Preservation and Sediment Cycling Beneath "Ghost Glaciers"

How Cold-Based Ice Dictates Arctic Landscape Evolution

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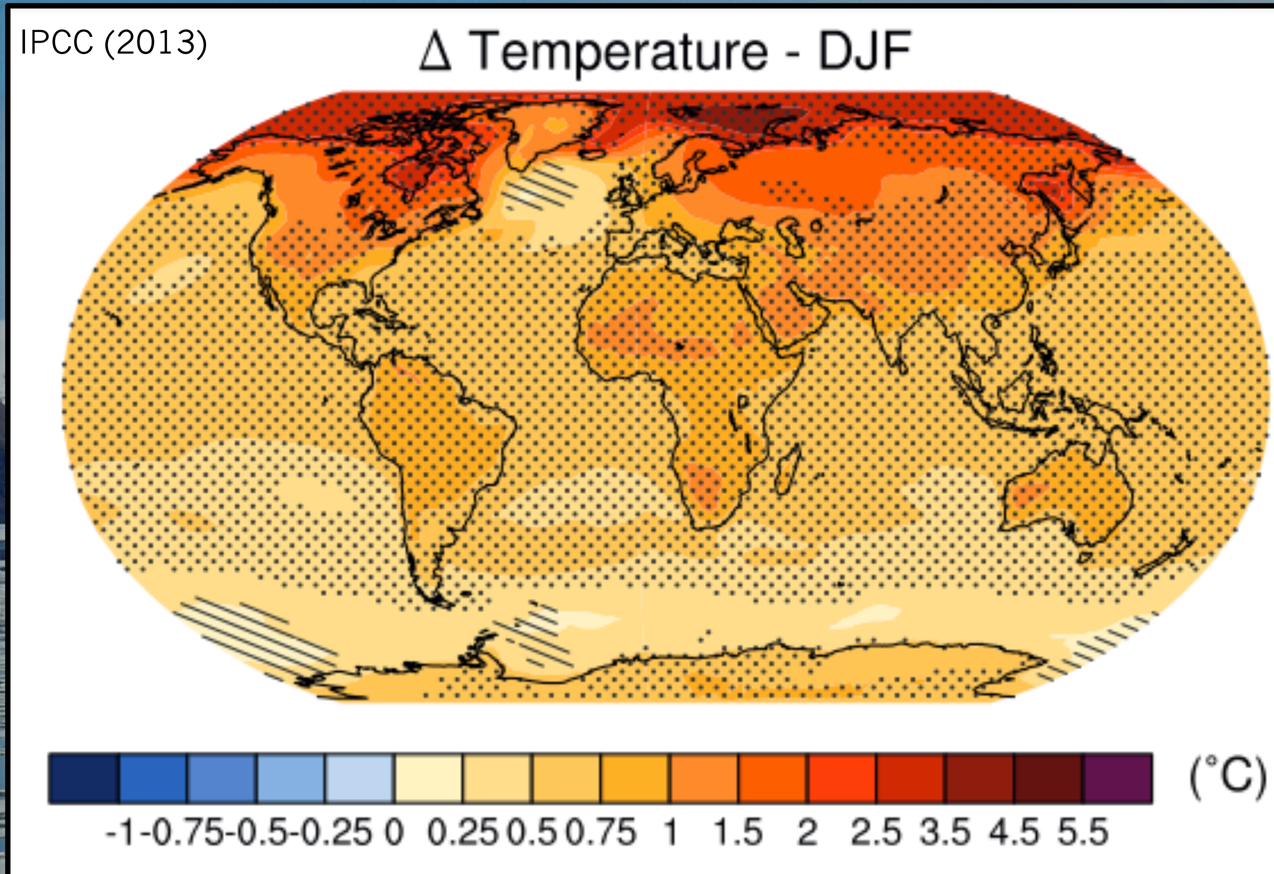
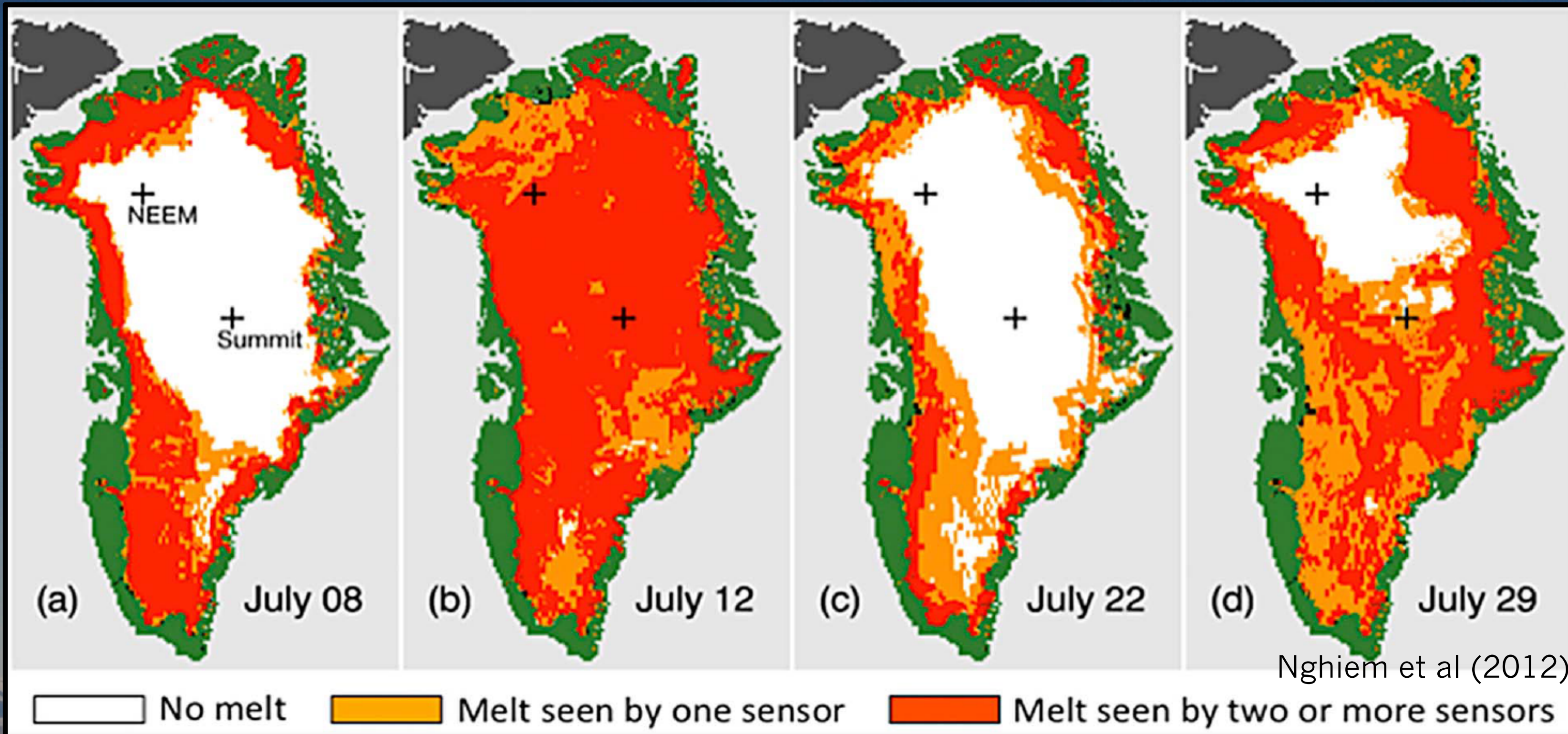
The high latitudes are warming…



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

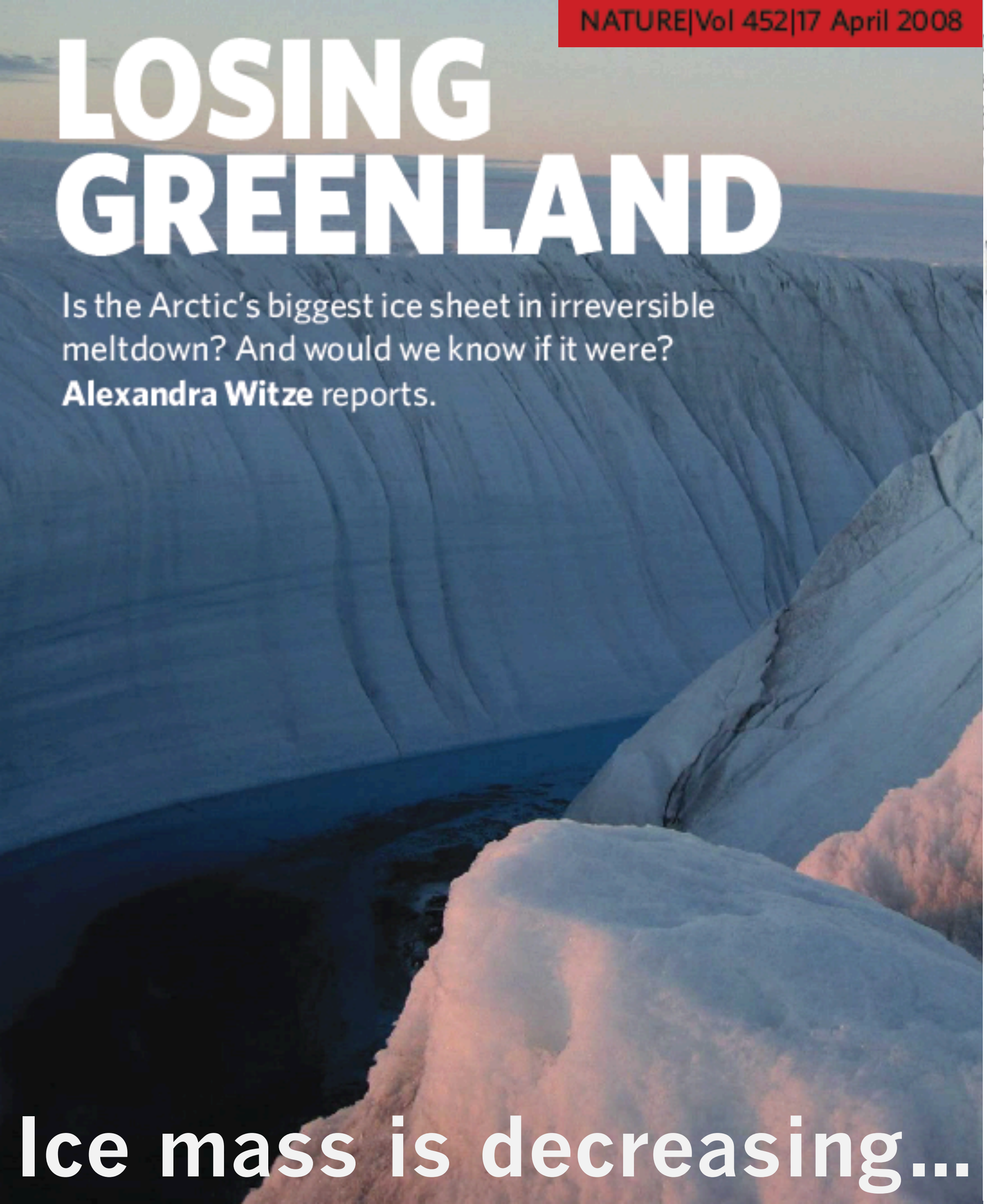


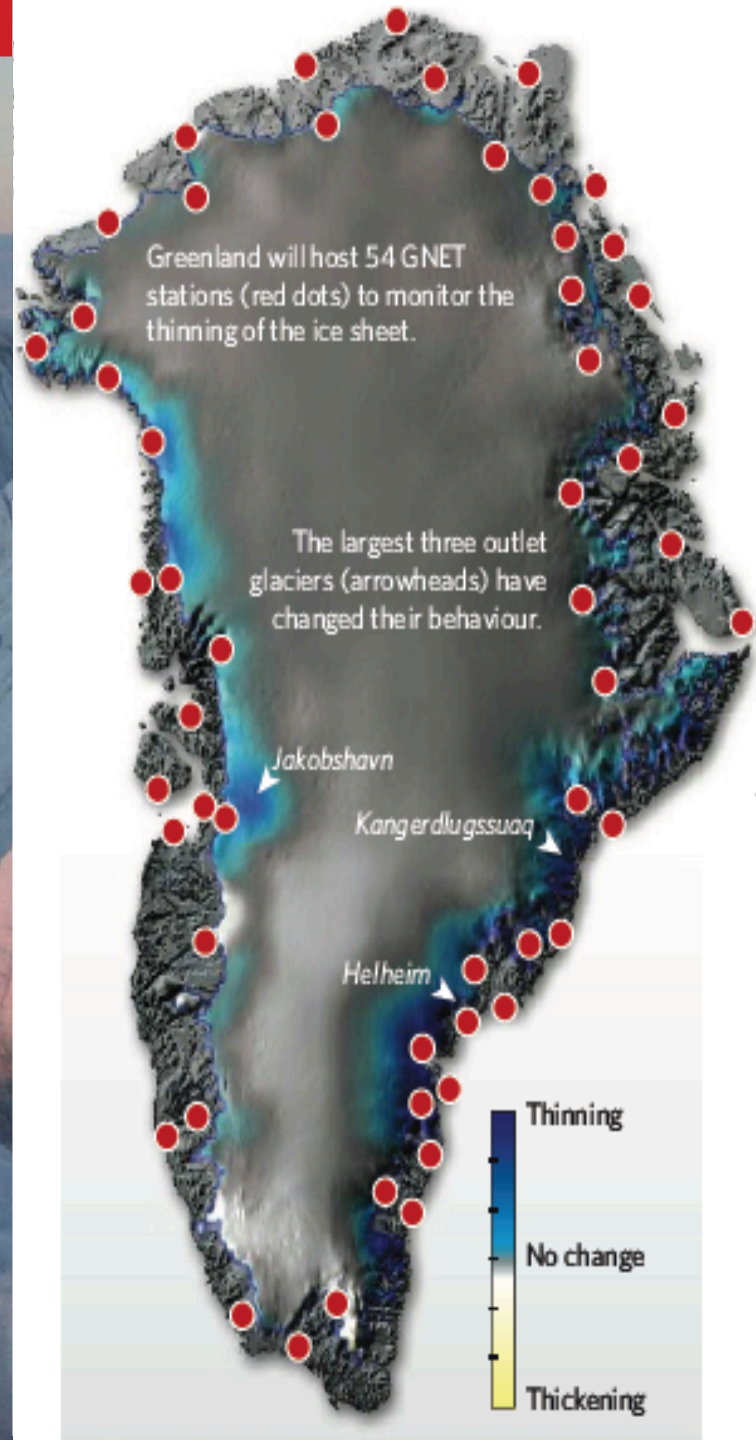
The New York Times

Rare Burst of Melting Seen in Greenland's Ice Sheet

By KELLY SLIVKA JULY 24, 2012

Surface melt is increasing…

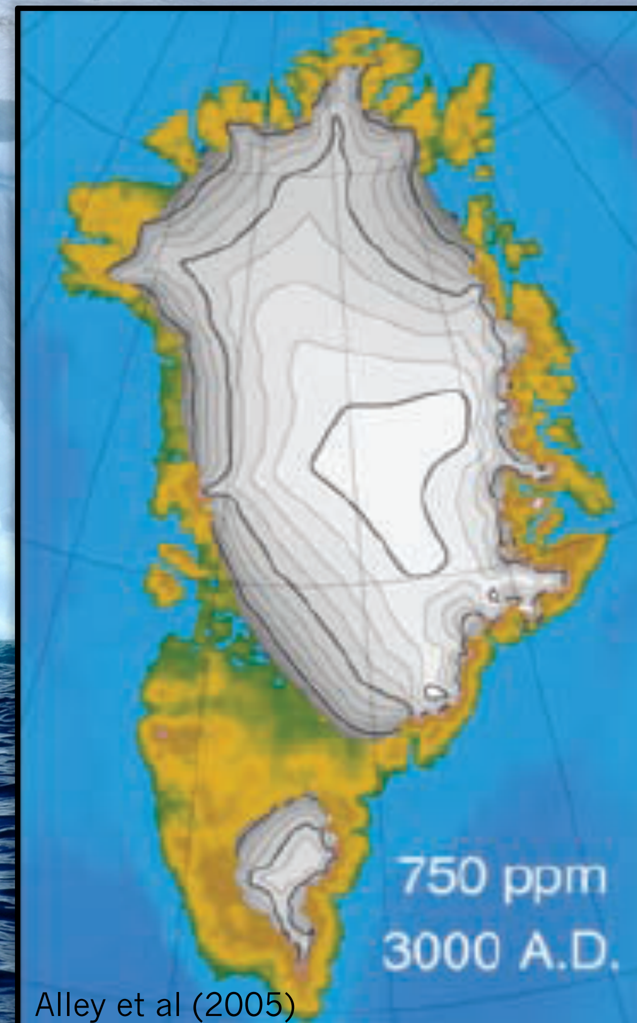




Ice mass is decreasing...

