Investigating the timing of deglaciation and the efficiency of subglacial erosion in central-western Greenland with cosmogenic ^{10}Be and ^{26}Al


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Thesis Road Map:

Optimizing sample preparation for ^{10}Be analysis by accelerator mass spectrometry

Paired bedrock and boulder ^{10}Be concentrations resulting from early Holocene ice retreat near Jakobshavn Isfjord, western Greenland

Constraining landscape history with ^{10}Be and ^{26}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

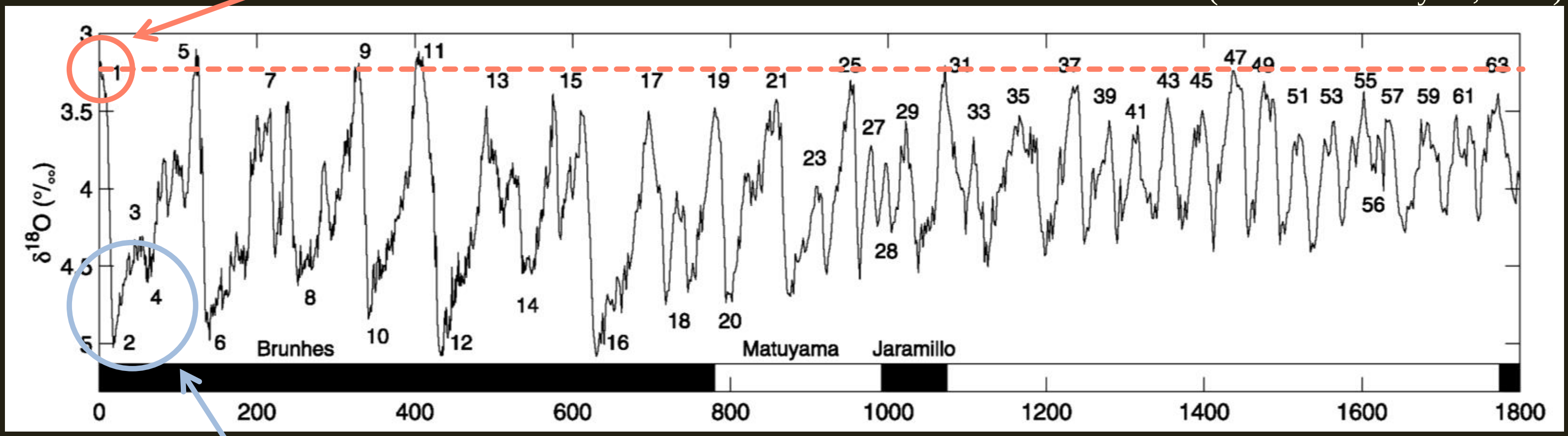
Climate is not static over time!

Holocene Period

Warmer

Colder

(Lisiecki and Raymo, 2005)



X-axis: thousands of years ago (“ka”)

Last “Ice Age”

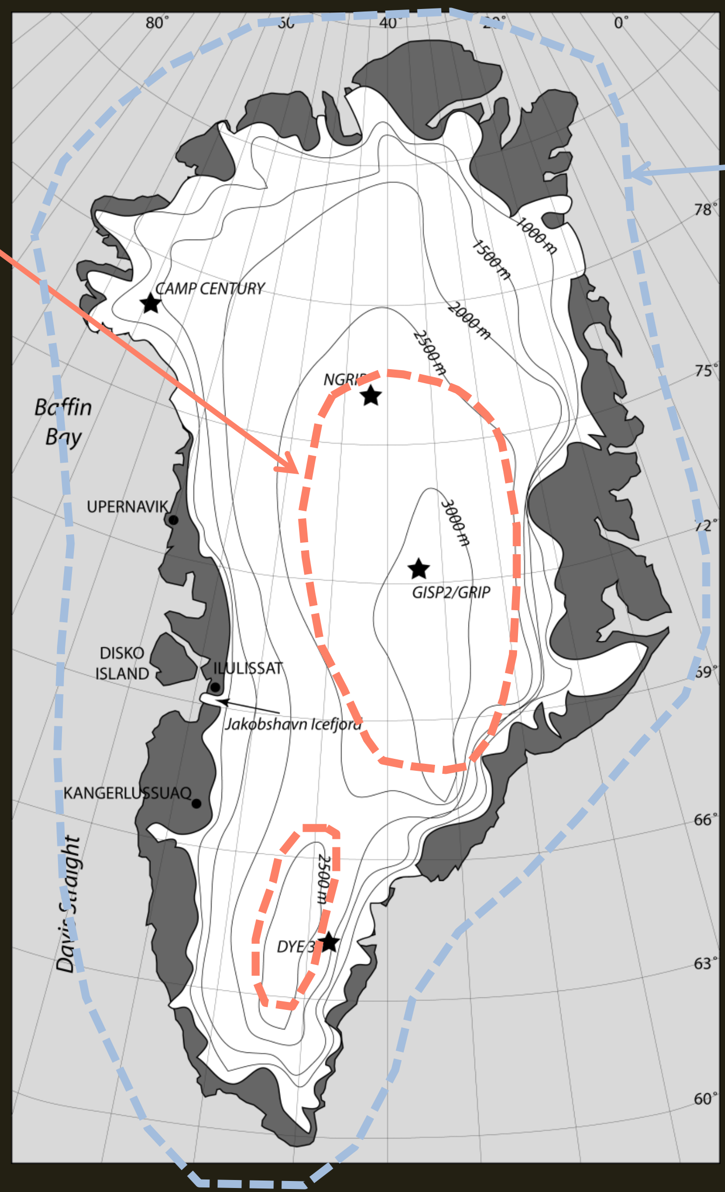
Warm periods: “Interglacial”

