# DETRITAL COSMOCHRONOLOGY OF THE GREENLAND ICE SHEET

A thesis progress report presented by

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# I. INTRODUCTION

## 1.1 Goals and Previous Work

How has the Greenland Ice Sheet behaved during past interglacial periods? Is it stable in size or has it melted significantly? These questions are difficult to answer in Greenland because little to no ice remains from before the most recent interglacial period (the Eemian, roughly 130ka). To address this question, I will develop and apply a new isotopic approach in order to understand how the ice sheet responded to warm periods during the past million years or more.

There is a growing body of knowledge suggesting that the Greenland Ice Sheet is a dynamic system that actively changes with climate. Modeling efforts by Letréguilly et al. (1991), Cuffey and Marshall (2000), Overpeck et al. (2006), and Otto-Bliesner et al. (2006) indicate that the ice sheet melted significantly during the Eemian. However, we know little about how the ice sheet responded during interglacial periods that preceded the Eemian. For my Master's thesis, I am investigating and testing a new approach to cosmogenic nuclide analysis (e.g. Granger and Muzikar, 2001). I am using cosmogenic burial dating of ice-bound rocks to study the response of the ice sheet during these warm periods. Isotopic analysis will provide information about times when the ice sheet shrank and these rocks were last exposed to cosmic radiation. I will also use cosmogenic analysis of bedrock surfaces, boulders, and small clasts outside of the current ice margin to better understand how the Greenland Ice Sheet behaves during interglacial periods.

## 1.2 Cosmogenic Nuclide Dating: Background and Techniques

Cosmogenic dating uses rocks as dosimeters to determine how long Earth materials have been bombarded by high-energy particles (e.g. Granger and Muzikar, 2001) and, in this case, how long the rocks have been buried allowing these nuclides to decay. Cosmic ray bombardment forms radioactive isotopes that are otherwise extremely rare (e.g. Lal, 1988), including $^{10}Be$, $^{26}Al$, $^{36}Cl$, and $^{14}C$ (half-lives of 1.3, 0.7, 0.3, and .005 million years, respectively) (Gosse, 2007; Nishiizumi et al., 2007). These cosmogenic nuclides are formed at known rates that vary spatially with geomagnetic field strength (Lal, 1991). Knowing the concentration of one or more cosmogenic nuclides in a sample, as well as their production and decay rates, allows inferences to be made about that sample's exposure to cosmic radiation.

Each time the Greenland Ice Sheet melts back from its current extent, interior Greenland is exposed to cosmic radiation. When the ice sheet re-advances, the production of cosmogenic nuclides in the rock ceases and the rock containing these nuclides is eroded and transported towards the ice margin. Over time, the ratio between any two nuclides with different half-lives becomes increasingly different from the nuclide ratio during exposure. Measuring these ratios in ice-bound clasts can provide information about how long ago exposure occurred, and indicates when the ice sheet was reduced in size.

**1.3 Hypotheses**

My work, which marks the first attempt at deducing ice-bound clast history, is unique; yet, there are indications that it will be a successful approach. The marine oxygen isotope record clearly indicates large changes in global ice volume over time (e.g. Lisiecki and Raymo, 2005). Additionally, it has been demonstrated that bedrock from the base of the GISP2 ice core in central Greenland contains cosmogenic nuclides (Nishiizumi et al., 1996). Therefore, I hypothesize that there will be detectable concentrations of cosmogenic nuclides in at least some of the samples I have collected. This is a noteworthy conclusion in and of itself, since it will demonstrate that the ice sheet has in fact been smaller in the past. Second, I hypothesize that there will be clustering in the burial age data due to different temporal patterns of exposure. For example, some clasts may exhibit only one exposure from the Eemian period. Others may exhibit multiple exposures from several different interglacial cycles.

**1.4 Implications**

This work has significant broader impacts both for the application of cosmogenic nuclides in paleoclimatic research and for understanding Greenland Ice Sheet dynamics.

- *Methodologically:* Cosmogenic nuclide dating has not yet been applied in this context. Successful development of the ice burial method will allow other researchers to apply the same technique at additional locations in Greenland and at other bodies of ice. Additionally, the sampling of bedrock, boulders, and small clasts outside of the current ice margin will provide insight about isotopic relationships between these different types of material.
- *Temporally:* Previous work has detailed climate in Greenland since the Eemian. My work investigates long-term ice sheet behavior, a temporal scale on which little is known.

- *Climatically:* My work will clarify how the Greenland Ice Sheet responded to interglacial warming periods, which is critical for predicting the impact of anthropogenic warming.
- *Culturally:* Complete melting of the Greenland Ice Sheet would cause 6-7 m of global sea level rise (Alley et al., 2005). The results of this work will provide important detail regarding the frequency, intensity, and spatial distribution of past melting events.

## II. PROGRESS: SPRING 2008 THROUGH FALL 2008

### 2.1 Fieldwork

During July of 2008, I spent three weeks doing fieldwork along the western margin of the Greenland Ice Sheet with Paul Bierman, Tom Neumann, Bob Finkel, and Joseph Graly. We collected samples from three different locations (figure 1): Kangerlussuaq (67˚N), Ilulissat (69˚N), and Upernavik (72˚N). These samples, 346 in total, fell into four families that are described below in more detail. All four of these families will aid in our understanding of ice sheet behavior during past interglacial periods.