…hence, we should look to the past to understand the present and future

130,000 years ago

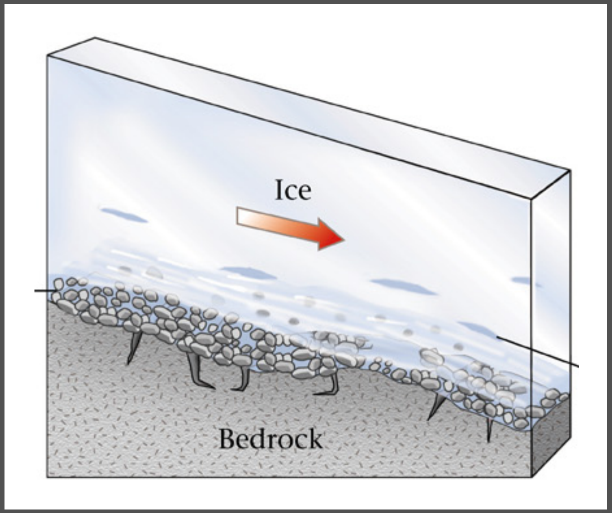


1,000 years from now

But, we have a problem:

A “normal” or “warm-based” glacier

Liquid meltwater is available at the bed, allowing erosion to occur



A “cold-based” glacier

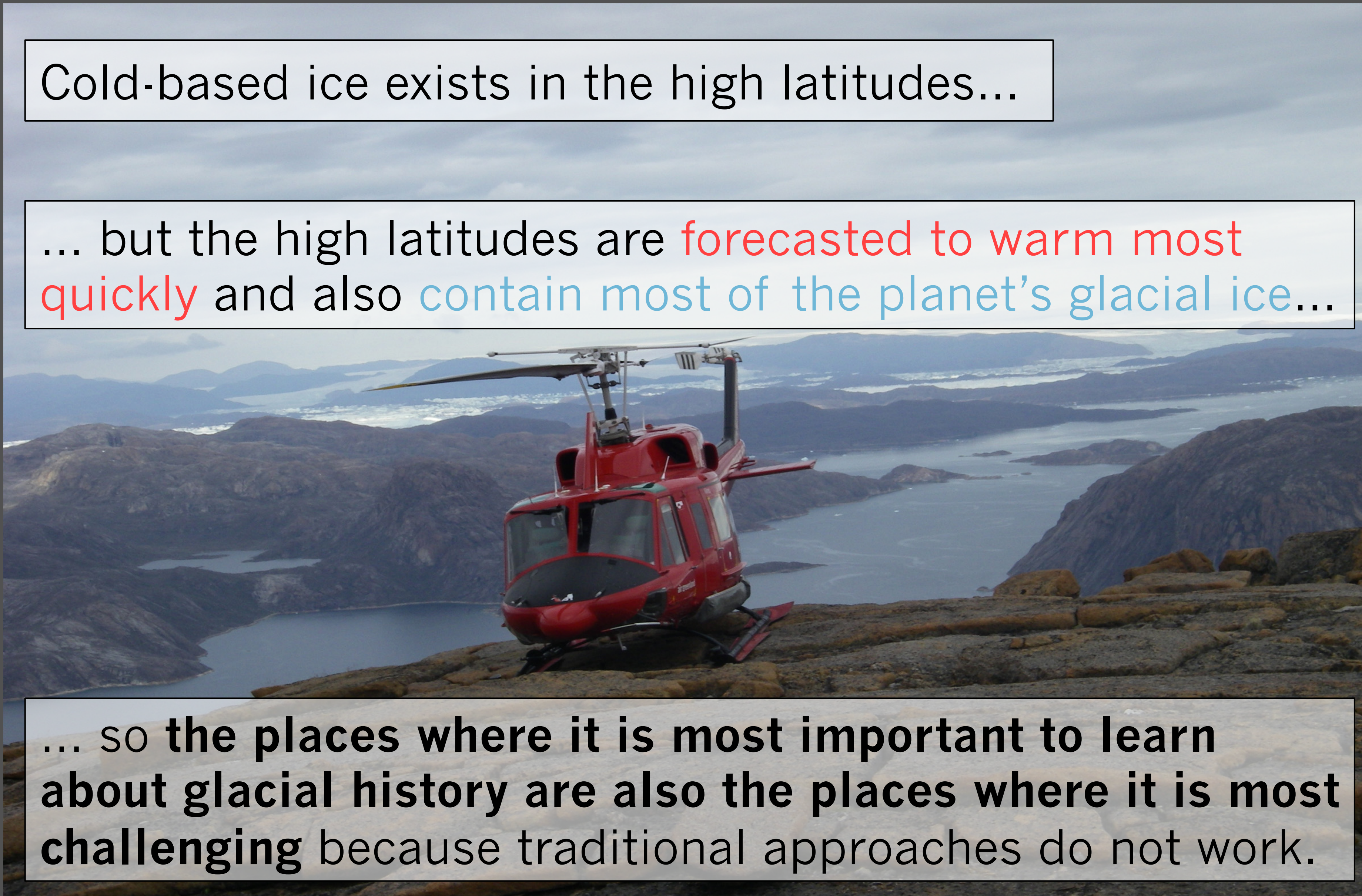
No liquid water is available at the bed, so no erosion can occur

The Problem

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”

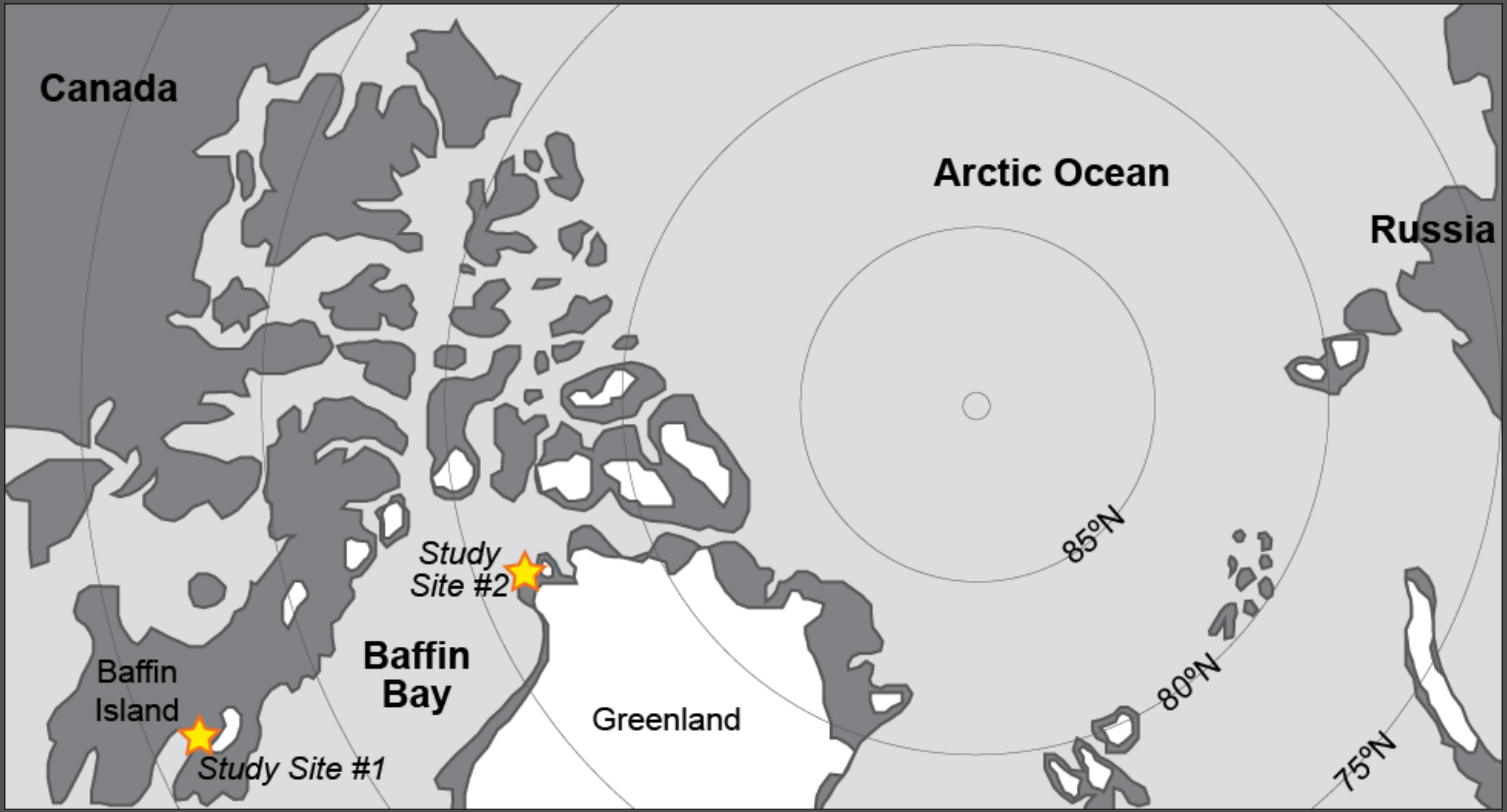


Cold-based ice exists in the high latitudes...

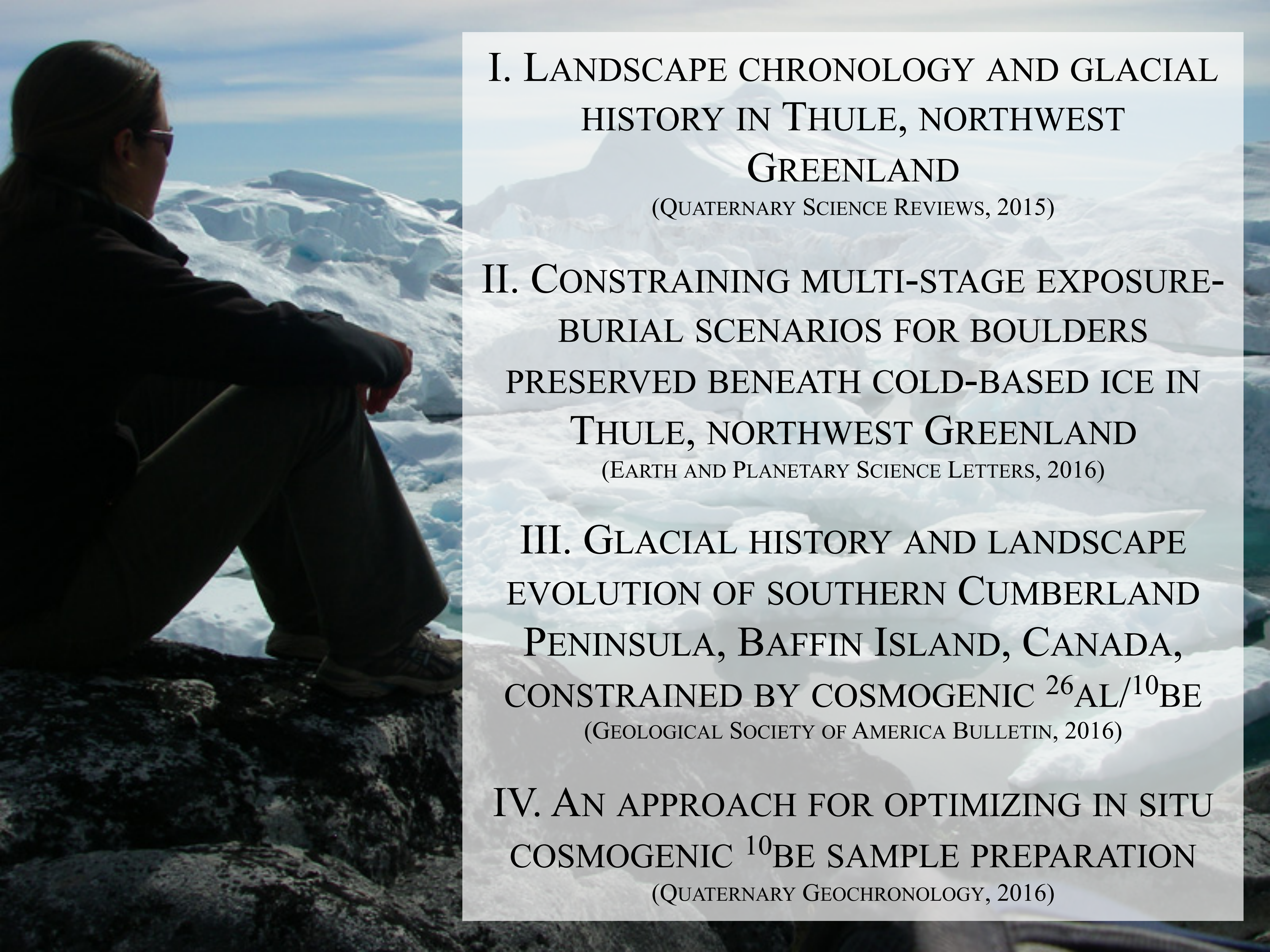
... but the high latitudes are forecasted to warm most quickly and also contain most of the planet’s glacial ice...

... 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.

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



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
(Earth and Planetary Science Letters, 2016)

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)

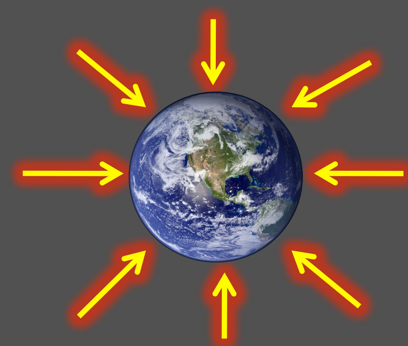
IV. An approach for optimizing in situ cosmogenic ^{10}Be sample preparation
(Quaternary Geochronology, 2016)

Tools: In situ Cosmogenic ^{10}Be & ^{26}Al

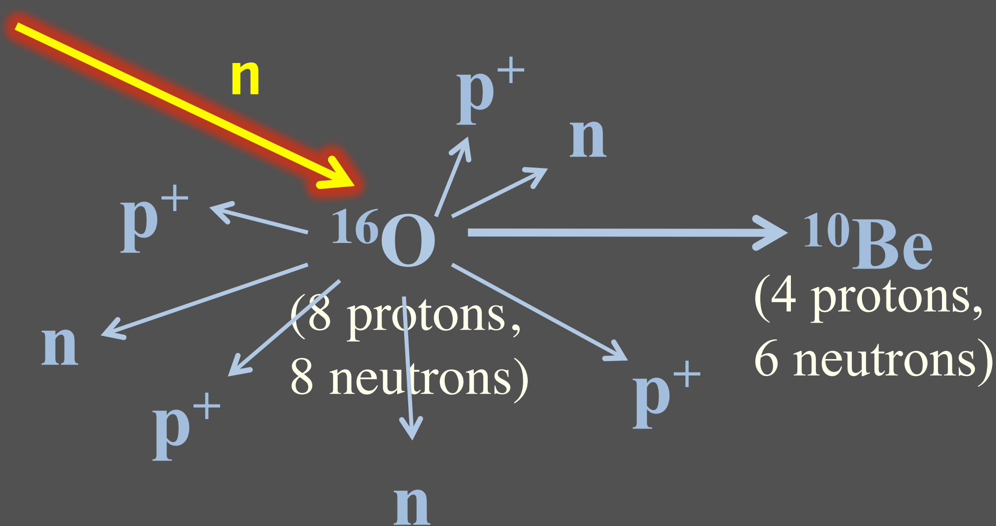
- *"In situ"*: produced within the mineral structure (quartz)
- "Cosmogenic": from cosmic rays
- "^{10}Be": rare, radioactive isotope of Be; $t_{1/2}$ = 1.36 Ma
- "^{26}Al": rare, radioactive isotope of Al; $t_{1/2}$ = 0.71 Ma

Formation of Cosmogenic Nuclides

Earth is bombarded by high-energy cosmic rays



...causing the formation of ^{10}Be in quartz (SiO_2)



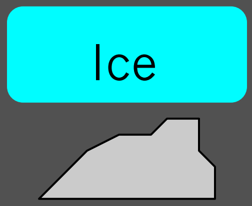
^{10}Be is produced only on the surface of a rock

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

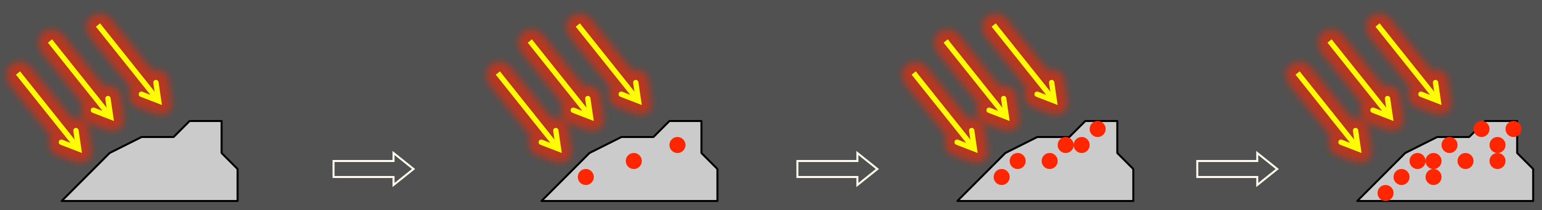
^{10}Be is radioactive and has a half-life of 1.36 million years

“Cosmogenic Dating”