Cold periods: “Glacial”

Variability of the Greenland Ice Sheet

Interglacial period ice extent

Cuffey and Marshall (2000)
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

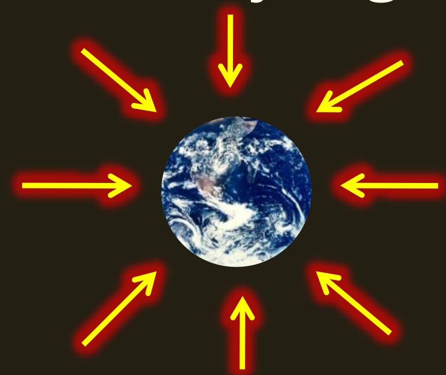
Tools,
Study Design,
&
Methodology

Tools: *in situ* cosmogenic ^{10}Be and ^{26}Al

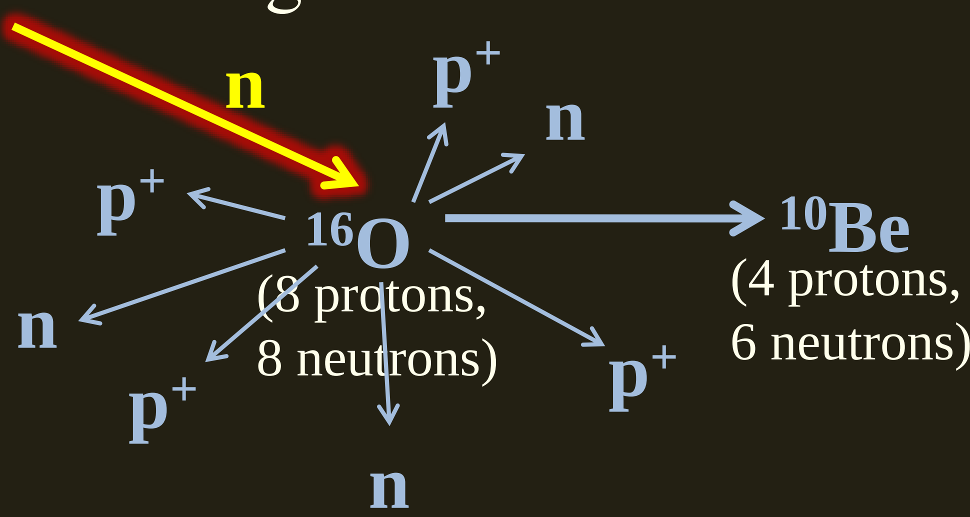
- *“In situ”*: produced within the mineral structure (quartz)
- “Cosmogenic”: from cosmic rays
- “^{10}Be”: rare, radioactive isotope of beryllium
- “^{26}Al”: rare, radioactive isotope of aluminum

Formation of *in situ* cosmogenic ^{10}Be

Earth is bombarded by high-energy cosmic rays



…causing the formation of ^{10}Be in quartz



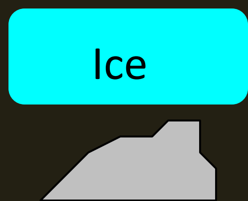
^{10}Be is produced only on the surface of a rock

