ENTRAINMENT AND TRANSPORT OF SUBGLACIAL SOILS AND ROCK IN WESTERN GREENLAND

A Progress Report Presented

by

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Introduction

The work presented in this progress report differs substantially from the scope of work laid out in my May, 2008 thesis proposal. There, I proposed to use the three-dimensional thermomechanical ice sheet model Glimmer [Rutt et al. 2009] to interpret cosmogenic isotopes in glacial detrital clasts from Western Greenland in terms of ice sheet mechanics and subglacial erosion rates. The implementation of this proposed work became difficult for two reasons. Delays in the reconstruction of Paul Bierman's laboratory deprived me of a dataset with which to control model parameters. And, Thomas Neumann's departure from the UVM faculty left me primarily working with Paul Bierman, who lacks expertise in ice dynamics. Furthermore, we have found interesting and unexpected meteoric ^{10}Beryllium values in sediment sampled from the western Greenland Ice Sheet. The analysis and interpretation of these data is now the primary focus of my research. The modelling component of the project has not been abandoned, but simpler two and one dimensional models are being employed.

In the summer of 2008, I traveled to Greenland with Paul Bierman, Tom Neumann, and Lee Corbett. We collected ice-marginal samples at three locations in western Greenland: Kangerlussuaq (67.1º N), Ilulissat (69.4 º N), and Upernavik (72.5º N) [Figure 1]. Our primary purpose was to sample glacial detrital clasts. But ice and ice-bound sediment were also collected. Cosmogenic ^{10}Be was measured in meteoric particles adhered to the ice-bound sediment grains. ^{18}O and ^{2}H were measured in the corresponding ice.

Background

Due to its size and sensitivity to changing climate conditions, the Greenland Ice Sheet has likely had a major role in sea level fluctuations over previous glacial /interglacial cycles [Huybrechts 2002]. Modelled arctic temperatures from the Eemian interglacial (~130-116 ka BP) closely resemble those forecasted for c. 2100 in global warming models [Overpeck et al. 2006]. A detailed understanding of the Greenland Ice Sheet's behavior during the Eemian would therefore aid in the prediction of future sea level change.

Results and Discussion

Regelation signal in stable isotope data

^{18}O values in Central Greenland ice cores generally vary between -30‰ and -40‰ [Dansgaard et al. 1982; Stuiver and Grootes 2000]. These values can be distinctly divided into Holocene, and Pleistocene cold and mild phases. Our measured ^{18}O values also fall within this range, but are generally below Holocene values from the southern Dye 3 site and above Pleistocene cold phase values found in the Summit cores. Deuterium excess is calculated by subtracting 8 times the ^{18}O value from the D value. The excess values in our samples vary from around 10‰, to below 0‰. Several of our excess values are well below those recorded in central Greenland ice cores [Johnsen et al.

some of the lowest ^{18}O and excess values in the dataset and may indicate regelation enrichment from Pleistocene cold phases.

Meteoric ^{10}Be, regelation and erosion rates

The 13 measured meteoric ^{10}Be values vary from $3.2*10^6$ to $2.1*10^8$ atoms/gram. While all three sites have similar lowest measured values, the highest measured value varies significantly by latitude, the higher latitude sites having progressively greater maximum values. It is unlikely that the northern latitude sites experienced longer exposure during past interglacial periods, so this variation is likely explained by differences in erosion rates.

In comparing meteoric ^{10}Be concentration and deuterium excess, we find that the highest ^{10}Be values are found in samples where deuterium excess is also high and open-system regelation is therefore unlikely [Figure 3]. Significant loss of deuterium excess through open-system regelation is unlikely where deuterium excess exceeds 8.25‰. These values are at or above the deuterium excess values found in all periods of the Greenland ice core records. Lowering of deuterium excess due to open-system regelation is likely below values of 3.25‰, as ice core deuterium excess values are seldom this low. Between values of 3.25‰ and 8.25‰, open-system regelation may have occurred depending on whether the ice was deposited during a Pleistocene mild phase.

Open-system regelation is most likely to occur where there is abundant subglacial water. As subglacial streams are one of the most effective agents of subglacial erosion [Alley et al. 1997], sediment entrained by open-system regelation is more likely to be sourced from an area where erosion rates are high. As subglacial water is often derived from surface melt [Das et al. 2008], lower latitudes may have higher rates of erosion.

