Understanding High Latitude Landscape Development in the Presence of Non-Erosive Glacial Ice

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The high latitudes are warming...

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

2013 IPCC Report
Greenland explores Arctic mineral riches amid fears for pristine region

London Mining’s £1.5bn iron ore mine and new oil drilling licences for BP and Shell spark concern for environment

Greenland iron ore mine gets green light

The Isua project will comprises of a mine, processing plant and 105km concentrate pipeline which connects the plant to a deepwater port capable of year round loading of 250,000t ships. Image from London Mining corporate video.
...hence, we need a better understanding of how high-latitude landscapes work.
But, we have a problem:

Ghost glacier???
Liquid water is present

Erosion by abrasion

Erosion by plucking/quarrying

NO liquid water present

No erosion can occur

Cold-based glacier

Ice Temperature

- 0°C  +

Depth

Annual temperature range

Pressure melting curve

Glacial ice

Glacier frozen to bed

Bedrock

Warm-based glacier

Ice Temperature

- 0°C  +

Increasing pressure

Pressure melting curve

Meltwater at base of glacier

Bedrock

Liquid water is present

Erosion by abrasion

Erosion by plucking/quarrying
Cold-based ice is widespread in the high latitudes...
Cold-based glaciers perform little erosion and therefore leave behind little evidence of their presence.

So how do we know if a landscape was covered by cold-based glaciers?
Project Goals

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
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; $t_{1/2} = 0.71 \text{ Ma}$
Earth is bombarded by high-energy cosmic rays

...causing the formation of $^{10}$Be in quartz ($\text{SiO}_2$)

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

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

$^{10}$Be is radioactive and has a half-life of 1.36 million years
“Cosmogenic Dating”

Glacial period: Bedrock is **shielded**

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

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
1. How old are the landscapes preserved in Baffin Island and Thule?

2. Is subglacial erosion homogeneous or heterogeneous?

3. Are glacial sediments (till) recycled over numerous glacial/interglacial cycles?

4. What is the lifecycle of these high-latitude landscapes, especially the relative portions of exposure and burial?

5. What new techniques and approaches can I develop to more effectively extract valuable climatic information from these complex landscapes?
Baffin Island, Canada
The Data Set

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

Bedrock & boulders
(65 bedrock)
(84 boulders)
Apparent Exposure Ages

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

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

- KM95-26: 12.1 ka
- KM95-27: 28.9 ka
Trends: Ages Increase with Elevation

- KM95-106: 110 ka, 600 m a.s.l.
- KM95-043: 9.7 ka, 110 m a.s.l.
Trends: $^{10}\text{Be}$ Ages > $^{26}\text{Al}$ Ages

KM95-107

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

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$R^2 = 0.97$

1:1 ratio
Trends: Multi-Modal Age Distributions

Boulders only

\( n = 84 \)
Exposure/Burial Modeling

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

Solving for the simplest path:
One period of exposure followed by one period of burial
Exposure/Burial Modeling

Minimum-limiting exposure durations: 4.8-213 ka

Minimum-limiting burial durations: 135-3691 ka

Minimum-limiting total histories: 189-3768 ka
Preliminary Baffin Conclusions

1.) Numerous age patterns indicate cold-based ice

2.) The preserved landscape is very old, sometimes millions of years

3.) Some areas of the landscape may pre-date initiation of the Laurentide Ice Sheet
Thule, Northwest Greenland
North Ice Cap  
(glaciologically separate)

Greenland Ice Sheet

TUTO Ice Dome  
(glaciologically separate)
Mapping

Stratigraphic Sections

Legend:
- Orange = Sandy glacial till and moraine material
- Yellow = Clay-rich glacial till
- Purple = Reworked glacial till
- Blue = Lake
- Green = Fjord
- Red = Anthropogenically-altered land surface
- Red = Moraine crest
- Blue = Channels
- Brown = Roads

Inset image shows a landscape with a geological map overlay.
Analysis of Cosmogenic $^{10}\text{Be}$ and $^{26}\text{Al}$

(n = 28 glacially-deposited boulders)
Single-Isotope Data

- $^{10}\text{Be}$
- $^{26}\text{Al}$
Two-Isotope Data

Two-isotope analysis:
Sample histories up to 700,000 yr!

Uncertainty analysis with Monte Carlo simulations:
Total History

Probability distributions of preserved total (minimum limiting) surface histories:

![Graph showing probability distributions](image-url)
Possible Scenarios (?)

Numerical modeling of possible exposure/burial histories:
<table>
<thead>
<tr>
<th></th>
<th>Preliminary Thule Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Initial deglaciation of the landscape occurred ~11 ka</td>
</tr>
<tr>
<td>2</td>
<td>Outlet glaciers re-advanced &lt;10 ka (coincident with the 8.2ka Event?)</td>
</tr>
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<td>3</td>
<td>Basal thermal conditions are heterogeneous, at least partly cold-based</td>
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<td>4</td>
<td>Certain surfaces have been preserved for long durations (hundreds of thousands of years) subglacially</td>
</tr>
<tr>
<td>5</td>
<td>Sediments (till) have been recycled over numerous glacial/interglacial periods</td>
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</tbody>
</table>
Subglacial erosion processes are heterogeneous over both space and time.

Cold-based ice can preserve surfaces subglacially, yielding ancient, relict landscapes.

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

Record preserved on a warm-based ice landscape

Record preserved on a cold-based ice landscape (Baffin study; median total history ~700 ka)