INVESTIGATING THE TIMING OF DEGLACIATION AND THE EFFICIENCY OF SUBGLACIAL EROSION IN CENTRAL-WESTERN GREENLAND WITH COSMOGENIC $^{10}$Be AND $^{26}$Al
Thesis Road Map:

**Optimizing sample preparation for $^{10}\text{Be}$ analysis by accelerator mass spectrometry**

**Paired bedrock and boulder $^{10}\text{Be}$ concentrations resulting from early Holocene ice retreat near Jakobshavn Isfjord, Western Greenland**

**Constraining landscape history with $^{10}\text{Be}$ and $^{26}\text{Al}$ in paired bedrock and boulder samples, Upernavik, Central-Western Greenland**
Background & Rationale
Why Greenland?

• Greenland Ice Sheet holds ~7 m global sea level equivalent
• Highly susceptible to warming climate

Goal: to investigate how the ice sheet behaved during past warming episodes in order to understand how it might behave in the future
Climate Basics

Climate is not static over time!

Warmer

Colder

Holocene Period

X-axis: thousands of years ago (“ka”) 

Warm periods: “Interglacial”

Cold periods: “Glacial”

(Lisiecki and Raymo, 2005)

Last “Ice Age”
Variability of the Greenland Ice Sheet

Interglacial period ice extent

Letréguilly et al. (1991)
Otto-Bliesner et al. (2006)
Overpeck et al. (2006)

Glacial period ice extent

Bennike et al. (2002)
Funder and Hansen (1996)
Winkelman et al. (2010)
Ice Can Lose Mass in Multiple Ways

- Melting
- Sublimation
- Calving
Research Goals

At two different sites in western Greenland:

• Make inferences about the efficiency of subglacial erosion
  – How effectively does ice erode bedrock surfaces?
  – Does this control the landscape we see today?

• Determine the chronology of ice retreat after the last glacial period
  – When did ice retreat begin?
  – How long did ice retreat last?
  – How rapid were ice retreat rates?

• Compare ice behavior between two sites
Tools, Study Design, & Methodology
Tools: *in situ* cosmogenic $^{10}$Be and $^{26}$Al

- “*In situ*”: produced within the mineral structure (quartz)
- “Cosmogenic”: from cosmic rays
- “$^{10}$Be”: rare, radioactive isotope of beryllium
- “$^{26}$Al”: rare, radioactive isotope of aluminum
Formation of *in situ* cosmogenic $^{10}\text{Be}$

Earth is bombarded by high-energy cosmic rays

...causing the formation of $^{10}\text{Be}$ in quartz

$^{16}\text{O}$ (8 protons, 8 neutrons) $\rightarrow$ $^{10}\text{Be}$ (4 protons, 6 neutrons)

$^{10}\text{Be}$ is produced only on the surface of a rock

$^{10}\text{Be}$ is produced at about 6 atoms per year per gram of quartz

$^{10}\text{Be}$ is radioactive and has a half-life of 1.38 million years
“Cosmogenic Dating”

Glacial period: Bedrock is **shielded**

Interglacial period: Bedrock is **exposed**

Assumption: Zero **inheritance** (i.e. no $^{10}$Be leftover from previous periods of exposure)
Sampling Scheme & Methodology

• Collect bedrock and boulder samples in a transect parallel to direction of ice flow

• Analyze $^{10}$Be concentrations
  – Isolate quartz, remove impurities
  – Isolate pure Be from quartz
  – Measure $^{10}$Be/$^{9}$Be ratios by accelerator mass spectrometry (AMS)
  – Calculate exposure ages

• Analyze $^{26}$Al contents (only certain samples)

• Make inferences about ice behavior
Sampling Scheme

“Dipstick” Sampling:

Sea Level

West (Ocean)  East (Interior Greenland)
Cosmogenic Inheritance

- More prevalent in bedrock than in boulders
  - Outcrop is exposed (earlier interglacial?)
  - Outcrop is covered by ice
  - Ice is non-erosive, doesn’t remove $^{10}$Be
  - Outcrop is exposed again