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

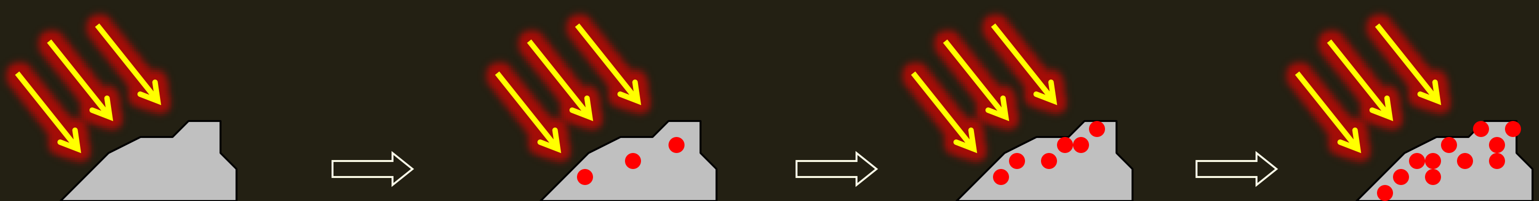
^{10}Be is radioactive and has a half-life of 1.38 million years

"Cosmogenic Dating"

Glacial period: Bedrock is **shielded**



Interglacial period: Bedrock is **exposed**



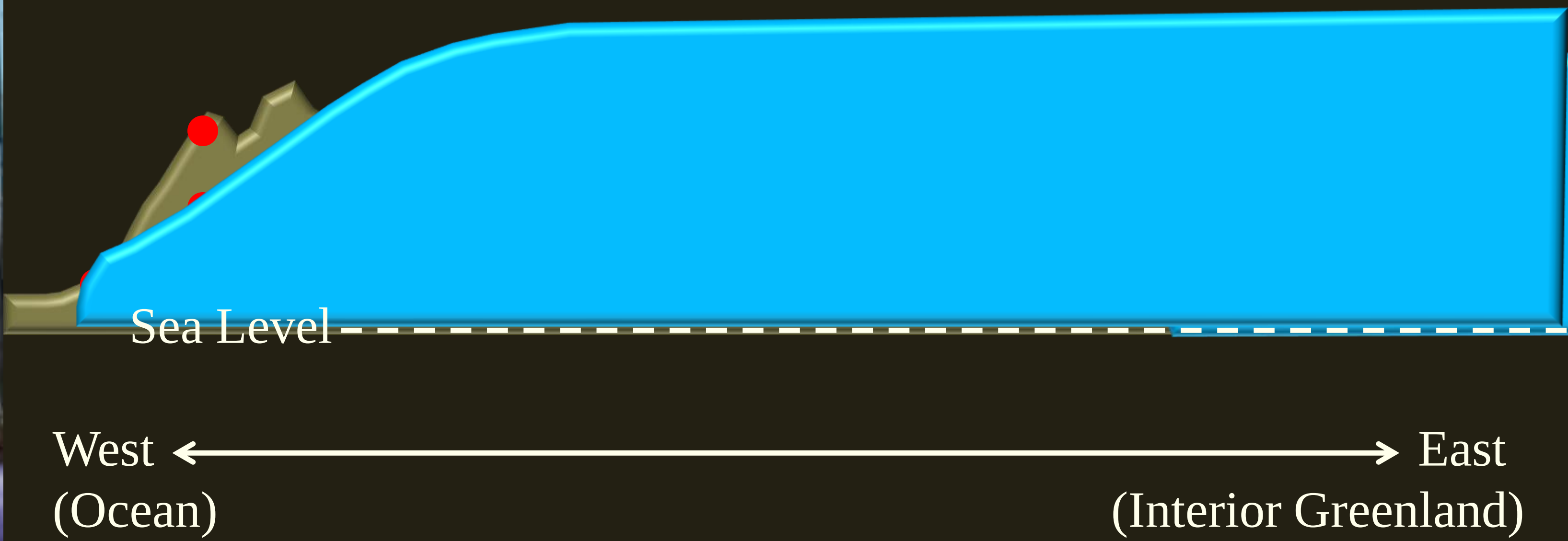
Assumption: Zero **inheritance** (i.e. no ^{10}Be leftover from previous periods of exposure)