Glacial period: Bedrock is **shielded**



Interglacial period: Bedrock is **exposed**

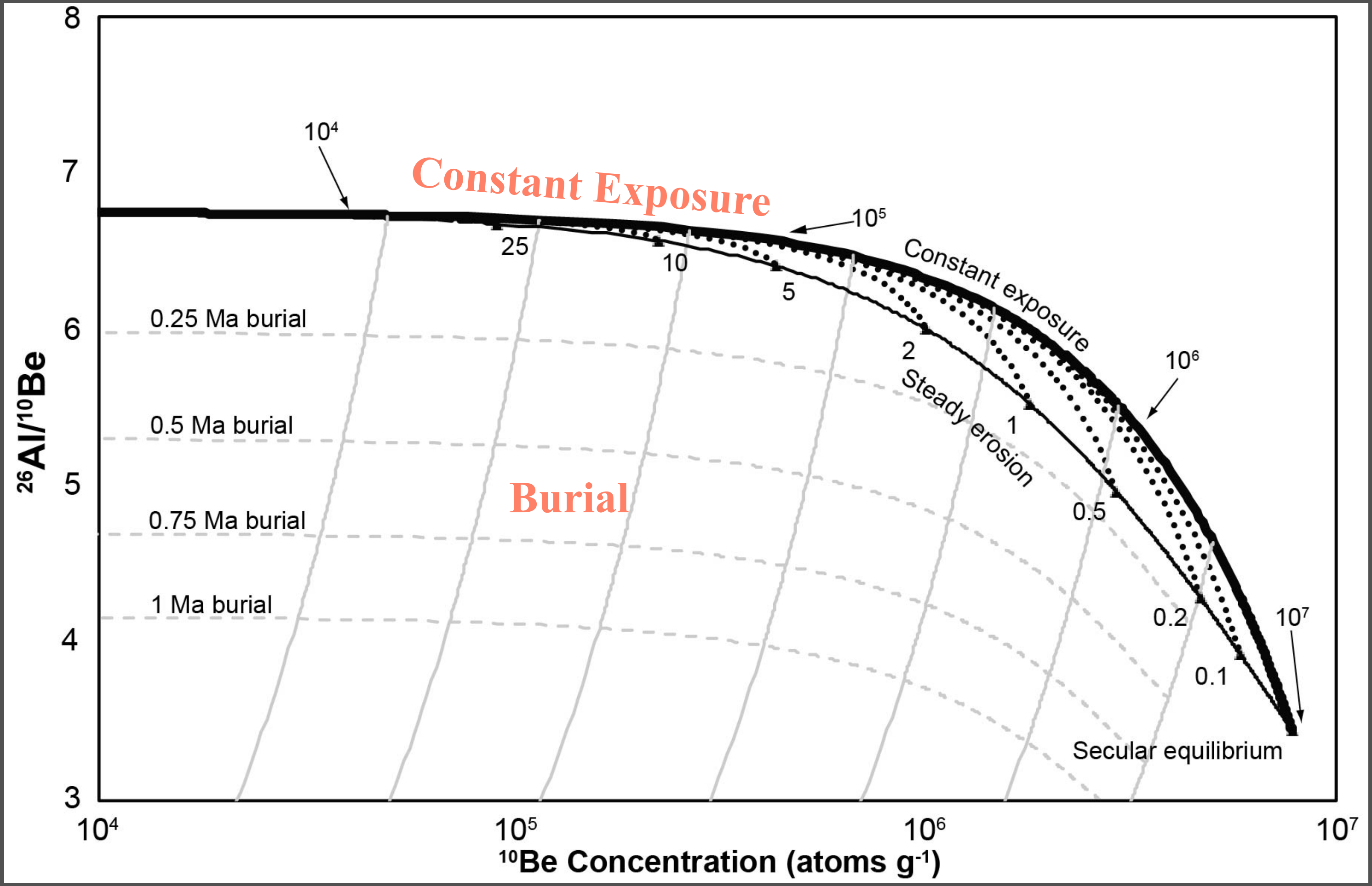


Assumption: **Zero inheritance**
(i.e. no ^{10}Be leftover from previous periods of exposure)
Hereafter referred to as “simple” exposure ages

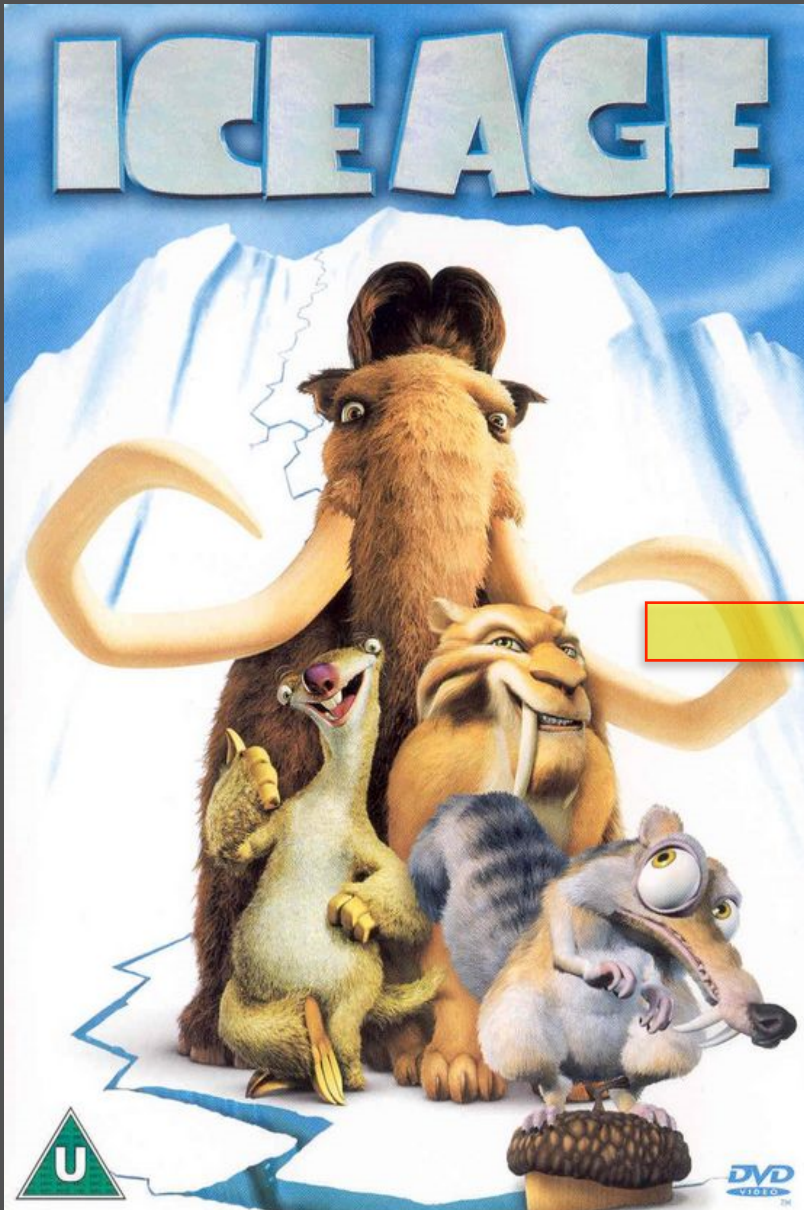
The Two-Isotope Approach

^{10}Be
Production Rate: ~4 atoms g^{-1} yr^{-1}
Half-life: 1.36 million yr

^{26}Al
Production Rate: ~26 atoms g^{-1} yr^{-1}
Half-life: 0.71 million yr



Other Important Background...



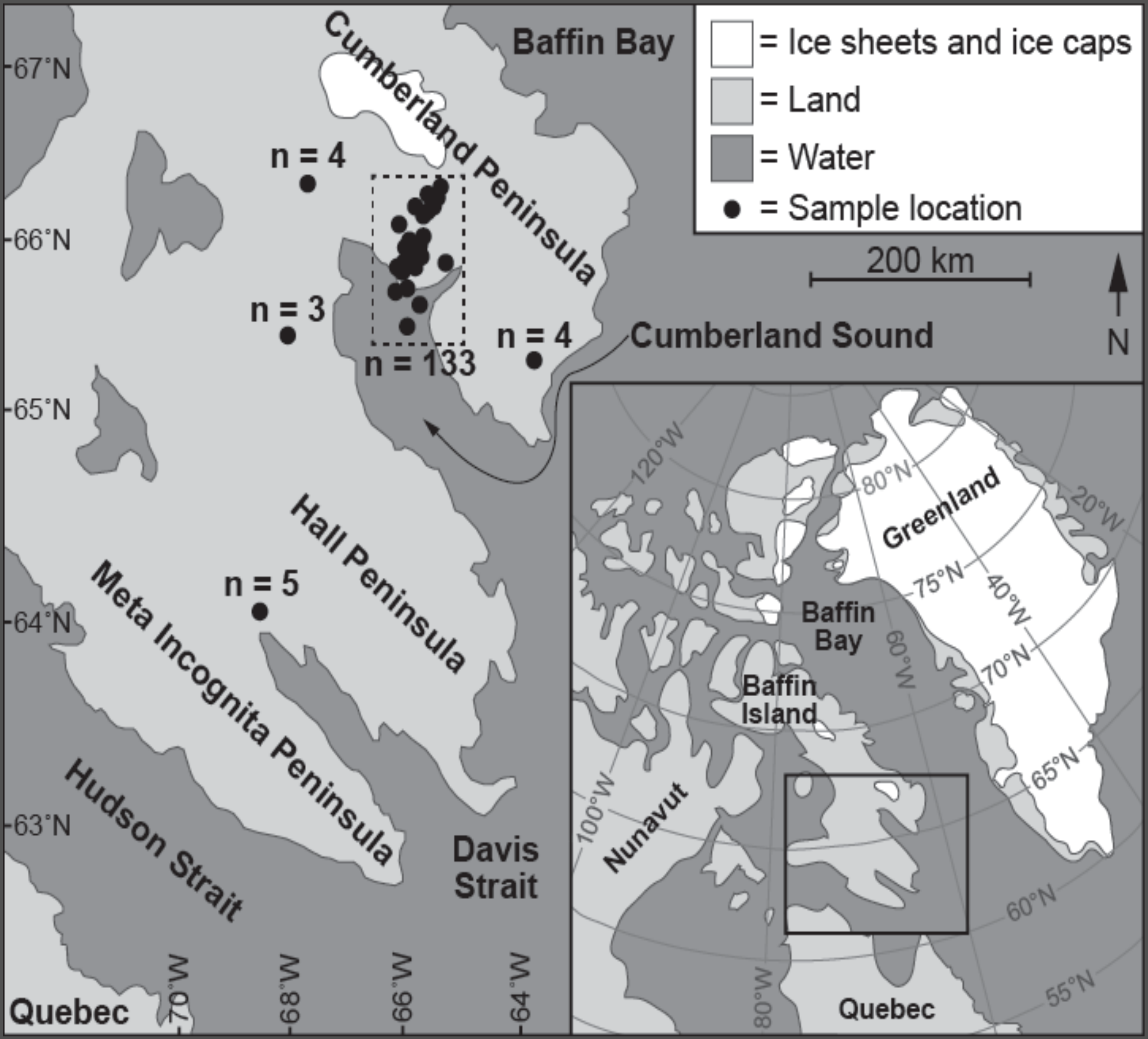
In the Arctic, the last “ice age” ended around 12,000 – 10,000 years ago (ka)


Baffin Island, Canada

The Data Set

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

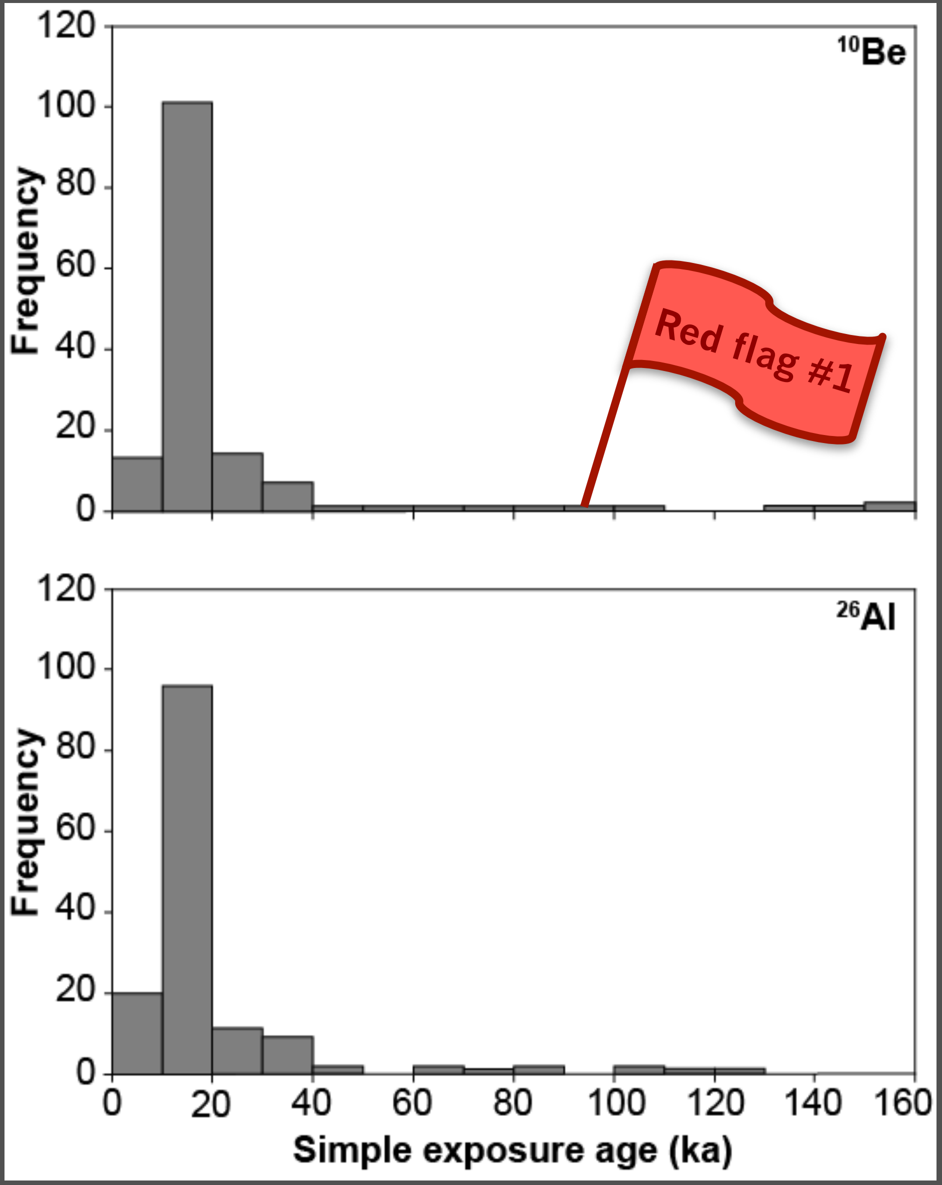
Bedrock & boulders
(65 bedrock)
(84 boulders)



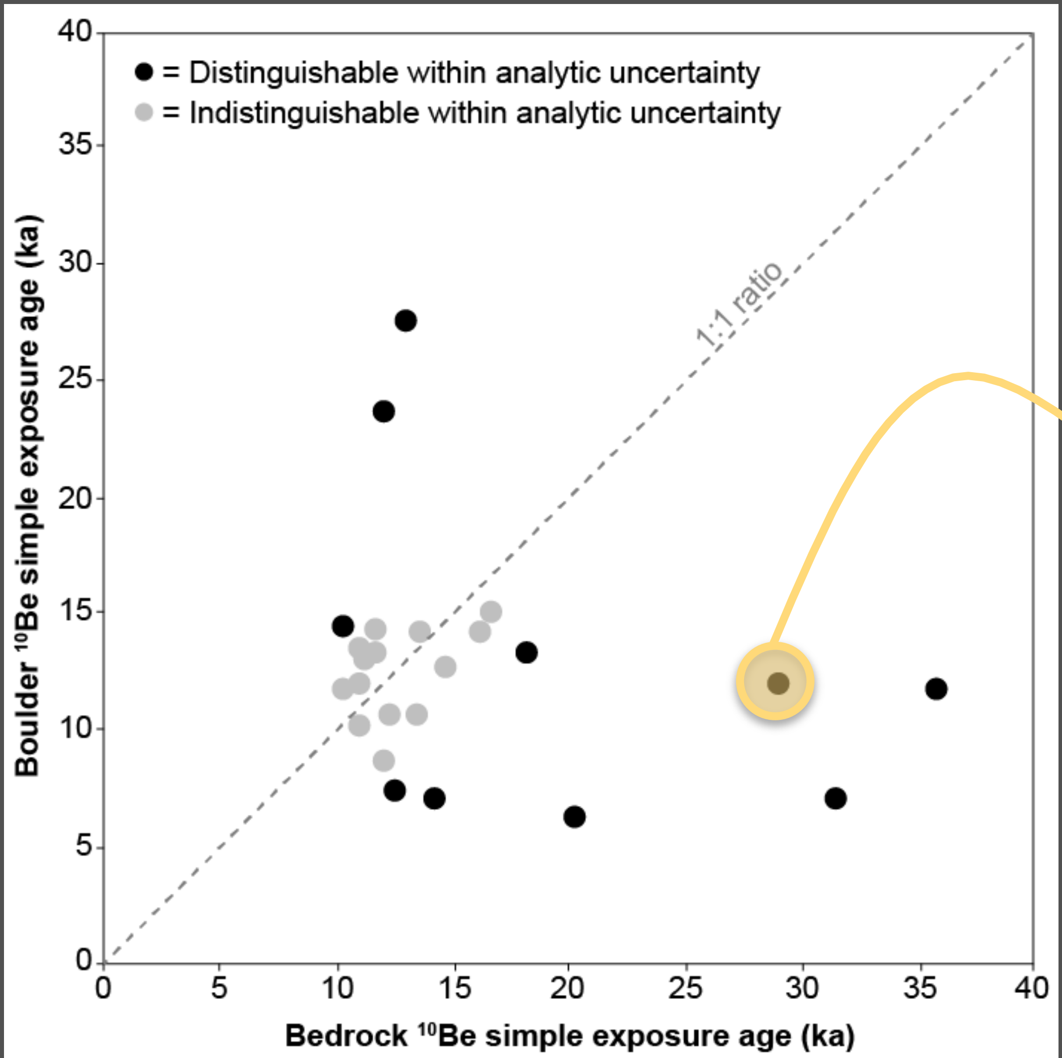
"Simple" Exposure Ages

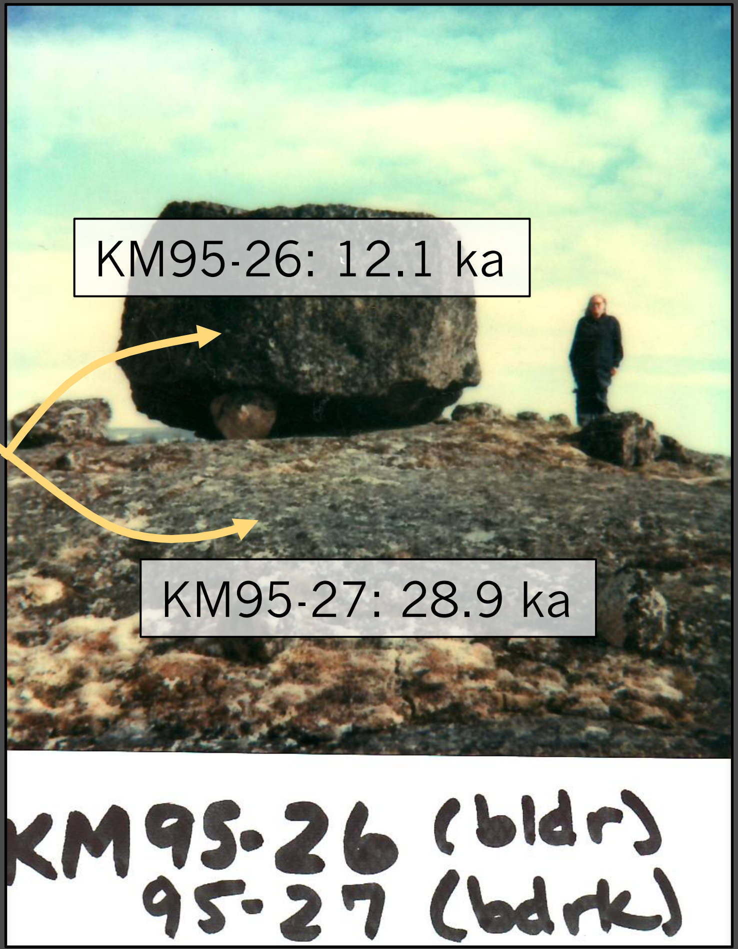
^{10}Be simple exposure ages:
6.3-160 ka (n = 146)