<u>Burial Dating Clasts</u>

At each of the three sites listed above, cobble-sized rocks were removed from the marginal areas of the ice sheet (figures 2-3). These samples will be the primary mechanism of addressing the research hypotheses and make up the bulk of the samples we collected (100 from Kangerlussuaq, 73 from Ilulissat, and 98 from Upernavik; 271 total). These samples were all taken from areas where we were confident that they had been sourced directly from the ice sheet, including: embedded in the ice (figure 4), melted out directly on top of the ice (figure 5), and in outwash deposits in close proximity to sub-glacial drainage channels (figure 6). The clasts ranged in diameter from 10 to 25 cm. The weight, lithology, angularity, approximate dimensions, and any other notable features (striations, weathering, etc) of each clast were recorded.

<u>Holocene Exposure Clasts</u>

At each of the three sites, we also collected clasts that had likely been exposed to cosmic radiation for the duration of the Holocene (3 from Kangerlussuaq, 4 from Ilulissat, and 3 from

Upernavik; 10 total). These samples, which were gathered off high-elevation, bare bedrock surfaces far outside of the Little Ice Age moraines, will be an indication of how an interglacial period of cosmic exposure affects the isotopic composition of a small clast. Additionally, this approach will allow us to determine whether these clasts have inherited cosmogenic nuclides from previous periods of exposure. Understanding the affect of interglacial exposure will aid in our interpretations of the 271 clasts sourced from the ice. Like the other family of clasts, the weight, lithology, angularity, approximate dimensions, and other notable features of each sample were recorded in the field.

<u>Bedrock Samples</u>

Bedrock sampling was conducted outside of the current ice margin to help constrain the chronology of the last deglaciation and will provide additional information that will be helpful as we begin to interpret the isotopic concentration of ice-bound clasts. The bedrock data will provide insight about the rate and spatial characteristics of ice retreat after the last glacial maximum and will aid in our understanding of how the ice sheet behaves during interglacial periods. These samples will also demonstrate whether the bedrock has any inherited cosmogenic nuclides from older interglacial periods and will allow us to make inferences about erosion rates under the Greenland Ice Sheet. Only one bedrock sample was collected from Kangerlussuaq, since Rinterknecht et al. (2008) have recently measured $^{10}$Be in bedrock from the same area. Ilulissat and Upernavik were sampled more extensively (16 and 20 places, respectively). These samples were taken in roughly linear transects stretching from the ice margin to the coast at high (>500 m), medium (200-500 m) and low (<200 m) elevations (figures 2-3). This strategy will help constrain not only the geographic extent of the ice sheet's retreat over time, but will also provide information about ice thickness.

<u>Boulder Samples</u>

Large boulders (>1 m) were sampled at the same locations that bedrock samples were taken, as long as boulders were present. The data generated from these boulders will help to clarify the isotopic relationship between glacially eroded bedrock and the large erratics deposited on top of it. By comparing the isotopic abundances between the bedrock and boulder samples, we will be able to make inferences about whether the bedrock, the boulders, or both, have any inherited cosmogenic nuclides from previous interglacial events. This data will be helpful as we begin to interpret the 271 ice-bound clasts and will provide information about erosion rates under the Greenland Ice Sheet. We sampled a total of 28 boulders: 15 from Ilulissat and 13 from Upernavik.

### 2.2 Laboratory Work

I will be measuring cosmogenic nuclides in quartz ($^{10}Be$, $^{26}Al$, and $^{14}C$) and potassium feldspar ($^{36}Cl$). These mineral phases must therefore be isolated from the rest of the rock for analysis to be performed. The first steps involve physically preparing the rocks. To perform these steps, I crush and grind each rock to create monomimerallic grains, and sieve the material to isolate the 250-710μm grain size fraction. I then magnetically separate this grain size fraction to isolate the felsic grains, which will continue on to the chemical preparation steps. Upon returning from Greenland, I completed the physical preparation steps on 170 of the 346 samples during the month of August. Joseph Graly is currently preparing the remainder of the samples.

After the felsic minerals have been isolated from a sample, a series of acid etches must be performed to isolate the quartz grains. First, I etch each sample twice for 24-hours in hot HCl to remove grain coatings, weathering products, and meteorically produced $^{10}Be$. Next, I etch a small mass (<40 g) of each sample three times for 24-hours in dilute, hot HF and $HNO_3$. This step removes almost all of the non-quartz grains and must be repeated until each sample has a yield of at least 25 g. If there are still mafic minerals in the sample, I use heavy liquid density separation to isolate the quartz. Finally, I etch the remaining material for 72-hours in very dilute, hot HF and $HNO_3$. Since the beginning of the fall semester, I have completed this process on all 65 of the bedrock samples and all 10 of the Holocene exposure clasts.