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

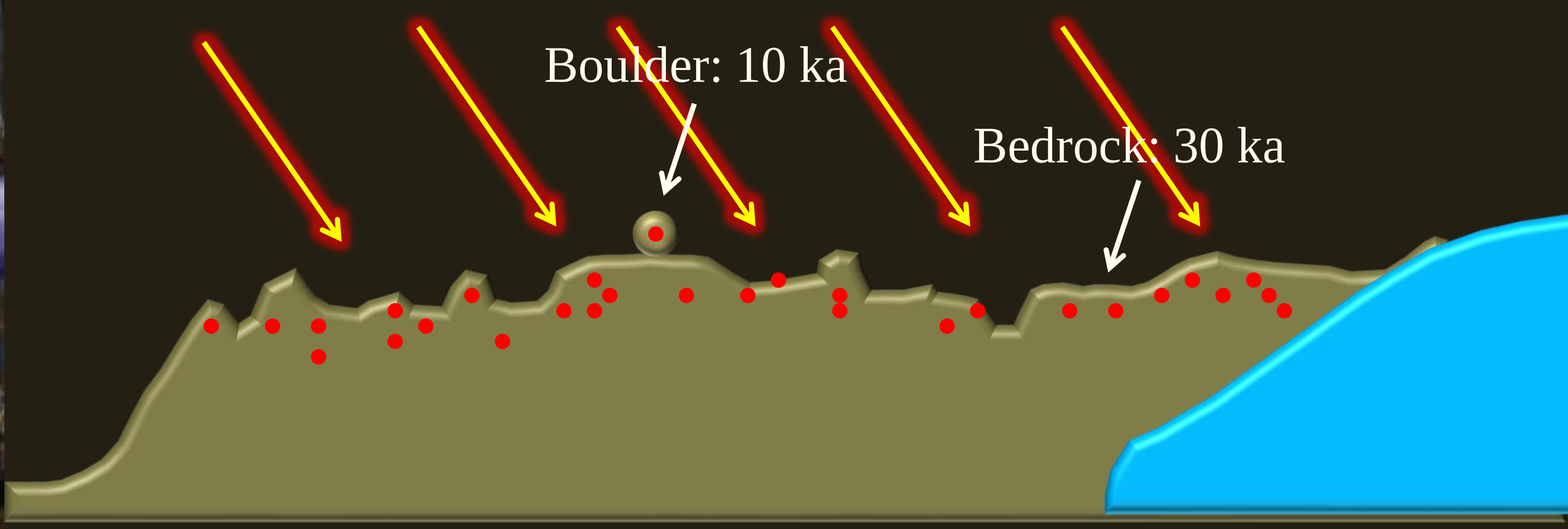
Sampling Scheme

"Dipstick" Sampling:



