk ^{10}Be analyses that we describe here could be profitably applied to these sequences and many others worldwide. For this initial study, however, we propose to work in a region which: (i) contains a thick, well studied sequence of glacial tills, (ii) contains deposits spanning the Quaternary, and (iii) is accessible in outcrops and subsurface borings. We believe that the sequence of tills covering southwest Minnesota and adjacent areas of South Dakota provides the best possible material for this study.

Southwest Minnesota and adjacent South Dakota contain one of the thickest accumulations of Quaternary glacial sediment in North America (Soller, 2001), and the entire sequence has been carefully mapped and well studied (Fig. 6). At least nine distinct till units (and possibly many more) are present, some of which have been correlated over large areas (Patterson, et al., 1999b; Patterson, 1997a, b; Patterson et al., 1995). The Minnesota Geological Survey (MGS) has carried out sedimentological and geochemical analyses of all of these units and identified their source areas. This is particularly important to our study of pre-glacial regolith removal because we must take into account the possibility of different source regions having different exhumation histories.

The available data show that this till sequence spans much of the Pleistocene. Patterson (1995,1999b) correlated tills in this area into several unconformity-bounded sequences separated by laterally extensive fluvial sand bodies. In the Minnesota River Valley (Figure 6), several Wisconsinan tills overlie two such sequences, to which Patterson (1999b) assigned middle Pleistocene ages based on long-distance correlation to a dated volcanic ash, boreholes containing magnetically reversed glacial sediment, and a gastropod-bearing silt dated by amino-acid racemization. Our initial burial dates (see C.4. above) indicate that tills in these two sequences are near ~ 0.85 and ~ 1.2 Myr old respectively, in agreement with Patterson's correlations. In the Coteau des Prairies highland to the south, a similar section overlies a distinct set of older tills of indeterminate early Pleistocene age. To extend this primary record (and to obtain samples of known age to test the burial-dating technique -- see section C4. above), we will also cooperate with Joe Mason of the Nebraska Geological Survey to obtain samples of tills associated with early Pleistocene volcanic ashes (Pearlette "S" erupted at 1.3 Myr, and Pearlette "B", 2.0 Myr) exposed in Nebraska. These, together with tills in the South Dakota part of our field area associated with the Pearlette "O" ash (0.62 Myr; Flint, 1955), will ensure that our measurements of meteoric ^{10}Be span the entire Quaternary.



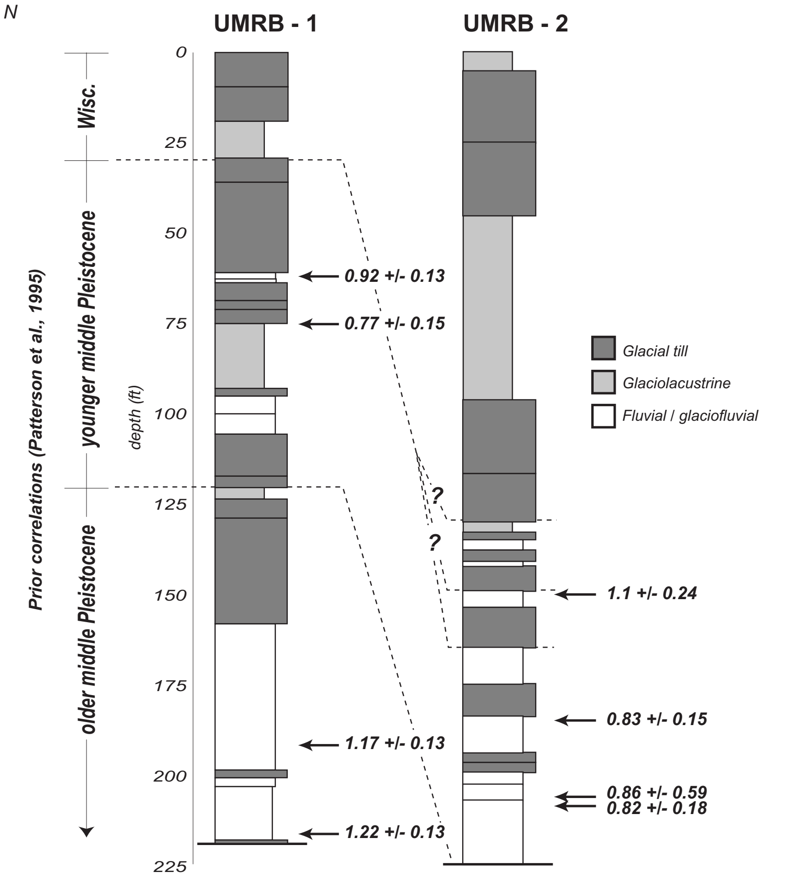


Figure 6. Map of proposed field area in Minnesota and South Dakota, showing deep boreholes and outcrop sites that we plan to study. The Minnesota River Valley, where the two boreholes shown at right are located, is underlain by several Wisconsinan tills of the Des Moines Lobe and then by two unconfomity-bounded packages of middle Pleistocene glacial sediment. The Coteau des Prairies highland to the south and west consists of thin Wisconsinan glacial deposits overlying several hundred feet of early and middle Pleistocene tills. Independent correlation of boreholes is by Patterson et al. (1995). Numerical ages are new burial dates described in this proposal.