^{26}Al simple exposure ages:
4.3-124 ka (n = 147)



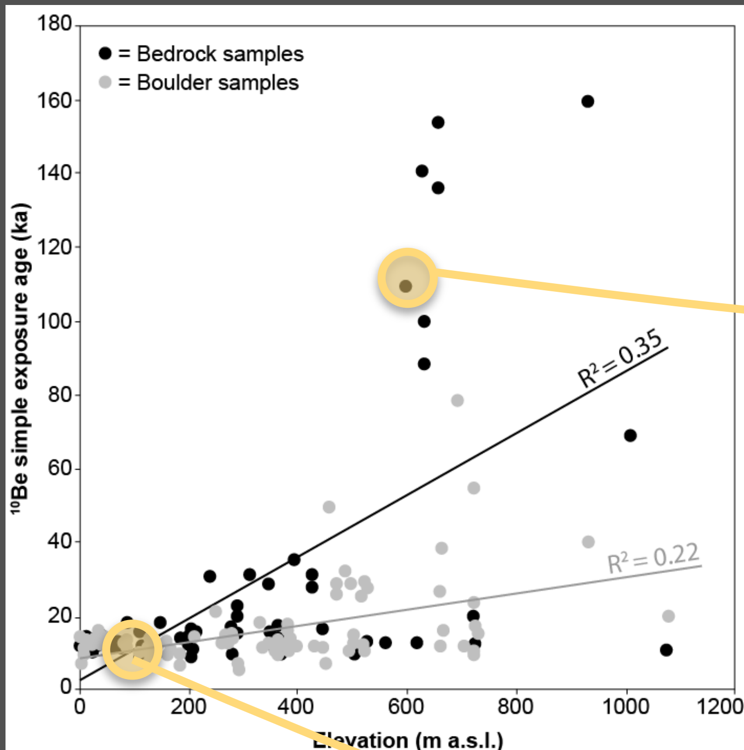
Trends: Bedrock Ages > Boulder Ages

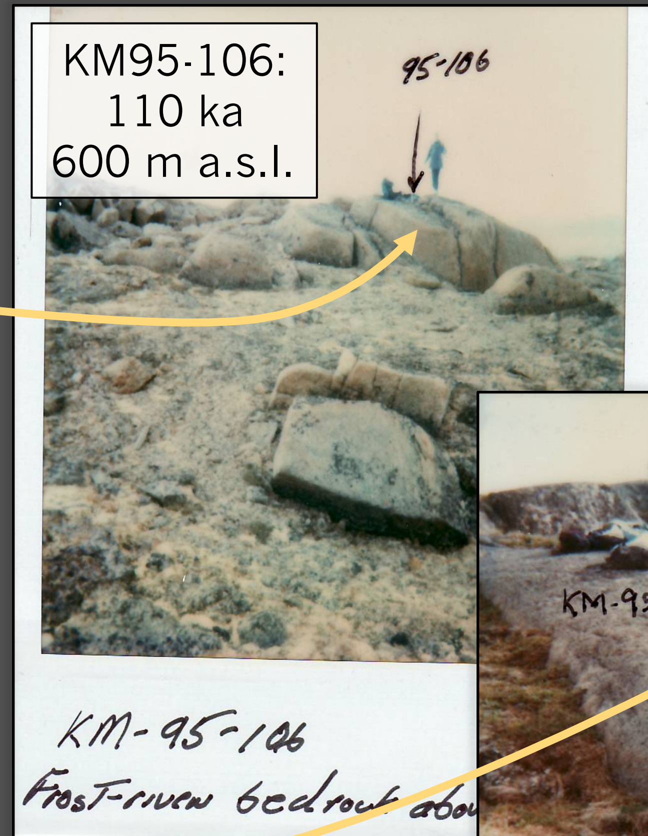




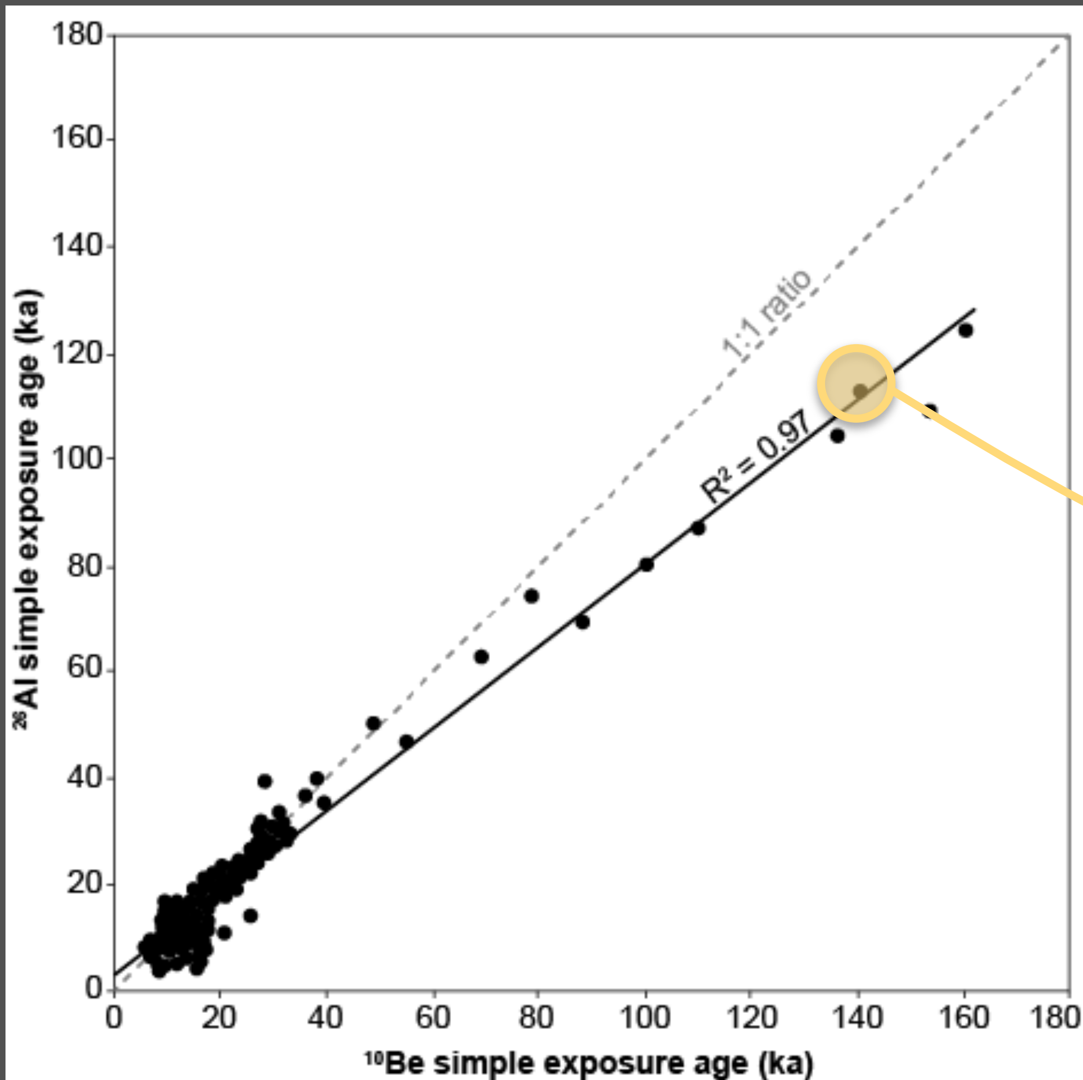
Red flag #2

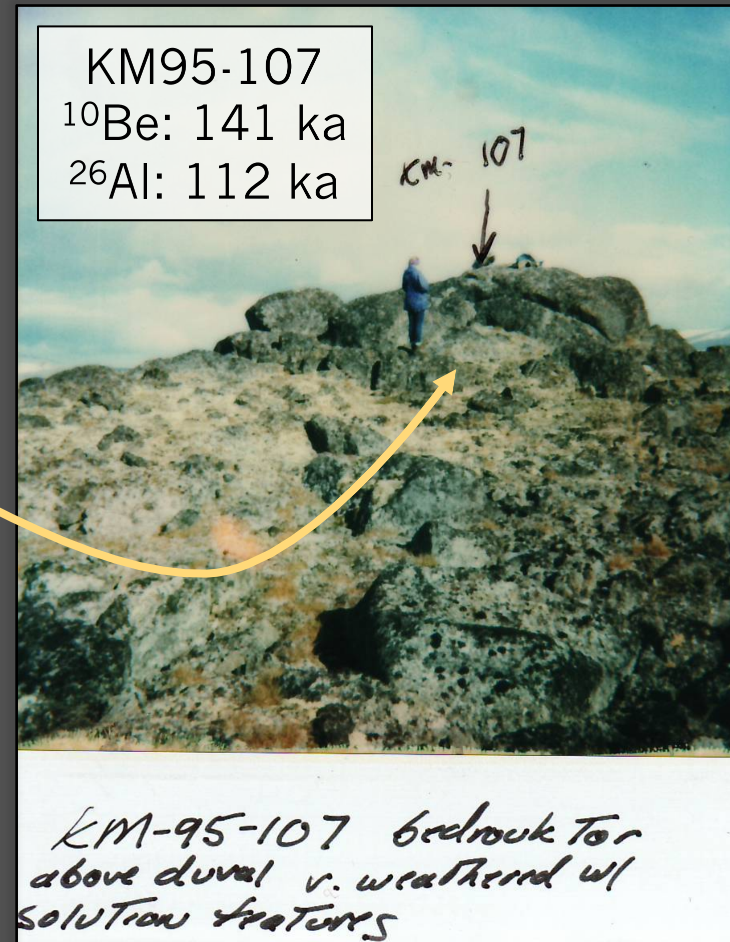
Trends: Ages Increase with Elevation





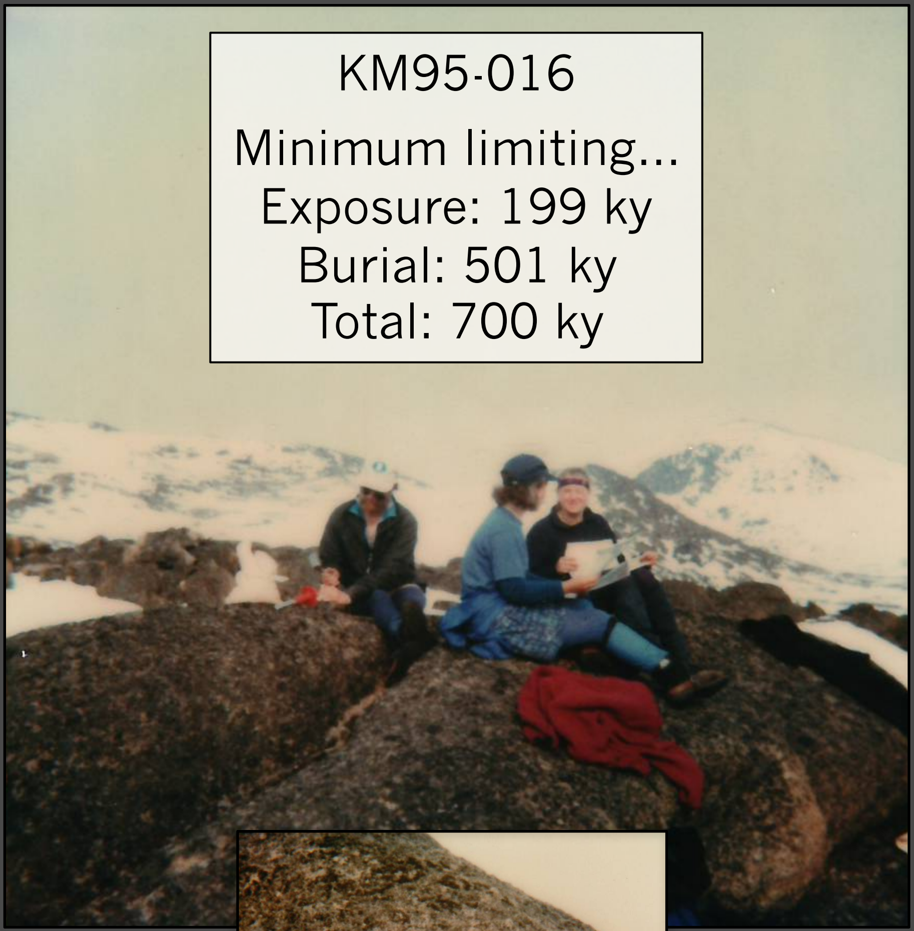
Trends: ^{10}Be Ages > ^{26}Al Ages





Red flag #4

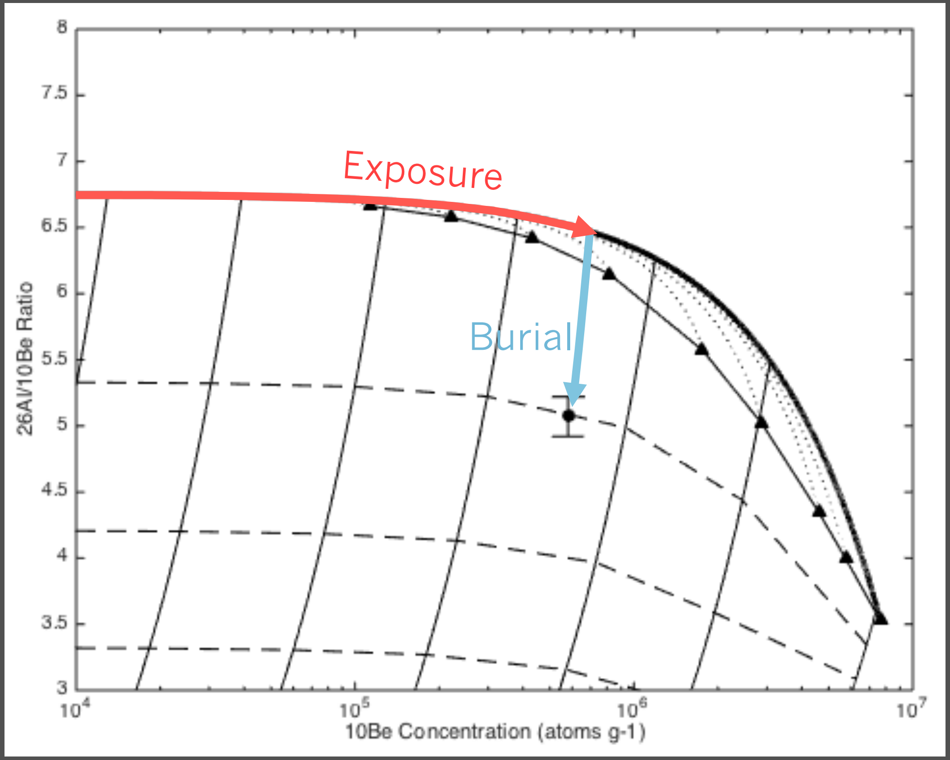
Exposure/Burial Modeling



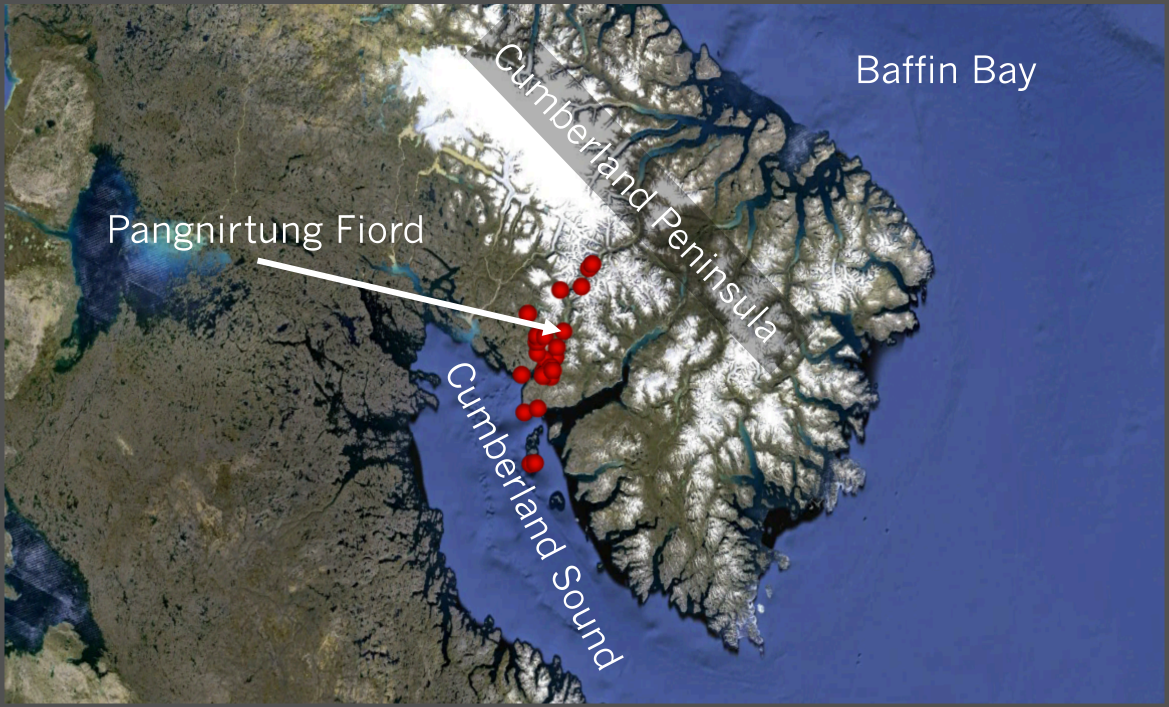
KM95-016

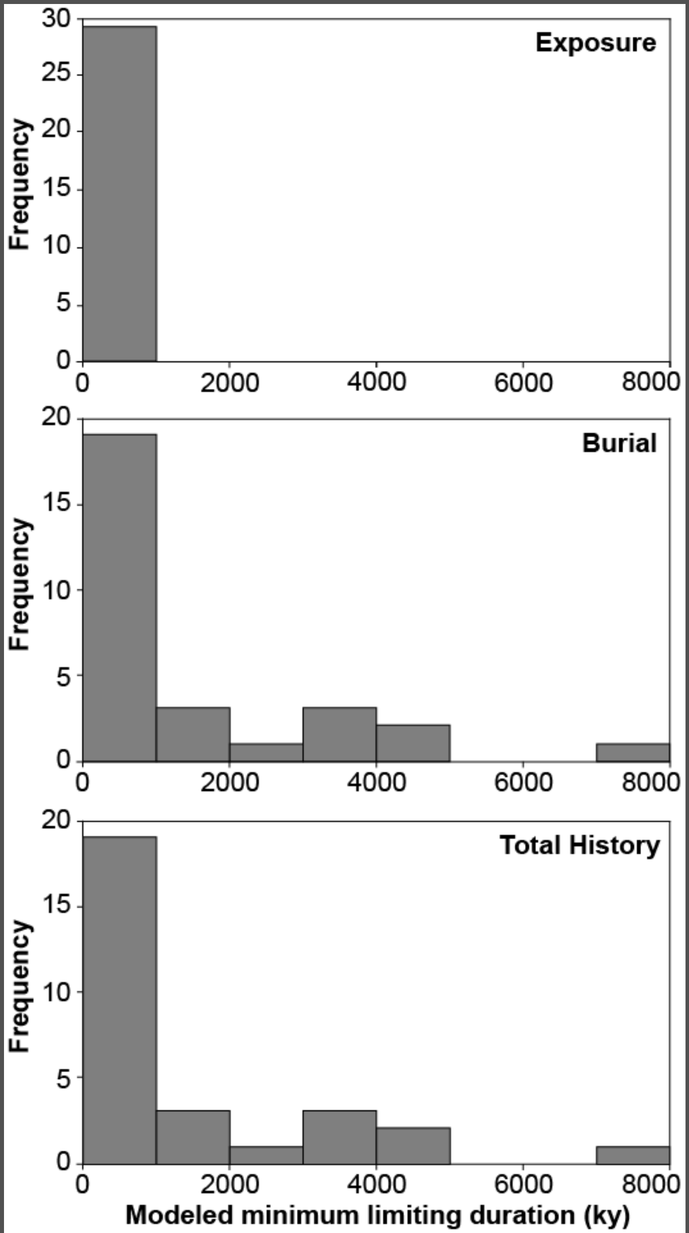
Minimum limiting...
Exposure: 199 ky
Burial: 501 ky
Total: 700 ky