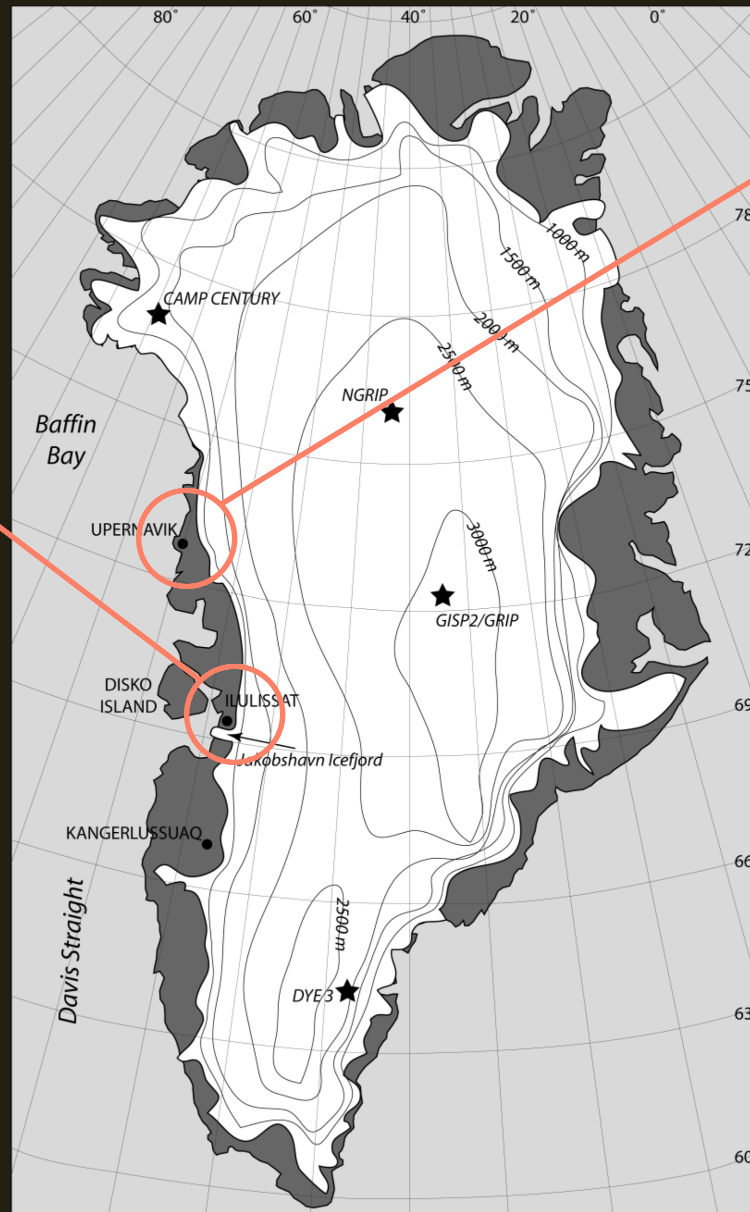
Cosmogenic Inheritance

- 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

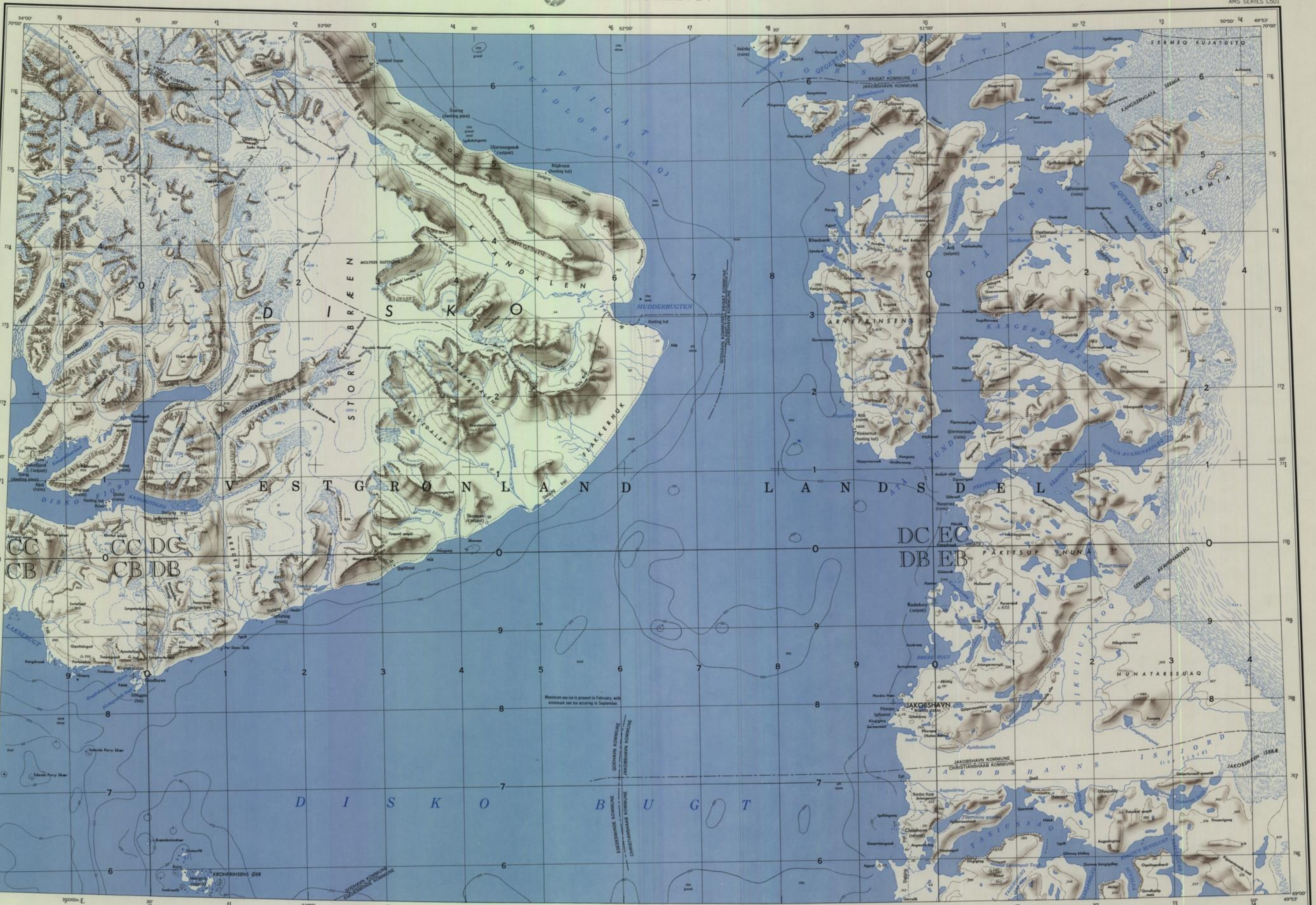


Study Sites

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



Upernavik:
- Latitude: 73°N
- Fjord-dissected terrain
- No major outlet glaciers



AMS C501
Edition 1-AMS (First Printing, 4-55)