Sediment entrained through closed-system regelation, in which all the melted water refreezes, is more likely to be sourced from the interior of the ice sheet, where subglacial water is scarce. The time necessary to transport the sediment from the interior to the margin also reduces the erosional signal in such sediment, the sediment retaining the ^{10}Be signal of the top layer of the soil prior to transit. If the sediment is sourced far enough from the margin, the transport times may equal most of the current glacial cycle [Figure 4].

In order to estimate these potential transport times, I use model ice velocities provided by Wei Li Wang of the Goddard Space Science Institute at NASA. These data are derived from geophysical data for the present Greenland Ice Sheet and physical equations that describe ice behavior [Wang et al. 2002]. Ice velocity is interpolated from horizontal data spaced along 1 km nodes and 100 vertical grid points. For each horizontal node, a total sediment transport time is calculated for sediment originating from that node. This method assumes that the basal layer had similar horizontal velocities during the Pleistocene and ignores the possibility that sediment might be deposited and later re-entrained by changing ice dynamics. Generally, sediment sourced within the first 100 km will arrive at the margin within 10,000 years. Possibly, much, if not all, of our sediment is so sourced. But these results nevertheless indicate the possibility that sediment was in transit for most of the last glacial cycle.

Soil ages and inheritance

In order to evaluate the potential ages of the soils from which our sediments were sourced, I compiled a global database of meteoric ^{10}Be soil profiles; a total of 86 profiles from 24 papers. ^{10}Be is mobile in the soil profile, and the maximum ^{10}Be concentration is often not in the top layers [Pavich et al. 1986]. I conservatively assume that the highest measured ^{10}Be value at each of our sites represents the maximum ^{10}Be concentration in source soils for that site's sediments. I compared peak ^{10}Be concentration to the total ^{10}Be inventory in 48 appropriate soil profiles from the global database [Barg et al. 1997; Bouchard and Pavich 1989; Brown et al. 1988; Harden et al. 2002; Maejima et al. 2004; McKean et al. 1993; Monaghan et al. 1983; Monaghan et al. 1992; Pavich et al. 1986; Pavich et al. 1984; Pavich et al. 1985; Pavich and Vidic 1993; Reusser and Bierman In Press; Shen et al. 2004; Stanford et al. 2000; Tsai et al. 2008]. I then use this correlation to estimate the total ^{10}Be inventory in the source soils of each of our 3 sites [Figure 5].

To convert a ^{10}Be inventory into a soil age, a ^{10}Be deposition rate must be known. ^{10}Be fallout in the interior of Greenland is well-constrained by measurements of ^{10}Be in ice cores [Finkel and Nishiizumi 1997]. To estimate the deposition rate in the coastal areas, I applied the deposition per unit of precipitation in the ice cores to the local annual rainfall at each of our field sites [Table 2]. The values generated by this method approximate ^{10}Be fluxes modelled through general circulation models for the coastal areas of Western Greenland [Field et al. 2006].

The implied soil age of 50-100 ka at the northernmost site may have been acquired over multiple glacial cycles. A recycled ^{10}

deposition rates estimated from ^{10}Be inventories in soil profiles. The method of assessing long term deposition rates from soil profiles was developed by Luke Reusser and Paul Bierman in their work in New Zealand. A soil profile from Waipaoa in New Zealand will be analyzed, as will selected published ^{10}Be soil profiles. Within the next two months, I intend to submit these papers to Geochemica et Cosmochemica Acta and Earth and Planetary Science Letters, respectively.

These two papers are critical for robust interpretation of the Greenland data. The global soil profile comparison provides the relationship between peak ^{10}Be concentration and total ^{10}Be inventory discussed above. A well-constrained ^{10}Be deposition rate is also essential in estimating the sediment-source soil ages. Once we have the complete meteoric ^{10}Be dataset for Greenland and these papers are submitted, I will begin work on a third paper that analyzes the Greenland meteoric ^{10}Be and stable isotope data. I hope to submit the Greenland paper in January.