Solving for the simplest path:
One period of exposure
followed by one period of burial



Exposure/Burial Modeling





Minimum-limiting exposure durations: 5.9-480 ky

Minimum-limiting burial durations: 140-7500 ky

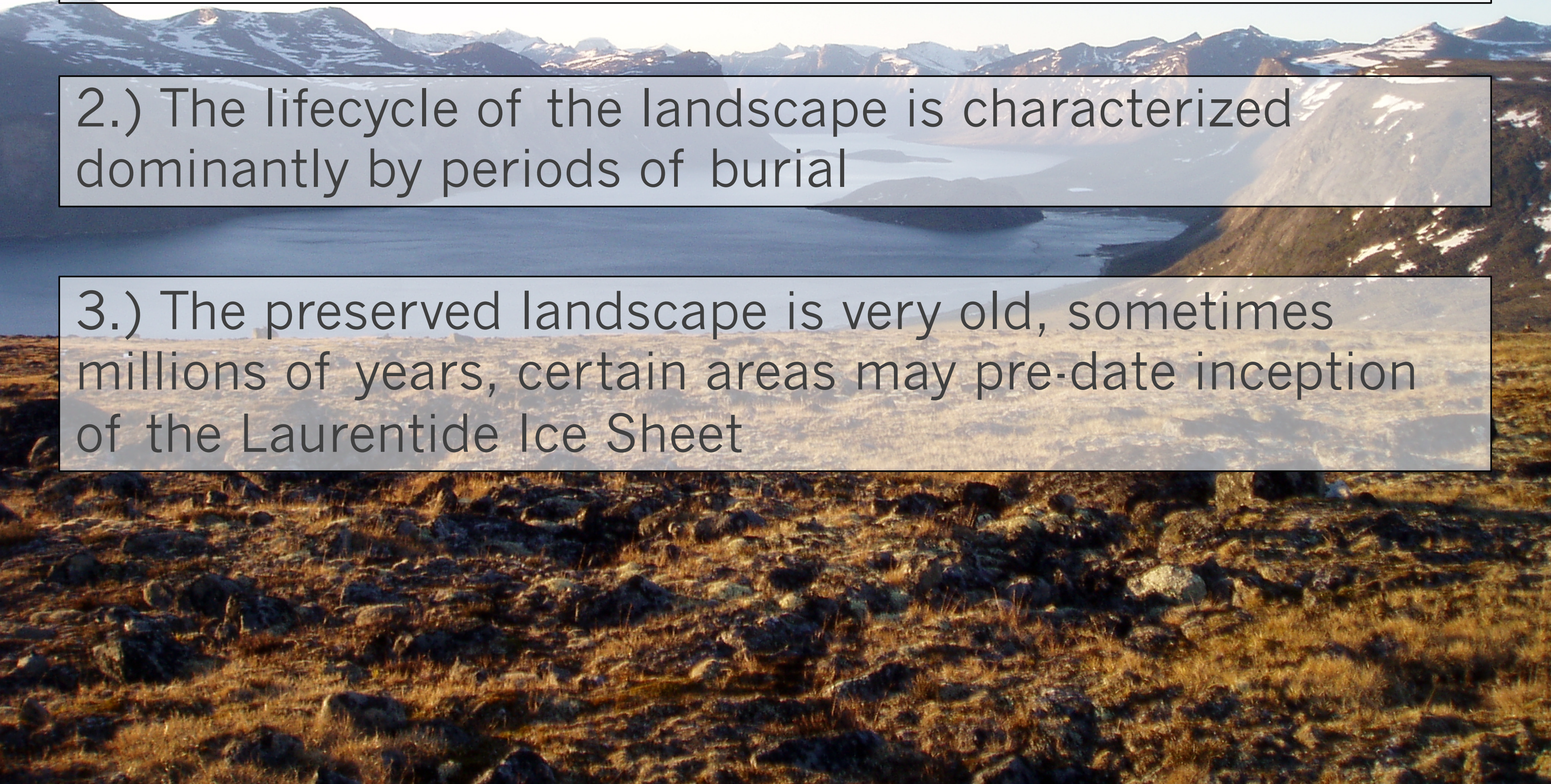
} Minimum-limiting total histories up to ~8 My!

Baffin Conclusions

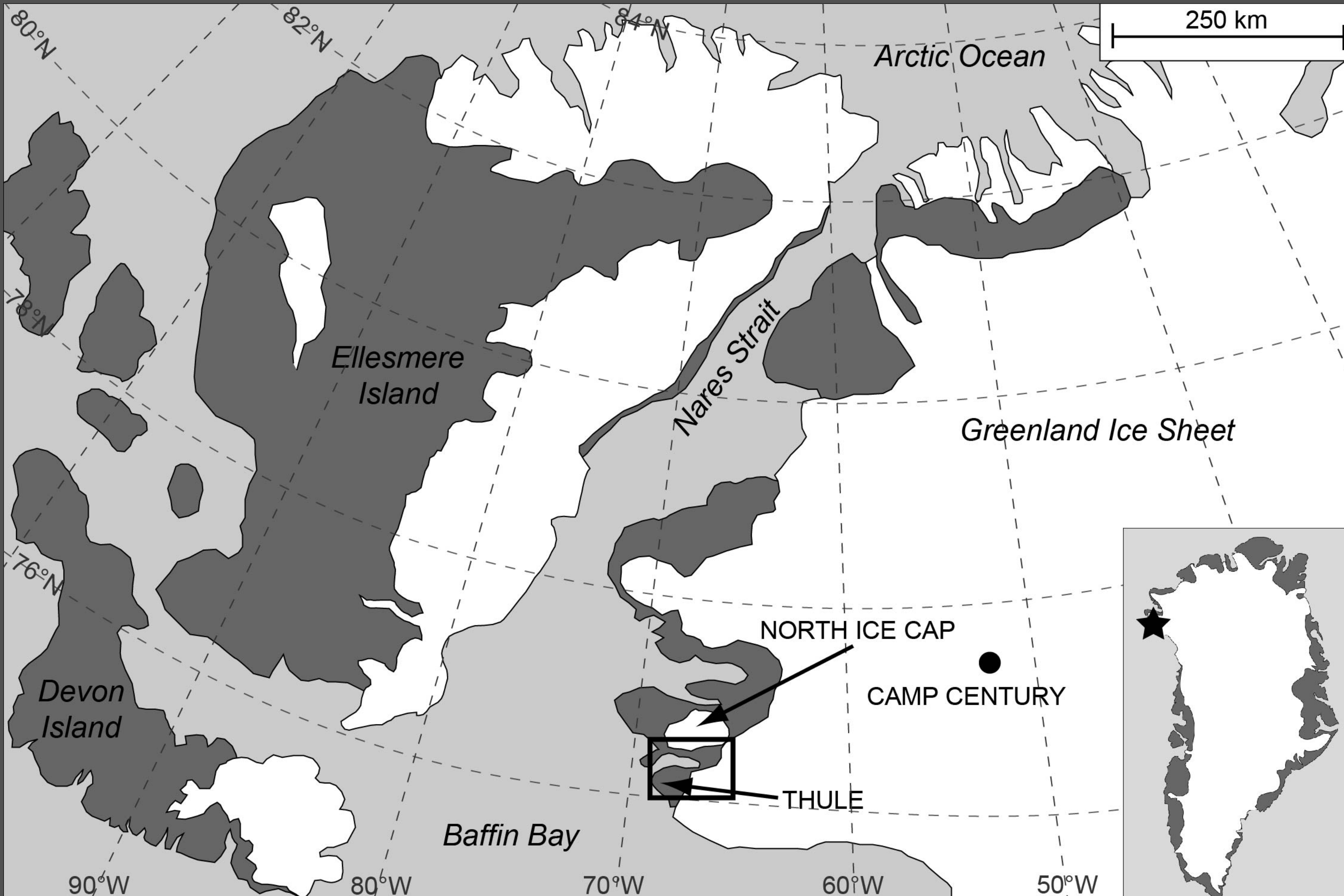
1.) Numerous age patterns indicate cold-based ice

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

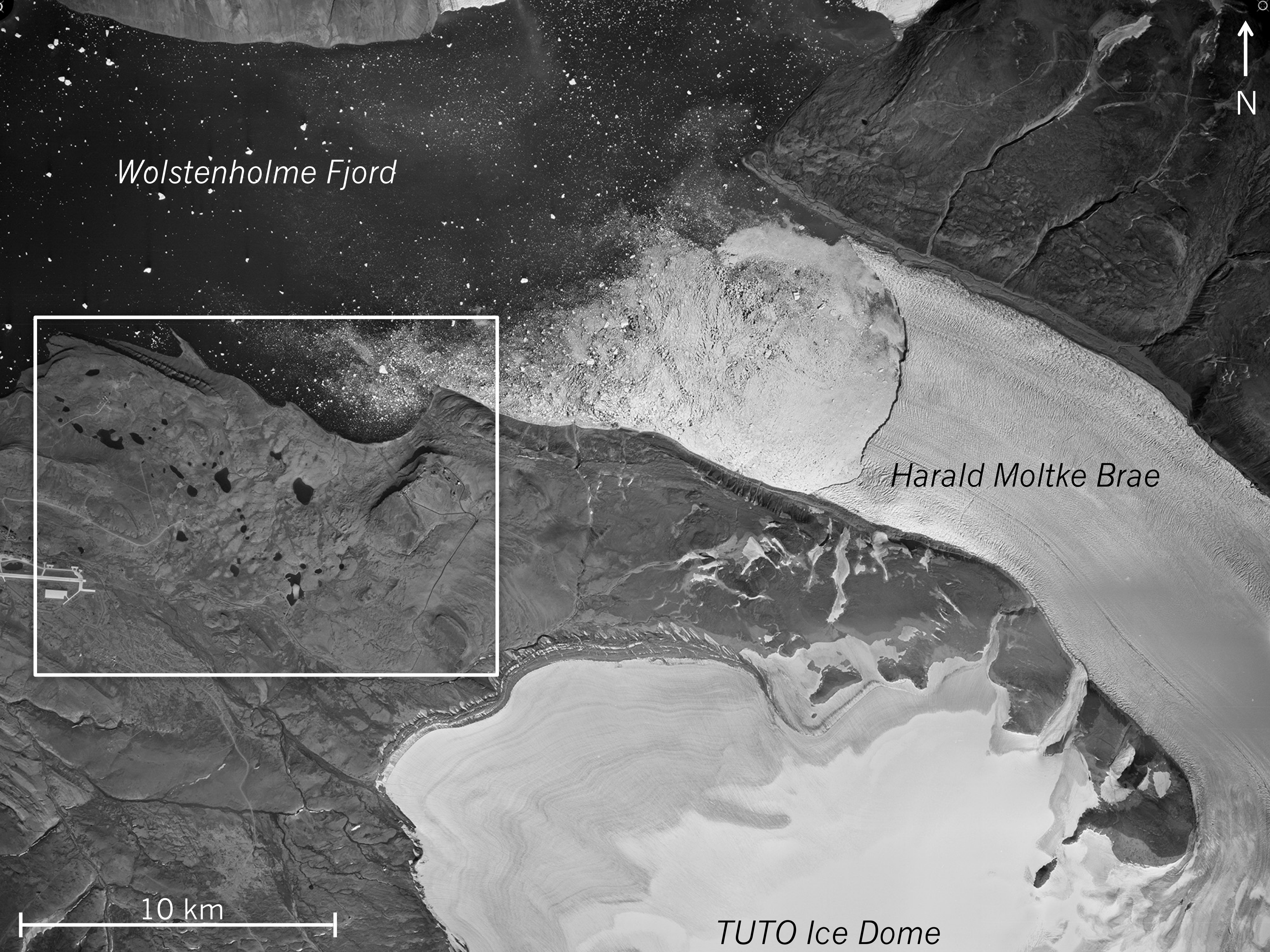
3.) The preserved landscape is very old, sometimes millions of years, certain areas may pre-date inception of the Laurentide Ice Sheet



