Preservation and Sediment Cycling Beneath “Ghost Glaciers”
How Cold-Based Ice Dictates Arctic Landscape Evolution

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The high latitudes are warming...

Projected surface air temperature change for years 2016-2035, relative to years 1986-2005

IPCC (2013)
Surface melt is increasing...

Nghiem et al (2012)
LOSING GREENLAND

Is the Arctic’s biggest ice sheet in irreversible meltdown? And would we know if it were? Alexandra Witze reports.

Ice mass is decreasing...
...hence, we should look to the past to understand the present and future

Cuffey and Marshall (2000) 130,000 years ago

Alley et al (2005) 1,000 years from now
But, we have a problem:

Ghost glacier???
A “normal” or “warm-based” glacier

Liquid meltwater is available at the bed, allowing erosion to occur
A “cold-based” glacier

No liquid water is available at the bed, so no erosion can occur
Cold-based glaciers perform little erosion and therefore leave behind little physical evidence of their presence.

So how do we know if a landscape was covered by cold-based glaciers?
The “Cold-Based Ice Irony”

Cold-based ice exists in the high latitudes...

... but the high latitudes are **forecasted to warm most quickly** and also **contain most of the planet’s glacial ice**...

... so the places where it is most important to learn about glacial history are also the places where it is most **challenging** because traditional approaches do not work.
1. Understand the **history** of these high-latitude landscapes
2. Understand cold-based ice **processes** and improve the **methods** for studying cold-based ice landscapes
I. Landscape chronology and glacial history in Thule, northwest Greenland
(Quaternary Science Reviews, 2015)

II. Constraining multi-stage exposure-burial scenarios for boulders preserved beneath cold-based ice in Thule, northwest Greenland

III. Glacial history and landscape evolution of southern Cumberland Peninsula, Baffin Island, Canada, constrained by cosmogenic $^{26}$Al/$^{10}$Be
(Geological Society of America Bulletin, 2016)

IV. An approach for optimizing in situ cosmogenic $^{10}$Be sample preparation
(Quaternary Geochronology, 2016)
Tools: In situ Cosmogenic $^{10}\text{Be}$ & $^{26}\text{Al}$

- "In situ": produced within the mineral structure (quartz)
- "Cosmogenic": from cosmic rays
- "$^{10}\text{Be}$": rare, radioactive isotope of Be; $t_{1/2} = 1.36 \text{ Ma}$
- "$^{26}\text{Al}$": rare, radioactive isotope of Al; $t_{1/2} = 0.71 \text{ Ma}$
Formation of Cosmogenic Nuclides

Earth is bombarded by high-energy cosmic cosmic rays...causing the formation of $^{10}\text{Be}$ in quartz ($\text{SiO}_2$)

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

$^{10}\text{Be}$ is produced at about 4 atoms per gram of quartz per year

$^{10}\text{Be}$ is radioactive and has a half-life of 1.36 million years
Glacial period: Bedrock is **shielded**

**Assumption:** Zero inheritance (i.e. no $^{10}\text{Be}$ leftover from previous periods of exposure)

Hereafter referred to as “simple” exposure ages

Interglacial period: Bedrock is **exposed**
The Two-Isotope Approach

$^{10}\text{Be}$
Production Rate: $\sim 4$ atoms g$^{-1}$ yr$^{-1}$
Half-life: 1.36 million yr

$^{26}\text{Al}$
Production Rate: $\sim 26$ atoms g$^{-1}$ yr$^{-1}$
Half-life: 0.71 million yr

![Graph showing the Two-Isotope Approach]

- Constant Exposure
- Burial
- Secular equilibrium
Other Important Background...

In the Arctic, the last “ice age” ended around 12,000 – 10,000 years ago (ka)
Baffin Island, Canada
The Data Set

149 samples (144 $^{26}\text{Al}/^{10}\text{Be}$) Collected 1992-1995

Bedrock & boulders (65 bedrock) (84 boulders)
“Simple” Exposure Ages

$^{10}$Be simple exposure ages: 6.3-160 ka (n = 146)

$^{26}$Al simple exposure ages: 4.3-124 ka (n = 147)
Trends: Bedrock Ages > Boulder Ages

- KM95-26: 12.1 ka
- KM95-27: 28.9 ka

Red flag #2
Trends: Ages Increase with Elevation

KM95-106: 110 ka 600 m a.s.l.

KM95-043: 9.7 ka 110 m a.s.l.

Red flag #3
Trends: $^{10}$Be Ages > $^{26}$Al Ages

$^{10}$Be: 141 ka
$^{26}$Al: 112 ka

Red flag #4
Exposure/Burial Modeling

KM95-016
Minimum limiting...
Exposure: 199 ky
Burial: 501 ky
Total: 700 ky

Solving for the simplest path:
One period of exposure followed by one period of burial
Minimum-limiting exposure durations: 5.9-480 ky

Minimum-limiting burial durations: 140-7500 ky

Minimum-limiting total histories up to ~8 My!
1.) Numerous age patterns indicate cold-based ice

2.) The lifecycle of the landscape is characterized dominantly by periods of burial

3.) The preserved landscape is very old, sometimes millions of years, certain areas may pre-date inception of the Laurentide Ice Sheet
Thule, Northwest Greenland
Stratigraphic Sections