Boulder: 10 ka
Bedrock: 30 ka
Study Sites

Ilulissat:
• Latitude: 69°N
• Continuous land surface
• Jakobshavn Isfjord

Upernavik:
• Latitude: 73°N
• Fjord-dissected terrain
• No major outlet glaciers
Site #1: Ilulissat, 69°N
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Site #2: Upernavik, 73 °N
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Site #2: Upernavik, 73 °N
Recap

- $^{10}$Be and $^{26}$Al are radioactive isotopes formed when cosmic rays interact with quartz.
- Use the production rate and concentration to calculate an exposure age.
- Two study sites in western Greenland: Ilulissat (69°N) and Upernavik (73°N).
- Samples collected in “dipsticks”.
- Goal: to understand subglacial erosion efficiency and ice retreat characteristics.
Thesis Part I: Methodological Development
Methodological Limitations

• Counting individual atoms!
• Limited by the number of atoms that can be counted in a given amount of time
• More atoms counted = higher precision
• AMS counting efficiency is controlled by the “beam current”
  – Purity of sample
  – Amount of sample
• Higher beam currents = higher counting efficiency = higher precision
Laboratory Methods

**Mineral Separation Lab**
- **Quartz Purification**
  - Rock material
  - Sieve
    - <250 um: archive
    - >850 um: archive
    - mag. fraction: archive
  - Magnetic separation
  - 2x HCl etches
  - 4L, 4L, 4L, 4L
  - Still dirty
  - Heavy liquid density separation
  - Clean
  - 1L, 0.5% HF/HNO₃ etch
  - 7-day 0.5% HF/HNO₃ etch
  - Quartz purity test
  - Sample “passes”: < ~150 ppm Al
  - < ~200-300 ppm cations
  - Continue to extraction!
  - 20 g of quartz for high-level samples, OR 40 g of quartz for low-level samples

**Cosmogenic Lab**
- **Be and Al Extraction**
  - Clean quartz
  - ⁹Be carrier
  - ²⁶Al carrier
  - Digestion in HF, HClO₃, HNO₃, & HCl
  - Remove aliquots
  - Aliquots to ICP
  - 3x HCl drydowns
  - Evaporation
  - 2x HCl drydowns
  - Centrifuge to remove Ti
  - Anion columns
  - 2x H₂SO₄ drydowns
  - Cation columns
  - Redissolve in 1% HNO₃
  - Be fraction: drydown
  - Al fraction: drydown
  - Redissolve in 1% HNO₃
  - Yield test aliquots
  - Archive for later use
  - Remove yield test aliquots
  - Remove yield test aliquots
  - Precipitate Be gel
  - Wash & dry Be gel
  - Wash & dry Al gel
  - Precipitate Al gel
  - Tamp into targets
  - Measure isotopic ratios
  - ¹⁰Be/⁹Be
Methodological Optimization

Part I: Methodological Development

Average AMS beam current after laboratory modifications = 22.5 μA

STDEV = 3.4 μA

Average AMS beam current before laboratory modifications = 13.4 μA

STDEV = 5.4 μA
Thesis Part II: Ilulissat, Greenland
Fjord Stade Moraine

(Photo courtesy of Nicolas Young)
All ages are Holocene

(Image courtesy of Landsat, 2000)
Bedrock/Boulder Comparison

Bedrock and boulder samples are in close agreement.

Little or no inheritance
Erosive glacial ice
Complicated Deglaciation Pattern

Age of outer land surface: $10.3 \pm 0.4$ ka ($n = 7$)
Age of inner land surface: $8.0 \pm 0.7$ ka ($n = 21$)
Just inside moraine: $8.2 \pm 0.1$ ka ($n = 2$)

Complicated deglaciation pattern!
Age of the Fjord Stade moraine is $\sim 8.2$ ka
Formation of the Fjord Stade Moraine

Fjord Stade moraine formed due to an ice margin re-advance in association with the “8200 Event”
Spatial Variability of Exposure Ages

There is no statistically significant difference between sample ages at high, medium, and low elevations.