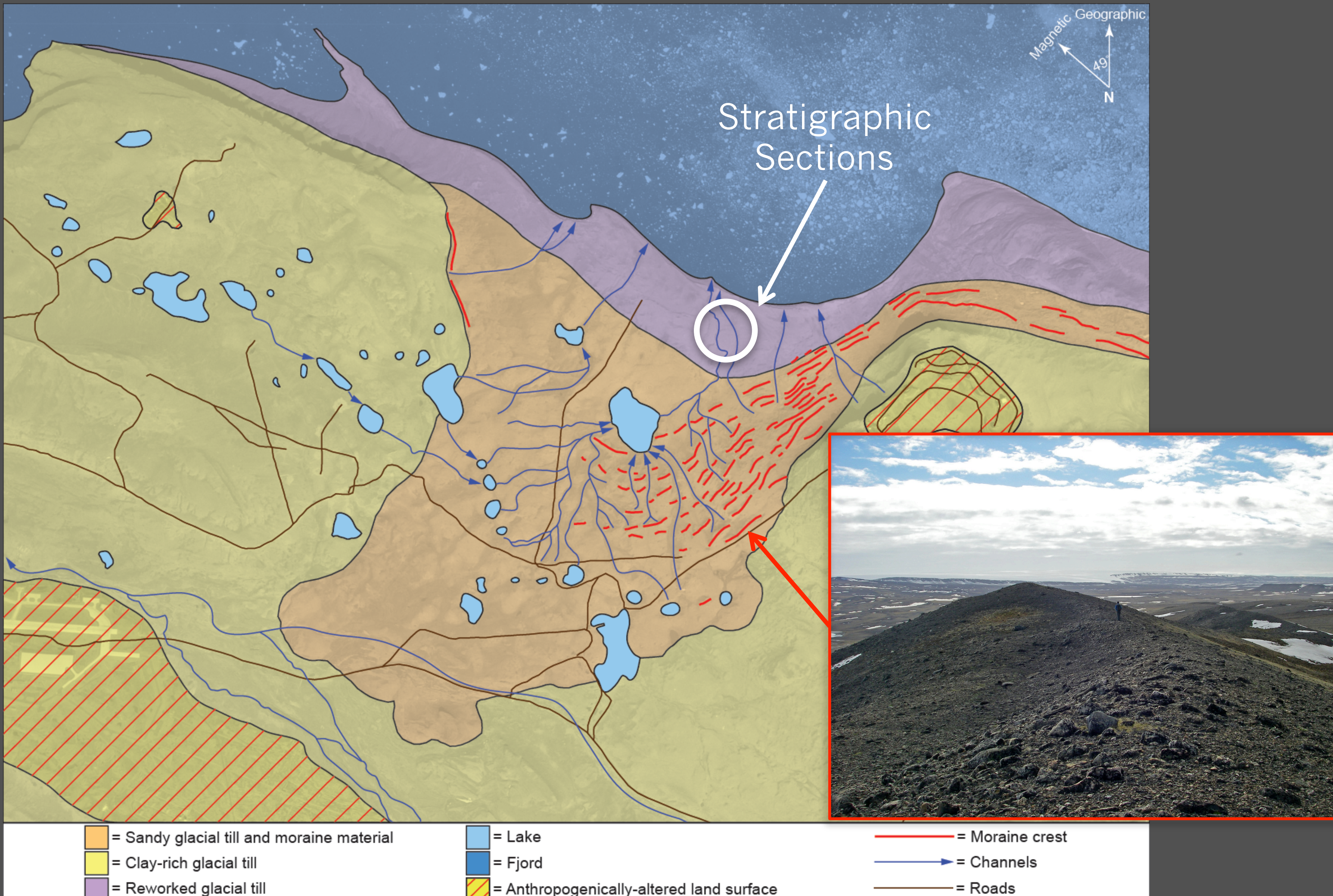
Thule, Northwest Greenland



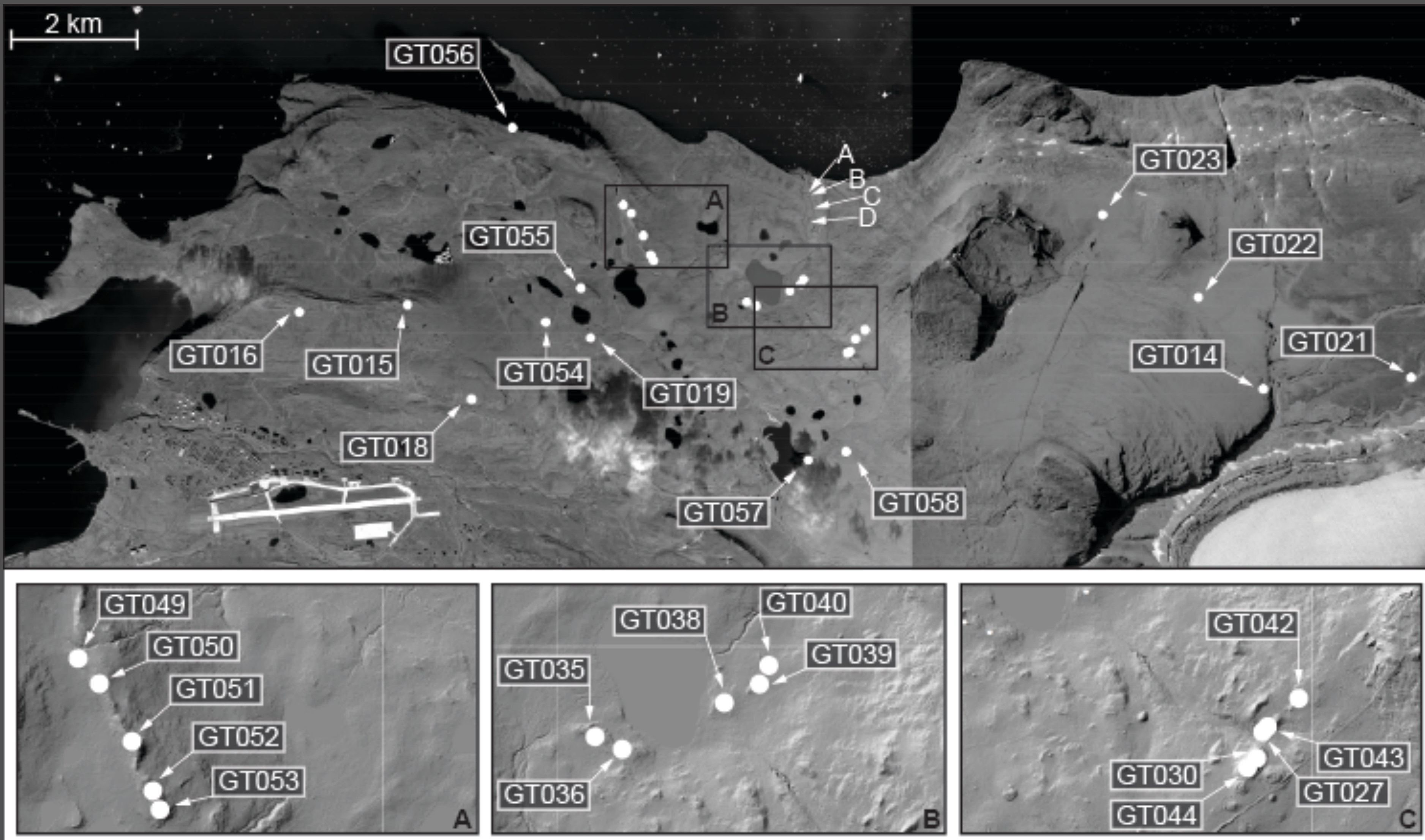
250 km
Arctic Ocean
80°N
82°N
84°N
78°N
76°N
Ellesmere Island
Nares Strait
Greenland Ice Sheet
Devon Island
NORTH ICE CAP
CAMP CENTURY
THULE
Baffin Bay
90°W
80°W
70°W
60°W
50°W


N
Wolstenholme Fjord
Harald Moltke Brae
10 km
TUTO Ice Dome

Mapping

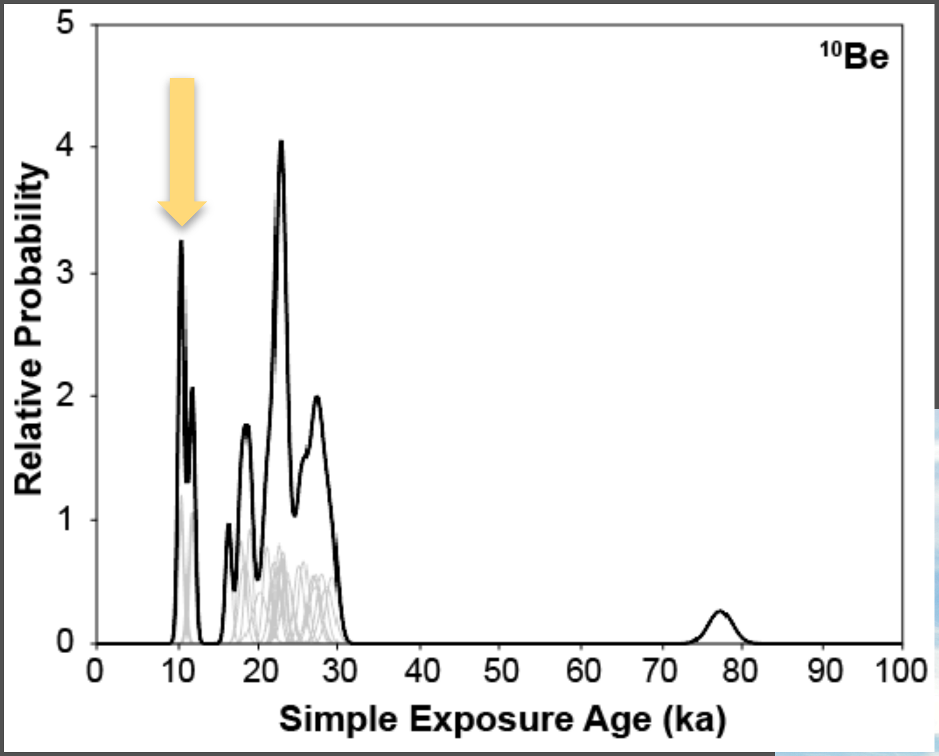

Geographic
Magnetic
49°
N
Stratigraphic Sections
= Sandy glacial till and moraine material
= Clay-rich glacial till
= Reworked glacial till
= Lake
= Fjord
= Anthropogenically-altered land surface
= Moraine crest
= Channels
= Roads

Analysis of Cosmogenic ^{10}Be and ^{26}Al



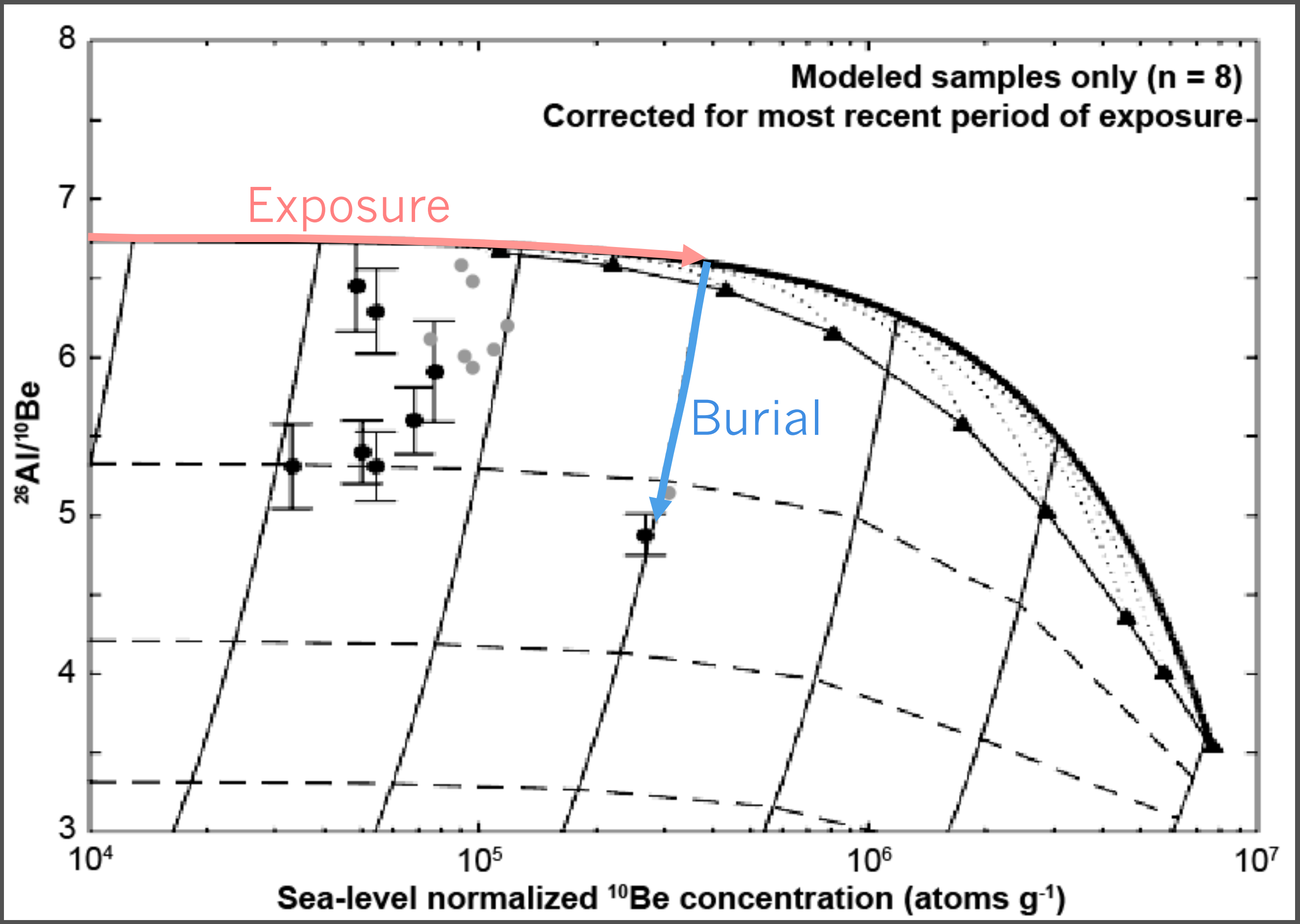
(n = 28 glacially-deposited boulders)

Deglaciation Timing



GT022: 10.7 ± 0.6 ka
GT023: 10.6 ± 0.6 ka
GT055: 10.7 ± 0.7 ka
(External uncertainties)

Two-Isotope Analysis



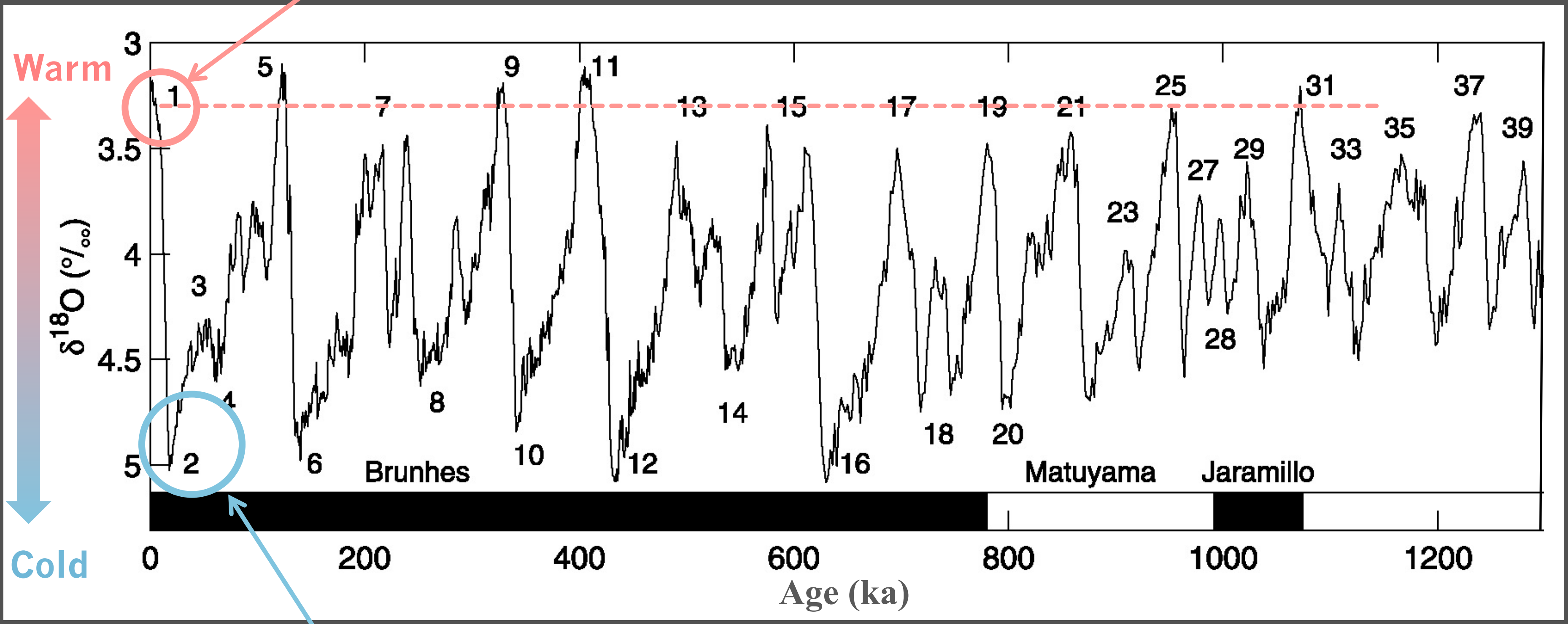
Model the simplest path:
one period of exposure
followed by
one period of burial

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

(Lisiecki and Raymo, 2005)

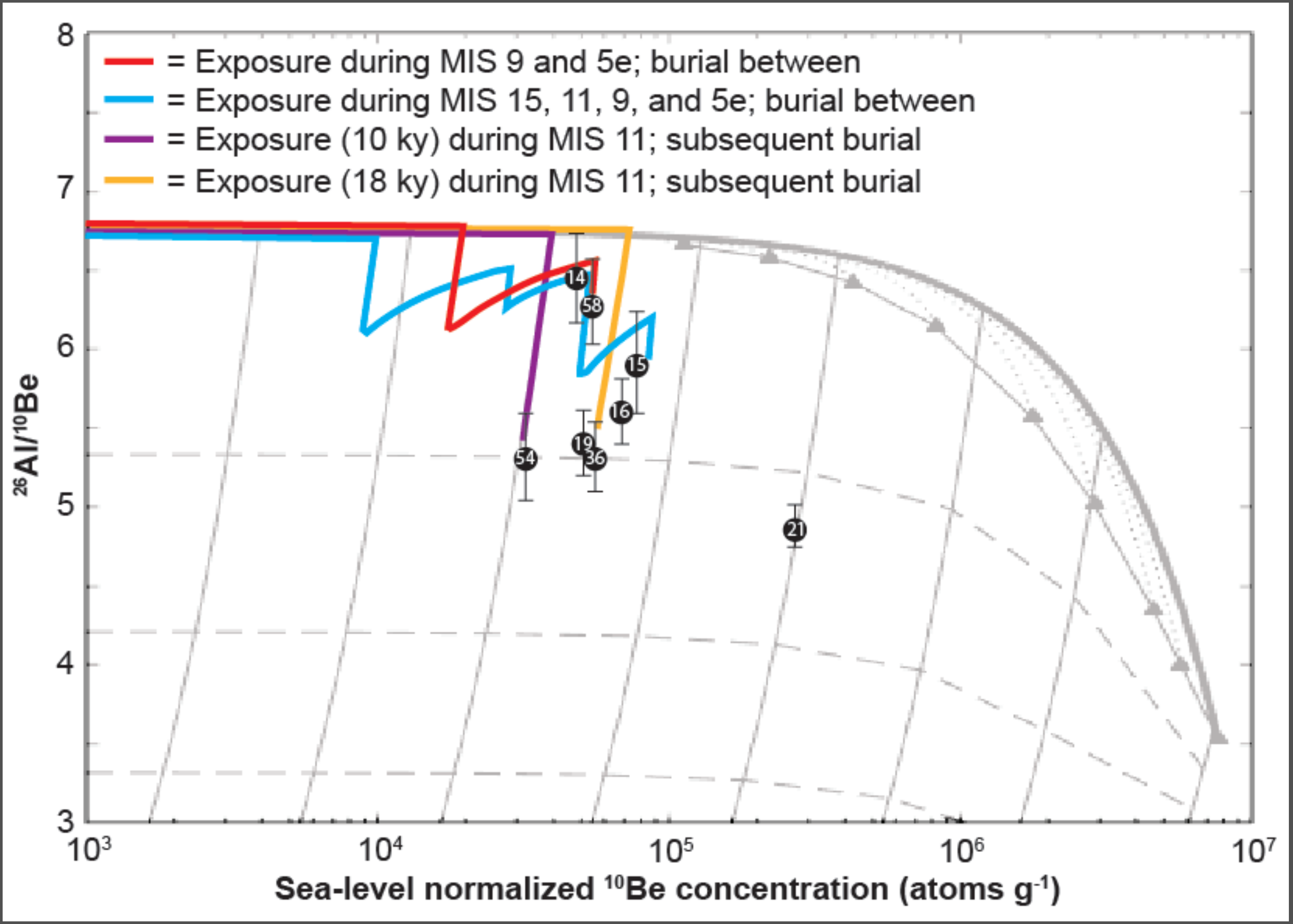


Last Glacial Maximum

Warm periods: “Interglacial”