### 2.3 Database and Geographic Information Systems (GIS) Work

In addition to the physical preparation of 170 samples and the chemical preparation of 75 samples that I completed since returning from the field, I have also done work outside the lab. After returning from Greenland, Joseph Graly and I constructed a comprehensive database that includes all of the field data and laboratory progress for each of the 346 rocks we brought back. This database allows us to organize our samples, store important information, and keep track of our progress. This fall, I used the information in the database to create GIS point layers for all of the samples, which can be viewed in GIS software or Google Earth. The data layers contain the information for each sample, and can be shared between members of our research team and colleagues doing similar work. Additionally, as part of the GIS Practicum (NR243), I have begun to work on creating digital elevation models and downloading satellite imagery for our field sites.

## III. FUTURE TIMELINE: WINTER 2008 THROUGH SPRING 2010

### 3.1 Continued Work with Bedrock, Boulders, and Holocene Exposure Clasts

As described above, I have made quartz for all of the bedrock samples, boulders samples, and Holocene exposure clasts. This winter, the quartz from these samples will be further processed in the new cosmogenic facility with the help of Jen Larsen. The quartz will be dissolved and sent through a series of steps that will remove the accessory cations (chiefly Fe and Ti). I will analyze the $^{10}Be$ and $^{26}Al$ content at the Livermore National Laboratory in the late winter of 2009, and will perform data analysis and manuscript writing in the spring of 2009.

### 3.2 Burial Dating Clasts

Between Thanksgiving break and Winter break, I will work with Joseph Graly to send all 271 out-of-ice clasts through two 24-hour etches in hot HCl. This will clean the samples and allow us to visually decide which ones to continue working on. Samples that have abundant potassium feldspar will be separated by density so that the feldspars can be set aside for $^{36}Cl$ analysis. During the late winter and spring, a subset of the 271 samples will be processed with the HF/$HNO_3$ etching described above to create quartz for the analysis of $^{10}Be$, $^{26}Al$, and $^{14}C$. If necessary, potassium feldspar will be isolated for the analysis of $^{36}Cl$.

Not all of the isotopes will be analyzed for each clast. First, a clast will be analyzed for $^{10}Be$ and $^{26}Al$. If the clast does not contain detectable concentrations of either of these isotopes, it is unlikely that it will contain $^{36}Cl$ and $^{14}C$ because the half-lives of $^{10}Be$ and $^{26}Al$ are much longer. If a clast does, however, contain $^{10}Be$ and $^{26}Al$, it will also be analyzed for $^{36}Cl$ if the rock contains potassium feldspar (to help constrain when exposure occurred) and $^{14}C$ (to rule out any Holocene exposure). Isotopic analysis will be performed during the majority of 2009.

### 3.3 Looking Ahead

By the early months of 2010, I hope to have completed all of the isotopic measurements, which will allow me to finish writing my thesis in the spring of 2010. During much of the next year, Joseph Graly will work on mathematical modeling of ice flow dynamics and isotopic behavior. Our combined efforts and different approaches will allow us to interpret the data more fully. I plan to present the results of the bedrock and boulder dating next year, either at the 2009 GSA or the 2009 AGU. The results from the burial clast work will be presented as well, likely at the 2009 or 2010 AGU.

| Time Period | Bedrock, Boulders, and Holocene Exposure Clasts | Burial Dating Clasts |
|---|---|---|
| *Fall 2008* | Make quartz | Finish crushing, grinding, etc. |
| *Winter 2008/2009* | Perform dissolutions, isolate Be and Al, perform isotopic analysis | Etch all samples in HCl, isolate kspar if possible, begin $HF/HNO_3$ etches |
| *Spring 2009* | Analyze data, begin writing manuscript | Continue $HF/HNO_3$ etches, begin dissolution and isotopic analysis |
| *Summer 2009* | Finish manuscript | Continue with etches and isotopic analysis |
| *Fall 2009* | Present results at GSA or AGU | Continue isotopic analysis, begin data analysis, present preliminary data at AGU(?) |
| *Winter 2009/2010* | Begin writing thesis | Continue data analysis, begin writing thesis |
| *Spring 2010* | Finish data analysis, finish writing thesis, present and defend | |
| *Summer 2010* | --- | Write manuscript |
| *Fall 2010* | --- | Present results at AGU |

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*Figure 1. Map of Greenland (1:4,000,000) (Geodetic Institute of Copenhagen, 1938). Blue circles show the three sites where samples were taken: Kangerlussuaq (67˚N), Ilulissat (69˚N), and Upernavik (72˚N)*

*Figure 2. Map of Ilulissat showing the locations where ice-bound clasts (red dots) and bedrock/boulder samples (green dots) were collected.*


*Figure 3. Map of Upernavik showing the locations where ice-bound clasts (blue squares with white labels) and bedrock/boulder samples (red dots with black labels) were collected.*

*Figure 4. Example of a large clast embedded in a vertical ice face (Upernavik).*

*Figure 5. Example of a large number of clasts that have melted out from a debris-rich band and now lie on the surface of the ice sheet (Kangerlussuaq).*

*Figure 6. Example of an outwash deposit below a subglacial drainage tunnel (Kangerlussuaq).*