Surface and subsurface samples of the entire sequence of tills in our chosen field area in southern Minnesota and South Dakota are readily accessible. Our initial samples come from two continuous Rotasonic cores collected by the MGS (locations shown in Fig. 6). This drilling technique yields nearly complete recovery of large (6" diameter) samples from both tills and sandy units at depths up to 250', which is often sufficient to reach bedrock. We expect to make extensive use of these and many similar cores in MGS archives. We will also cooperate with the South Dakota Geological Survey to obtain archived core samples from the portion of the field area in eastern South Dakota (see attached letter of support), and with the Nebraska Geological Survey to obtain samples of similar material from Nebraska. This large core archive makes the proposed field area especially attractive for this study, both because our sampling is not restricted by available outcrops and because the use of core samples avoids problems in burial dating that may arise from re-exposure of samples collected close to the modern surface. We will also take advantage of outcrops throughout our field area, in particular a set of large outcrops along the Yellow Medicine River which expose several of middle Pleistocene tills (Figure 6), to provide better stratigraphic context and make more detailed meteoric ^{10}Be measurements in some units.

In addition to the technical and logistical advantages of this field area discussed above, constraints we derive on advances of the southern margin of the LIS in this region may be particularly important to Quaternary climate. The drainage direction of much of North America, and thus a significant portion of the fresh water supply to the North Atlantic, is sensitive to the southward extent of the LIS (Licciardi et al., 1999). Furthermore, the ages we obtain for middle and early Pleistocene advances in this region can be taken with other evidence of drainage re-organization in the Ohio River system and meltwater supply to the Gulf of Mexico (Granger et al., 2001; Joyce et al.,1993) to yield a more complete picture of glacial advances along the southern Laurentide margin.

C7. Project timeline and research goals.

This project will involve collaboration between John Stone and graduate student Greg Balco at the University of Washington, and Carrie Patterson at the Minnesota Geological Survey. Patterson will co-ordinate fieldwork and description and correlation of stratigraphic units sampled in outcrop and cores. Stone will focus on the cosmogenic isotope work. Balco will work closely with both. We have budgeted for all three personnel to participate in aspects of the work taking place in Minnesota and Seattle. This will ensure exchange of ideas, sound interpretation of results and careful integration of new cosmogenic isotope data with existing information on the age and provenance of glacial sedimentary sequences in the field area.

The major research tasks will be as follows:

1. Fieldwork to be completed during the first two years. We will obtain core material from the MGS archive at Hibbing, Minnesota, and supplement this with material from outcrops along tributaries of the Minnesota River. We will obtain samples of modern surficial sand and Wisconsinan-age glacial sediments from around the state.
2. Burial dating of glacial sediments bracketing till in the study area and in cores from South Dakota and Nebraska - Years 1 and 2. In the first year we will analyse material already collected, and use the results to develop the sampling program for year 2. Initially we will focus on borehole samples, especially those with existing chronological control, to further

test the burial dating method. Also in the first year we will check the initial $^{26}Al/^{10}Be$ ratios of "control" sands from modern surficial environments.

3. Meteoric ^{10}Be analysis of surviving pre-glacial regolith and tills. In the first year, we will analyse bulk ^{10}Be in soils and in deeply-weathered remnants from natural exposures and mines in saprolite near Redwood Falls, Minnesota. These areas lie within the Wisconsin glaciation limit and will be used to verify the expected contrast in ^{10}Be concentrations between ancient regolith and post-glacial soils. Bulk ^{10}Be analyses of the entire sequence of tills will be spread over years 1 and 2, using our burial dating results to select samples with ages spanning a wide range of Pleistocene time.
4. Synthesize and apply results to existing models of the stratigraphy and glacial dynamics. In the second and third year we will analyse and present our findings, accelerating this schedule if early analyses bear out our interesting initial findings.

C.8. Summary of likely outcomes of this research.

The research described here will establish the pattern of cosmogenic isotope abundances in glacial sediment.

Measurements of *in-situ*-produced ^{10}Be and ^{26}Al in quartz from glacial sedimentary sequences will provide bracketing ages for the most extensive advances of the Laurentide ice sheet. Up to now, these advances have been difficult to date, and obtaining ages for them will result in significant progress toward understanding the pre-LGM dynamics of the ice sheet, its role in Pleistocene climate change and the relationship between terrestrial and marine records of Northern Hemisphere glaciation. These ages will also be of great use to geologists in Minnesota, South Dakota and Nebraska for establishing the stratigraphy of glacial deposits across the region, which will in turn facilitate land use and hydrogeologic resource studies (see attached letters of support).

Measurements of meteoric ^{10}Be in tills deposited at different times throughout the Pleistocene will allow us to track the removal of weathered pre-glacial regolith by the Laurentide ice sheet. This will yield new information about the rate and style of erosion beneath large ice sheets. Our initial measurements suggest that older Laurentide till deposits are largely derived from deeply-weathered pre-glacial material, and younger ones from erosion of fresh rock. The follow-up work we propose will test this further, and place tighter age constraints on the erosional history. The results will help to address the important paleoclimatological question of how conditions at the bed of the ice sheet may have affected climate variability, and will shed light on the geomorphic question of whether the topography of glaciated regions has been carved by subglacial erosion of hard rock, or is largely a relic of deep pre-glacial weathering.

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