Cold periods: “Glacial”

Numerical Models of Boulder Scenarios



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

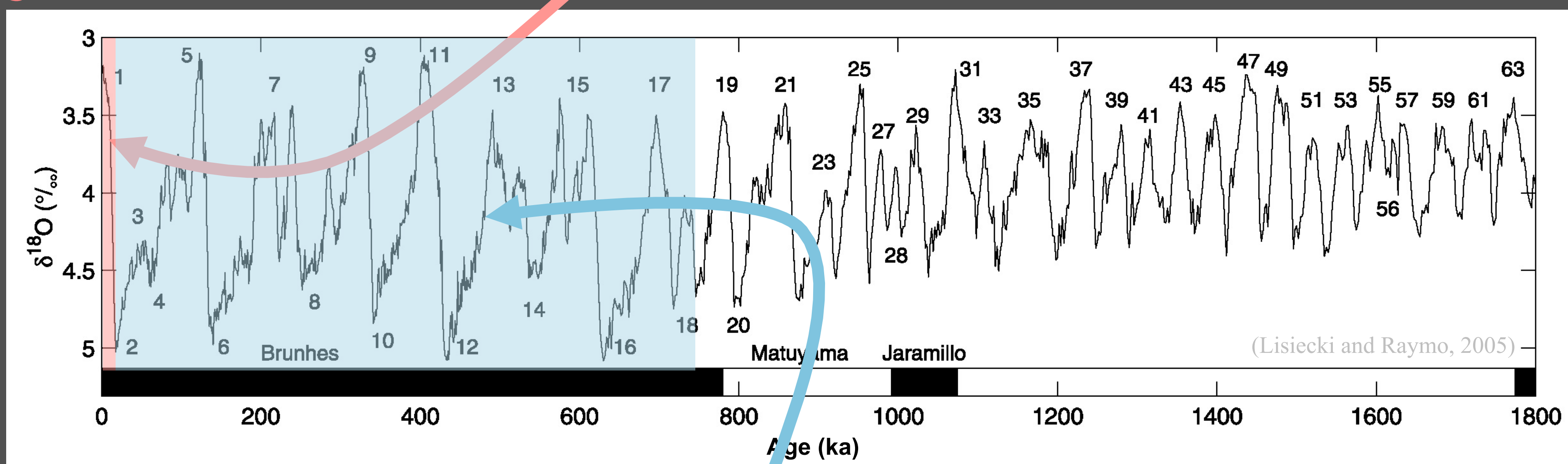
Cold-based “ghost glaciers” preserve surfaces subglacially, creating ancient, relict landscapes

New techniques are needed to understand these complex surfaces

Cold-Based Ice: An Opportunity?

Record preserved on a warm-based ice landscape

Interglacial



Glacial

Record preserved on a cold-based ice landscape
(e.g. Baffin study; median total history ~750 ka)

UVM Geomorphology, Quaternary Geology, and Glacial Geology Colleagues

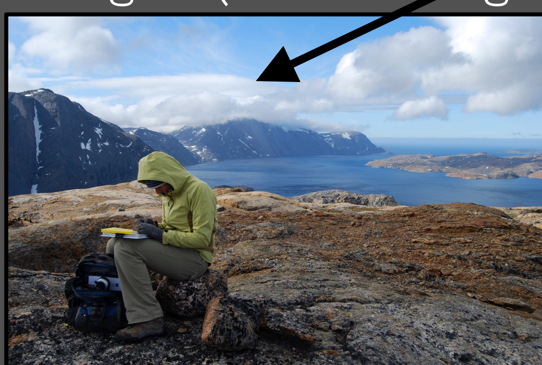
Paul Bierman
Ben DeJong
Alison Denn
Jane Duxbury
Joseph Graly
Sophie Greene
Will Hackett
Matt Jungers
Christine Massey
Andrea Lini
Tom Neilson
Tom Neumann
Eric Portenga
Luke Reusser
Veronica Sosa-Gonzalez
Stephen Wright



1989: Looking at rocks

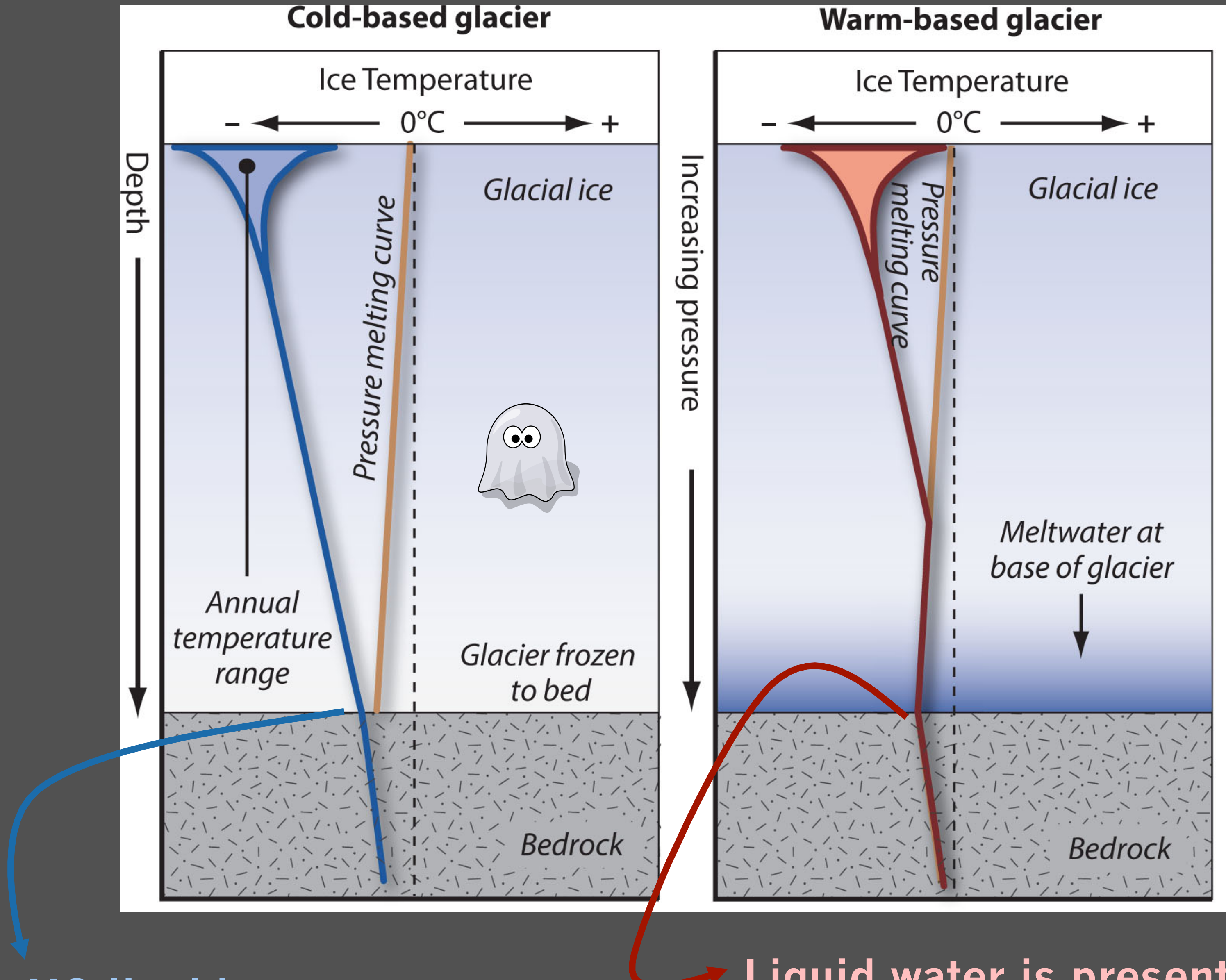
2007: BA degree (looking at rocks)

2011: MS degree (more looking at rocks)



2016: PhD degree (still looking at rocks)

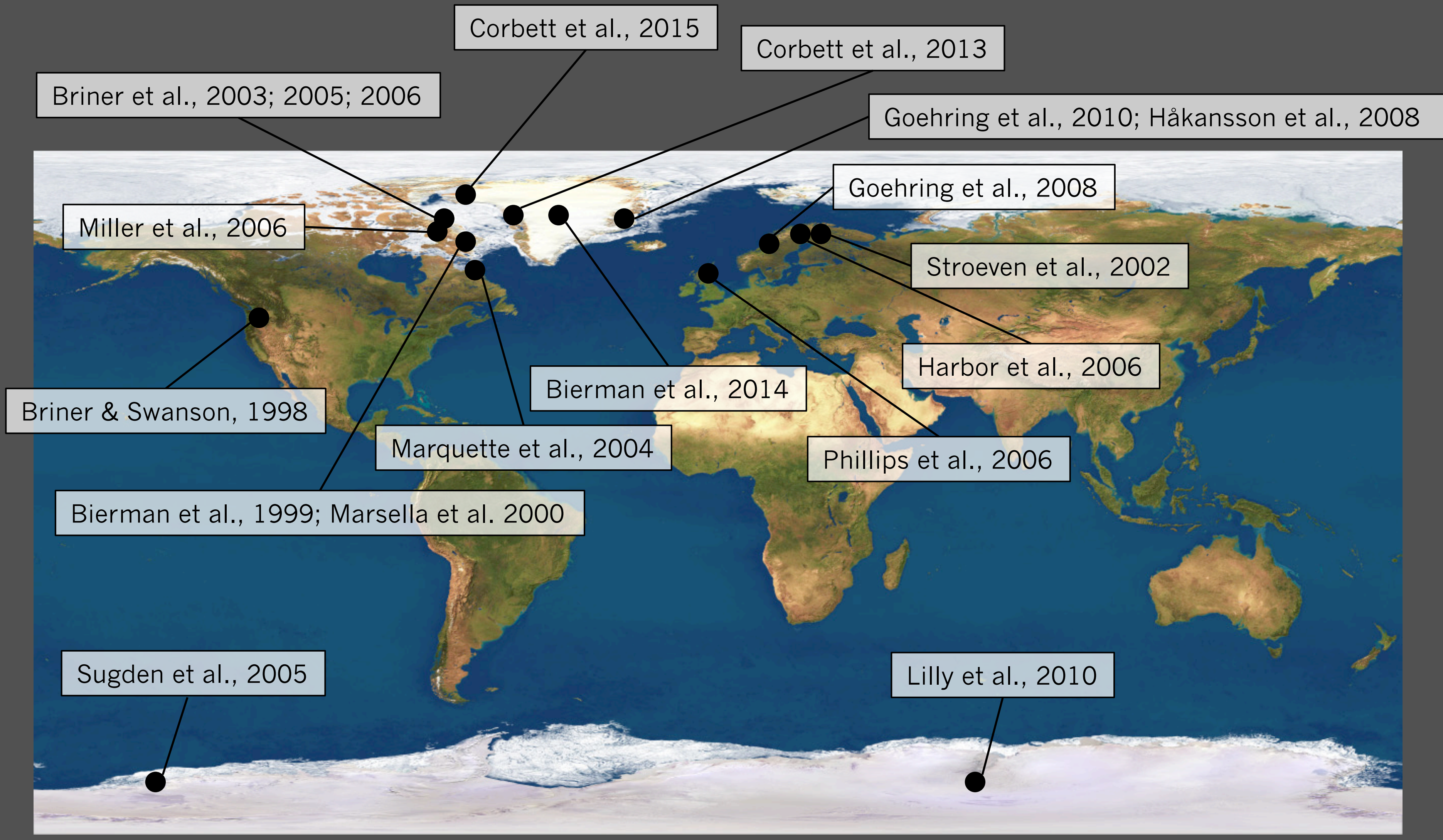


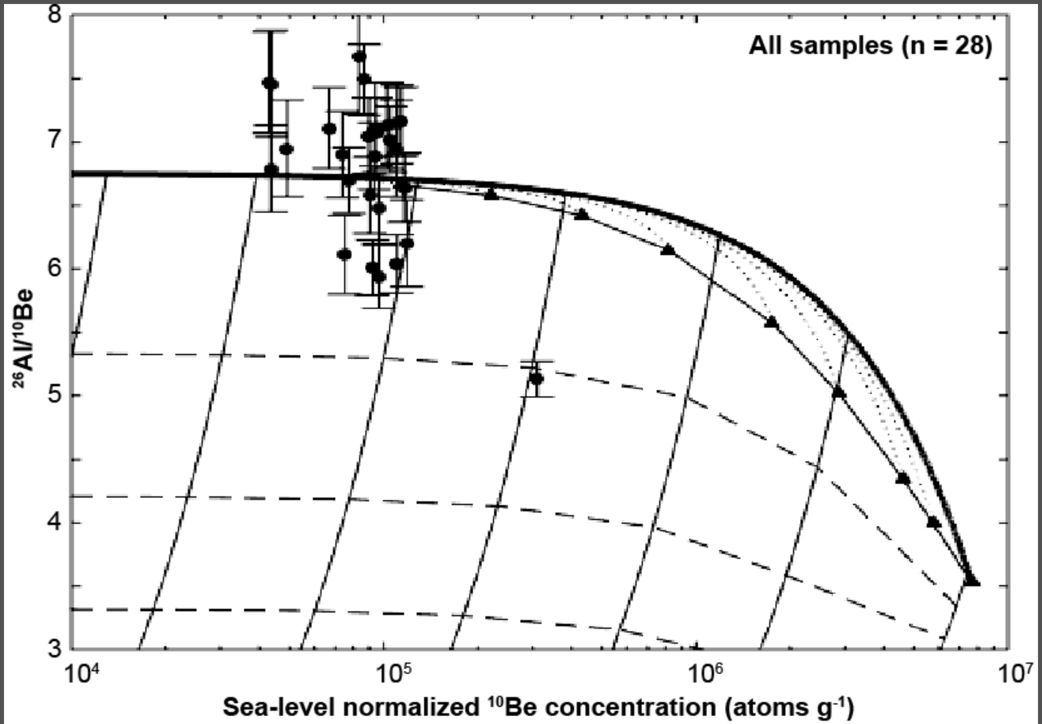
NO liquid water present
No erosion can occur

Liquid water is present
Erosion by abrasion
Erosion by plucking/quarrying

Cold-based ice is widespread in the high latitudes



Thule Two-Isotope Data



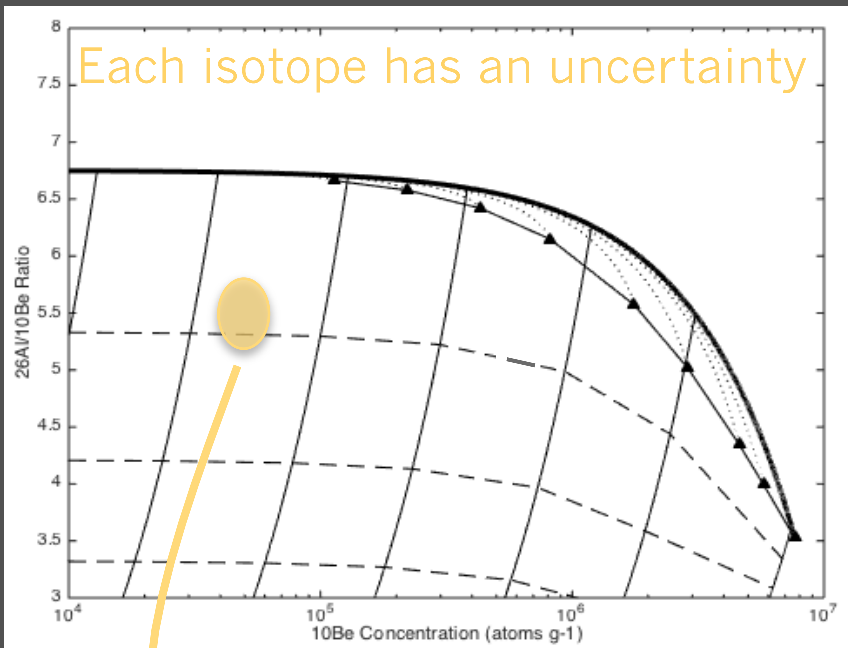
Case #1
(n = 3)
^{10}Be ages: deglacial
$^{26}Al/^{10}Be$: constant exposure