The ice sheet thinned rapidly, at rates greater than what we can detect within the uncertainties associated with $^{10}$Be dating.
How do we quantify ice margin retreat rates?

Ice went behind the present-day margin ~7.6 ka
Ice Margin Retreat

Retreat rate estimate:
40 km of retreat in 400 yrs ≈ 100 m/yr
Ilulissat Overview

• All ages are Holocene
• Agreement between bedrock and boulder samples indicates little to no inheritance
• Efficient subglacial erosion (>2 m)
• Deglaciation chronology is complicated due to the presence of a moraine: two land surfaces
• Fjord Stade moraine may be associated with the “8200 Event”
• Ice retreat began from the coast ~10.3 ka, ice went behind the present-day margin ~7.6 ka
• Ice retreated at ~100 m/yr
Thesis Part III:
Upernavik, Greenland
Sample Ages

Something is going on here… why do we have such old exposure ages?
Bedrock/Boulder Comparison

Bedrock samples are much older than paired boulder samples; inheritance is present. Glacial ice is non-erosive or weakly erosive.
Using Cosmogenic $^{26}\text{Al}$

- Higher production rate than $^{10}\text{Be}$
- Shorter half-life than $^{10}\text{Be}$
- The two isotopes behave differently when burial occurs and production ceases
The Two-Isotope Plot

Part III: Upernavik, Greenland

- Constant Exposure
- Constant Exposure With Erosion
- Burial

$\frac{^{26}\text{Al}}{^{10}\text{Be}}$ vs. $^{10}$Be Concentration (atoms g$^{-1}$, sea level)
The Two-Isotope Plot

Samples have experienced both exposure and burial. They have long total histories.
Landscape History

Landscape history represented by Upernavik samples

Warmer

Colder

(Lisiecki and Raymo, 2005)
Inheritance and Elevation

There is more inheritance at higher elevations.
High-elevation ice is less erosive.
Subglacial Erosion and Elevation

- There must be meltwater in order for ice to perform erosion
- "Warm-based" ice has meltwater at its bed due to warmer basal temperatures
  - With thicker ice, overlying weight decreases the pressure melting point
  - Low elevations
- "Cold-based" ice has no meltwater at its bed due to colder basal temperatures
  - With thinner ice, overlying weight is not sufficient to decrease the pressure melting point
  - High elevations

Part III: Upernavik, Greenland
How do we quantify ice margin retreat rates?
Spatial Variability of Exposure Ages

6 youngest samples have statistically indistinguishable ages of $11.3 \pm 0.5 \text{ ka}$

Numerical modeling yields a statistically most likely retreat rate of $\sim 170 \text{ m/yr}$
Paleoclimate Context

Rapid loss of ice may have occurred during warming after the Younger Dryas
Upernavik Overview

- Most ages are old, few are Holocene
- Poor agreement between bedrock and boulder samples indicates ample inheritance
- Low subglacial erosion rates
- Ice retreat occurred rapidly at $\sim 11.3 \pm 0.5$ ka
- Ice retreated at $\sim 170$ m/yr
- Rapid ice retreat may have coincided with warming after the Younger Dryas
Conclusions &

The Big Picture
Comparisons Between Sites

<table>
<thead>
<tr>
<th>ILULISSAT</th>
<th>UPERNAVIK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ages are Holocene</td>
<td>no inheritance</td>
</tr>
<tr>
<td></td>
<td>Many old ages</td>
</tr>
<tr>
<td>Ice is highly erosive</td>
<td>everywhere</td>
</tr>
<tr>
<td></td>
<td>Ice has low erosion efficiency</td>
</tr>
<tr>
<td>Ice sheet is thicker</td>
<td>Ice sheet is thinner</td>
</tr>
<tr>
<td>Ice retreat lasted from 10.3 – 7.6 ka</td>
<td>Ice retreat occurred around 11.3 ka</td>
</tr>
<tr>
<td>Retreat rates were ~100 m/yr</td>
<td>Retreat rates were ~170 m/yr</td>
</tr>
<tr>
<td>Slower retreat rates due to fjord-based ice margin</td>
<td>Faster retreat rates due to floating ice margin</td>
</tr>
<tr>
<td>Fjord Stade moraine formed during the &quot;8200 Event&quot; (?)</td>
<td>Rapid ice retreat occurred after the Younger Dryas (?)</td>
</tr>
</tbody>
</table>

High degree of variability between two sites only 500 km apart
What Does It All Mean?