To further analyze the entrainment of relict soils in the Greenland Ice Sheet, we are expecting to receive ice samples from the sediment-rich basal layer of the GISP2 core, drilled at Summit, Greenland. This winter we will analyze the meteoric ^{10}Be and stable isotopes in this basal ice as well. This will provide broader context for the marginal samples.

In late winter / early spring we expect to have at least 100 *in situ* ^{10}Be measurements from the detrital clasts. The analysis of these clasts will primarily be the subject of Lee Corbett's thesis. However, I plan to create two-dimensional models of the retreat of the Greenland Ice Sheet during past interglacial periods, the isostatic response of Greenland, and the subglacial entrainment of detrital clasts during the subsequent glacial period advance. These models will allow us to estimate the extent of interglacial retreat and subsequent glacial erosion, based on the observed cosmogenic isotope data.

In late spring, I intend to defend my masters thesis. I have funding to remain working over the summer. We will likely then be working on academic papers emerging from the *in situ* cosmogenic isotope data.

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Table 1: Rock type and angularity sampled by location.

Banded Gneiss	Granitoid	Foliated Granitoid	Meta Sedimentary	Other	Total	Total

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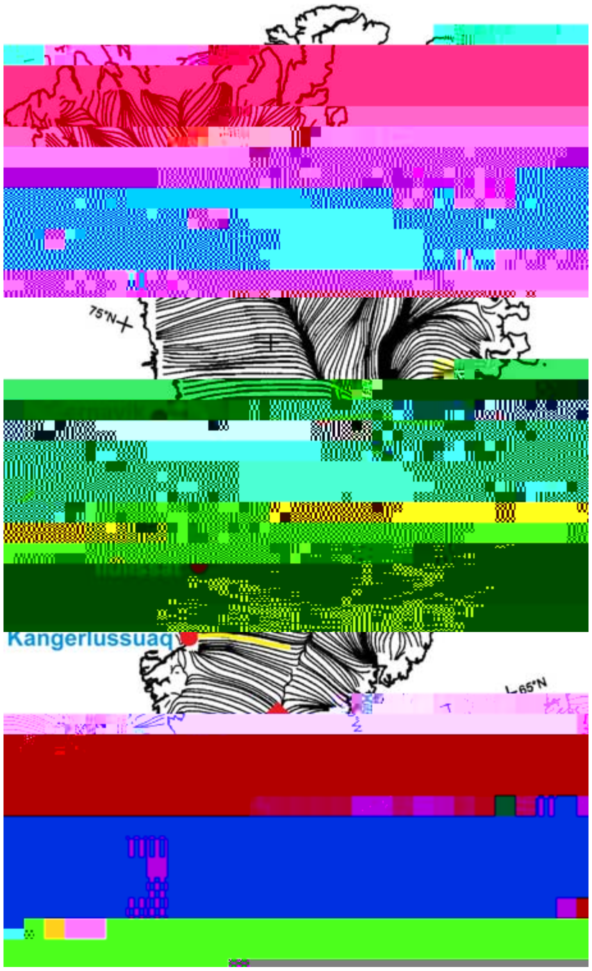

Figure 1: Modelled glacial flowlines of Greenland (modified from Zwally and Giovinetto, [2001]) showing the locations of our three field sites and the flowlines along which sediment may be sourced to these sites. The locations of Dye 3 and Summit Station are also shown.