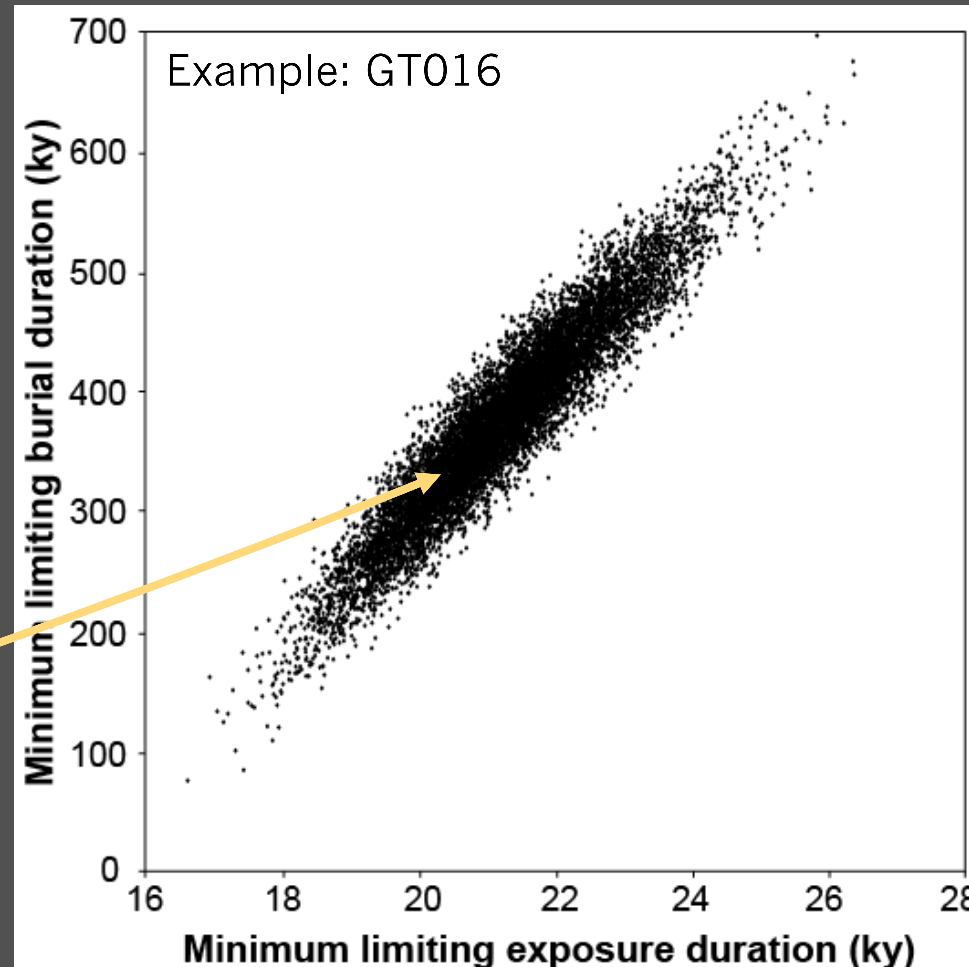
Case #2
(n = 8)
^{10}Be ages: old
$^{26}Al/^{10}Be$: burial

Case #3
(n = 17)
^{10}Be ages: old
$^{26}Al/^{10}Be$: constant exposure

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

Constraining Uncertainties



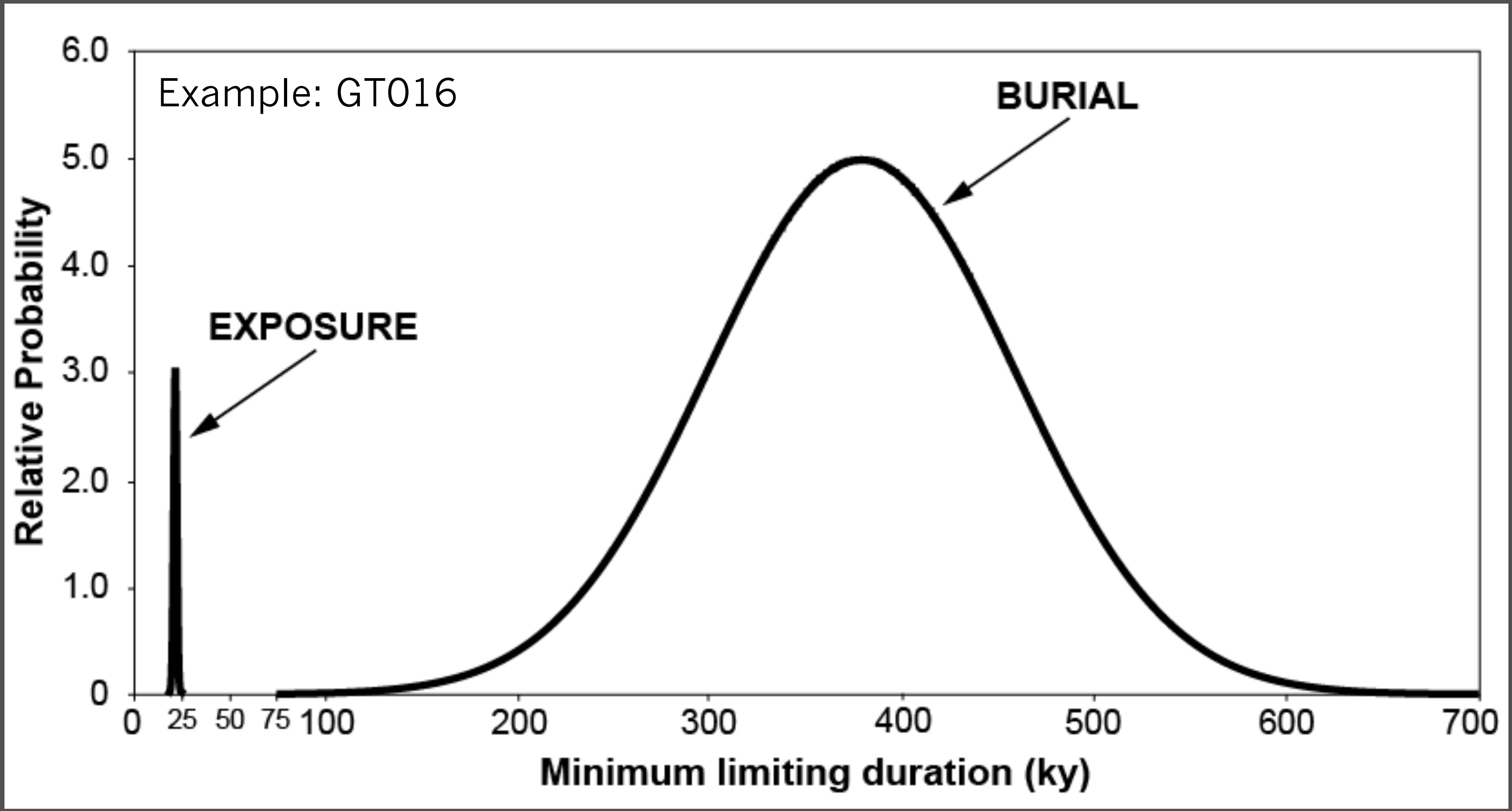


Monte Carlo simulations (n = 10,000)

Choosing random, independent ^{10}Be and ^{26}Al concentrations from a normally-distributed population of possible values based on the 1 σ analytic uncertainty

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

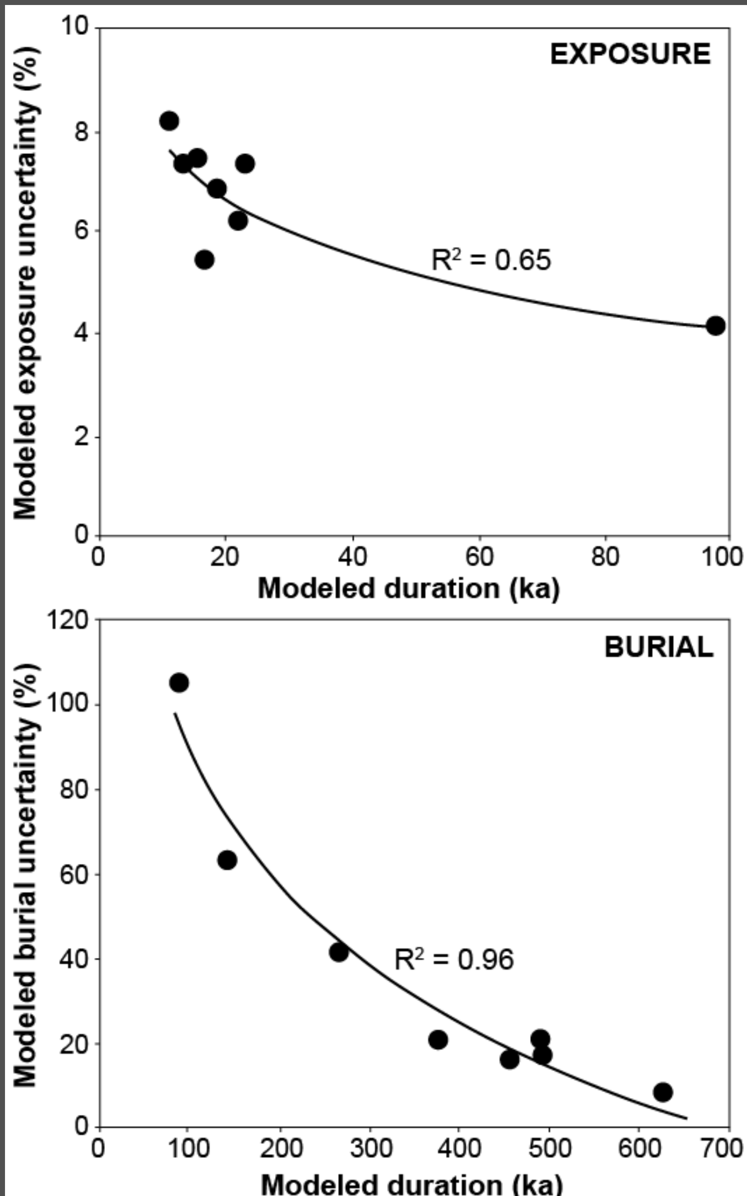
Constraining Uncertainties



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



<u>Exposure</u>

Minimum duration: 11 – 96 ky (av. 26 ky)

Uncertainties (yr): 1 – 4 ky (av. 2 ky)

Uncertainties (%): 4 – 8 % (av. 7 %)

<u>Burial</u>

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, $^{26}Al/^{10}Be$ ratios indicative of constant exposure

A Conundrum!

GT043

^{10}Be: 26.9 ± 1.5 ky

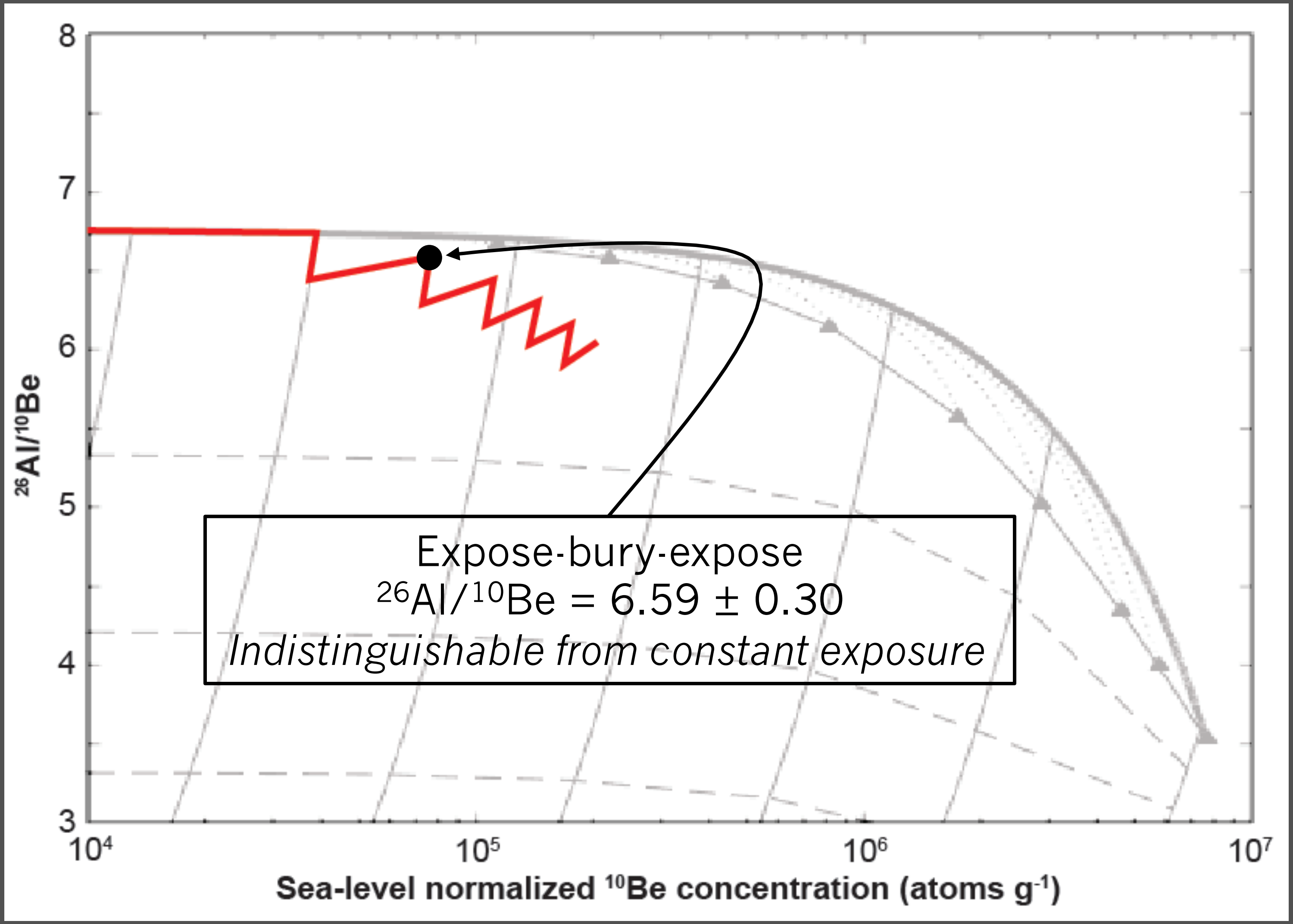
^{26}Al: 27.7 ± 1.9 ky

$^{26}Al/^{10}Be$: 6.95 ± 0.38

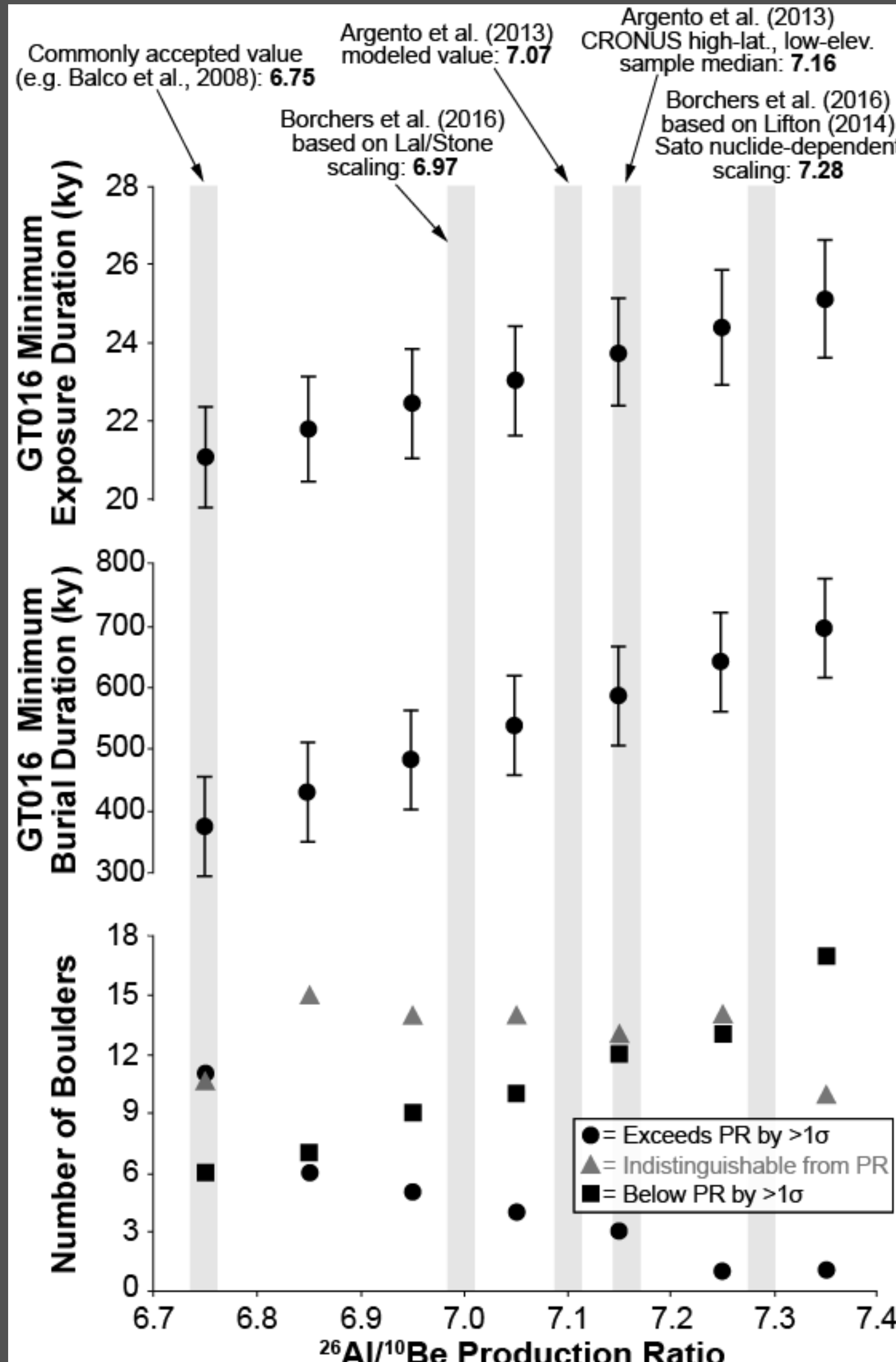
Old but not buried?!?

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%)


Commonly accepted value
(e.g. Balco et al., 2008): 6.75
Argento et al. (2013)
modeled value: 7.07
Argento et al. (2013)
CRONUS high-lat., low-elev.
sample median: 7.16
Borchers et al. (2016)
based on Lal/Stone
scaling: 6.97
Borchers et al. (2016)
based on Lifton (2014)
Sato nuclide-dependent
scaling: 7.28
GT016 Minimum Exposure Duration (ky)
GT016 Minimum Burial Duration (ky)
Number of Boulders
= Exceeds PR by >1σ
= Indistinguishable from PR
= Below PR by >1σ
26Al/10Be Production Ratio