- Sandy glacial till and moraine material
- Clay-rich glacial till
- Reworked glacial till
- Lake
- Fjord
- Anthropogenically-altered land surface
- Moraine crest
- Channels
- Roads
Analysis of Cosmogenic $^{10}\text{Be}$ and $^{26}\text{Al}$

(n = 28 glacially-deposited boulders)
Deglaciation Timing

GT022: 10.7 ± 0.6 ka
GT023: 10.6 ± 0.6 ka
GT055: 10.7 ± 0.7 ka
(External uncertainties)
Minimum limiting exposure durations: 11 – 96 ky
Minimum limiting burial durations: 88 – 627 ky
Total histories: 111 – 734 ky
Numerical Models of Boulder Scenarios

Holocene Period

Last Glacial Maximum

Warm periods: “Interglacial”
Cold periods: “Glacial”

(Lisiecki and Raymo, 2005)
Numerical Models of Boulder Scenarios

- Exposure during MIS 9 and 5e; burial between
- Exposure during MIS 15, 11, 9, and 5e; burial between
- Exposure (10 ky) during MIS 11; subsequent burial
- Exposure (18 ky) during MIS 11; subsequent burial

$^{26}\text{Al}/^{10}\text{Be}$ vs. Sea-level normalized $^{10}\text{Be}$ concentration (atoms g$^{-1}$)
Thule Conclusions

1.) Initial deglaciation of the landscape occurred ~11 ka

2.) Basal thermal conditions are very heterogeneous

3.) Certain boulders have been preserved for long durations (hundreds of thousands of years) subglacially, but most have only been buried for shorter durations

4.) Boulders have likely been recycled through numerous generations of glacial till
The Big Picture

High-latitude subglacial erosion processes are heterogeneous over both space and time.

Cold-based “ghost glaciers” preserve surfaces subglacially, creating ancient, relict landscapes.

New techniques are needed to understand these complex surfaces.
Cold-Based Ice: An Opportunity?

Record preserved on a warm-based ice landscape

Interglacial

Record preserved on a cold-based ice landscape (e.g. Baffin study; median total history ~750 ka)
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Tom Neumann
Eric Portenga
Luke Reusser
Veronica Sosa-Gonzalez
Stephen Wright
Liquid water is present

Erosion by abrasion

Erosion by plucking/quarrying

NO liquid water present

No erosion can occur
Cold-based ice is widespread in the high latitudes

Corbett et al., 2013
Corbett et al., 2015
Bierman et al., 1999; Marsella et al. 2000
Bierman et al., 2014
Marquette et al., 2004
Stroeven et al., 2002
Harbor et al., 2006
Phillips et al., 2006
Lilly et al., 2010
Goehring et al., 2008
Goehring et al., 2010; Håkansson et al., 2008
Briner & Swanson, 1998
Briner et al., 2003; 2005; 2006
Miller et al., 2006
Sugden et al., 2005
Thule Two-Isotope Data

Case #1
(n = 3)
$^{10}\text{Be}$ ages: deglacial
$^{26}\text{Al}/^{10}\text{Be}$: constant exposure

Case #2
(n = 8)
$^{10}\text{Be}$ ages: old
$^{26}\text{Al}/^{10}\text{Be}$: burial

Case #3
(n = 17)
$^{10}\text{Be}$ ages: old
$^{26}\text{Al}/^{10}\text{Be}$: constant exposure
Monte Carlo simulations (n = 10,000)
Choosing random, independent $^{10}$Be and $^{26}$Al concentrations from a normally-distributed population of possible values based on the $1 \, \sigma$ analytic uncertainty.

Case #2: Old ages, $^{26}$Al/$^{10}$Be ratios indicative of burial

Constraining Uncertainties
Constraining Uncertainties

Minimum limiting exposure duration: 21 ± 1 ky (1 σ), 6% uncertainty
Minimum limiting burial duration: 378 ± 80 ky (1 σ), 21% uncertainty
Case #2: Old ages, $^{26}$Al/$^{10}$Be ratios indicative of burial

**Constraining Uncertainties**

### Exposure
- **Minimum duration:** 11 – 96 ky (av. 26 ky)
- **Uncertainties (yr):** 1 – 4 ky (av. 2 ky)
- **Uncertainties (%):** 4 – 8 % (av. 7 %)

### Burial
- **Minimum duration:** 88 – 627 ky (av. 368 ky)
- **Uncertainties (yr):** 55 – 112 ky (av. 87 ky)
- **Uncertainties (%):** 9 – 105 % (av. 37 %)
Case #3: Old ages, $^{26}\text{Al}/^{10}\text{Be}$ ratios indicative of constant exposure

A Conundrum!

<table>
<thead>
<tr>
<th>Sample</th>
<th>$^{10}\text{Be}$ Age (ky)</th>
<th>$^{26}\text{Al}$ Age (ky)</th>
<th>$^{26}\text{Al}/^{10}\text{Be}$ Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>GT043</td>
<td>$26.9 \pm 1.5$</td>
<td>$27.7 \pm 1.9$</td>
<td>$6.95 \pm 0.38$</td>
</tr>
</tbody>
</table>

Old but not buried?!?
Case #3: Old ages, $^{26}$Al/$^{10}$Be ratios indicative of constant exposure

Short Burial Durations

Models assume 100 ky of burial alternating with 10 ky of exposure; use average $^{26}$Al/$^{10}$Be ratio uncertainty of all Thule samples ($n = 28$, 4.5%)