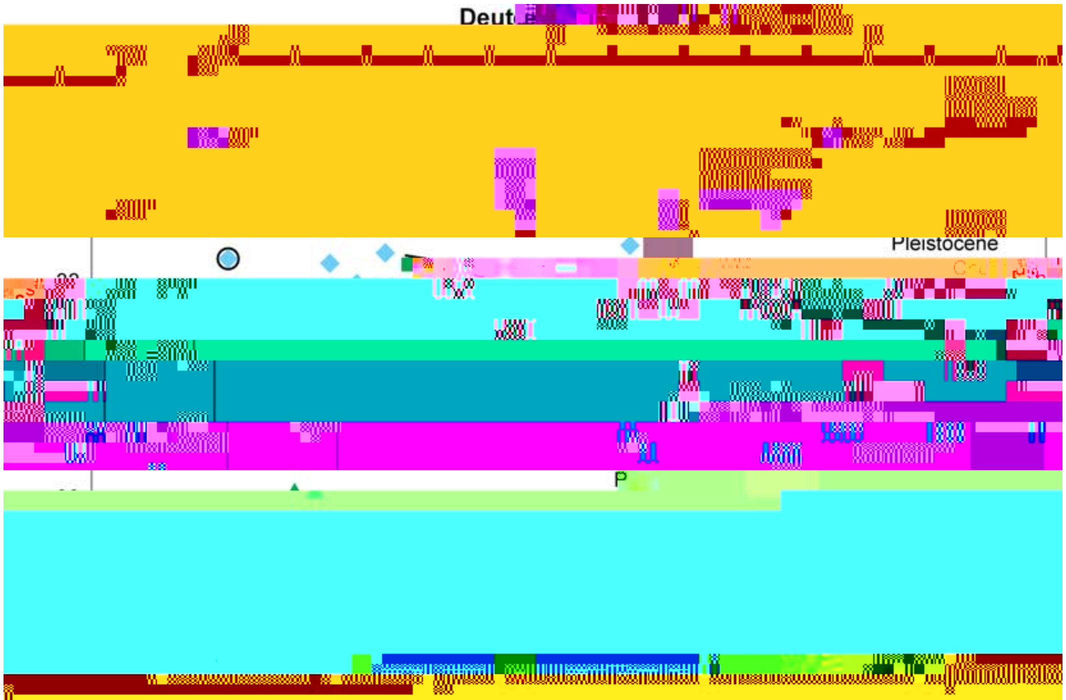

Figure 2: Deuterium excess versus ^{18}O in ice water samples. The general value ranges for the Summit and Dye 3 ice cores are also shown. Circles indicate meteoric ^{10}Be was measured in the sample's sediment.

Figure 3: Relation between meteoric ^{10}Be in sediment and deuterium excess ice in samples where both were measured. The highest meteoric ^{10}Be concentrations come from sediment bound in ice where open-system regelation is unlikely to have occurred. Where open-system regelation is possible or likely, a range of values is found.

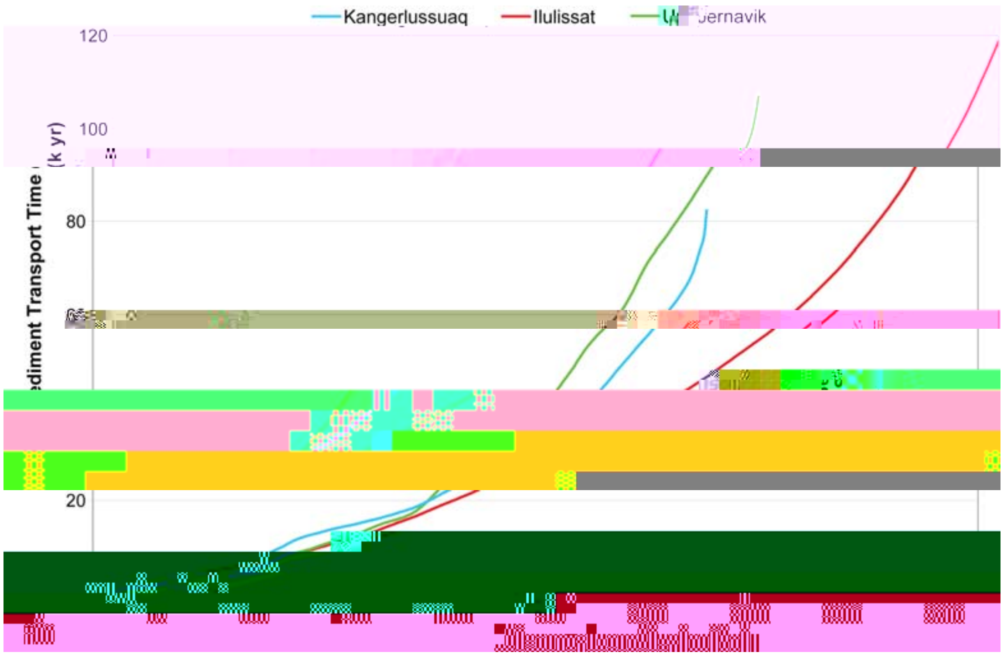

Figure 4: Modelled transport times for sediment entrained in the basal layer of the Greenland Ice Sheet along flowlines providing sediment to our three sampling sites. For