Subglacial Erosion Rates

- Subglacial erosion efficiency is controlled by local or regional factors
- Ice can be incredibly erosive, leading to sculpted, fresh landscapes
- Ice can be non-erosive, leading to old, heavily-weathered landscapes
Ice Retreat Rate Comparisons

Integration time (yrs before present)

Retreat rate (m/yr)

- Sikujuitsoq Fjord, West Greenland (Corbett et al., 2011)
- Disko Bugt, West Greenland (Long and Roberts, 2003)
- Jakobshavn Isfjord, West Greenland (Young et al., in press)
- Jakobshavn Isfjord, West Greenland (Csatho et al., 2008)
- Sisimiut Fjord, West Greenland (Rinterknecht et al., 2008)
- McCarthy Glacier, AK, USA (Wiles and Calkin, 1993)
- Icy Bay Glacier System, AK, USA (Porter, 1989)
- Sam Ford Fjord, Baffin, Canada (Briner et al., 2009)
- Laurentide Ice Sheet, USA (Andrews et al., 1973)
- Upernavik, West Greenland (Corbett et al., In Preparation)
What Does It All Mean?

Ice Retreat

- Ice retreat rates are controlled by local or regional factors.
- When the ice margin is constrained, retreat rates are limited; when the ice margin is unconstrained, retreat rates are more rapid.
- Retreat rates of floating margins can be an order of magnitude faster than retreat rates of grounded margins.
- Ice-loss through calving has important implications for future sea-level rise.
What Does It All Mean?

Rates

Many geologic processes take place over geologic time scales.

- Continents move at cm/yr
- Mountains erode at fractions of a mm/yr

Ice retreat in Greenland has, and will again, retreat over human time scales.

- Ice retreats at hundreds of m/yr
Paul Bierman, University of Vermont
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Burial Scenarios

### Burial under warm-based ice
- **Interglacial** Cosmic ray bombardment
- **Glacial** Burial by warm-based ice
- **Results**
  - Boulder sample age: ~10 ka
  - Bedrock sample age: ~10 ka
  - Boulder \(^{26}\)Al/\(^{10}\)Be ratio: ~6.75
  - Bedrock \(^{26}\)Al/\(^{10}\)Be ratio: ~6.75

### Burial under cold-based ice
- **Young Boulder, Old Bedrock**
  - **Interglacial** Cosmic ray bombardment
  - **Glacial** Burial by cold-based ice, but no erosion.
  - **Results**
    - Boulder sample age: 10's of ka
    - Bedrock sample age: 100's of ka
    - Boulder \(^{26}\)Al/\(^{10}\)Be ratio: <6.75
    - Bedrock \(^{26}\)Al/\(^{10}\)Be ratio: <6.75

### Burial under cold-based ice
- **Old Boulder, Old Bedrock**
  - **Interglacial** Cosmic ray bombardment
  - **Glacial** Burial by cold-based ice, but no erosion.
  - **Results**
    - Boulder sample age: 10's of ka
    - Bedrock sample age: 100's of ka
    - Boulder \(^{26}\)Al/\(^{10}\)Be ratio: <6.75
    - Bedrock \(^{26}\)Al/\(^{10}\)Be ratio: <6.75

### Burial under cold-based ice, burial under snowfields
- **Interglacial and/or Glacial** Burial by perennial snowfields
  - No erosion occurs, but the surface is partially or completely shielded from cosmic ray bombardment.
  - **Results**
    - Boulder sample age: 10's of ka
    - Bedrock sample age: 100's of ka
    - Boulder \(^{26}\)Al/\(^{10}\)Be ratio: <6.75
    - Bedrock \(^{26}\)Al/\(^{10}\)Be ratio: <6.75