Prepared by the Army Map Service (AM), Corps of Engineers, U. S. Army, Washington, D. C. Compiled in 1954 from: Grønland, 1:250,000, Geodætisk Institut, Sheets 69 V. 1, 69 V. 2, 1931-33; USHO Chart 5616, 1946. Major revisions to planimetry and relief made from aerial photography.
Names data was taken directly from Danish sources, except that q Q has been used for ĸ, K or ĸ, K.

GLOSSARY

Bræ, bræen	glacier	Isbræ	glacier
Bugt, -bugten	bay, cove	Næs, -næs	point
Dal, -dalen	valley	-passet	pass
elv	river	Ryg	ridge
fjeld, -fjeldet	mountain	Skær, -skær	rock
Gletscher	glacier	Sund	sound
Havn	harbor	Ø, -ø, Øer	island(s)

LEGEND

POPULATED PLACES

- Over 1,000 — GODTHAAB
- 750 to 1,000 — HOLSTEINSBORG
- 500 to 750 — FREDERIKSHAAB
- 250 to 500 — Godhavn
- Less than 250 — Christianshaab

ROADS

- Loose surface, graded, all weather
- Loose surface, dry weather, or dirt
- Trail

BOUNDARIES

- Landsdel
- Kommune

Landplane airport · Landing area · Seaplane airport · Seaplane anchorage · Spot elevation in meters

Landmark feature · Horizontal control point · Astronomic position · Glacier · Glacial moraine

Rocks: Awash; Sunken · Wrecks: Exposed; Sunken · Limit of danger; Reef · Foreshore flat · Depth curves in fathoms

Scale 1:250,000

20 Statute Miles · 30 Kilometers · 10 Nautical Miles

RELIEF SHOWN BY FORM LINES AND HACHURES

TRANSVERSE MERCATOR PROJECTION

BLACK NUMBERED LINES INDICATE THE 10,000 METER UNIVERSAL TRANSVERSE MERCATOR GRID, ZONE 22, INTERNATIONAL SPHEROID

THE LAST FOUR DIGITS OF THE GRID NUMBERS ARE OMITTED

1950 MAGNETIC DECLINATION FOR THIS SHEET VARIES FROM 54°15' WESTERLY FOR THE CENTER OF THE WEST EDGE TO 52°00' WESTERLY FOR THE CENTER OF THE EAST EDGE. MEAN ANNUAL CHANGE IS 0°15' EASTERLY.

USERS NOTING ERRORS OR OMISSIONS ON THIS MAP ARE URGED TO MARK HEREON AND FORWARD DIRECTLY TO COMMANDING OFFICER, ARMY MAP SERVICE, WASHINGTON, D. C. MAPS SO FORWARDED WILL BE RETURNED OR REPLACED IF DESIRED.

LOCATION DIAGRAM FOR NR 21, 22-9

RELIABILITY DIAGRAM

Fair · Poor · Photography

PRINTED BY ARMY MAP SERVICE, CORPS OF ENGINEERS. 4-55 774001

TO GIVE A STANDARD REFERENCE ON THIS SHEET TO NEAREST 1000 METERS

GRID ZONE DESIGNATION: 22W

100,000 M. SQUARE IDENTIFICATION: CC, DC, EC, CB, DB, EB

Site #1: *Ilulissat, 69 °N*

Site #1: *Ilulissat, 69 °N*

Site #1: *Ilulissat, 69°N*

UPERNAVIK

EDITION 1-AMS

NS 21, 22-11
SERIES C501

C501
Edition 1-AMS
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Names data was taken directly from Danish sources, except that q Q has been used for ĸ, K or ĸ, K.

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POPULATED PLACES
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ROADS
Loose surface, graded, all weather
Loose surface, dry weather, or dirt
Trail

BOUNDARIES
Landsdel
Kommune

Landplane airport
Landing area
Seaplane airport
Seaplane anchorage
Spot elevation in meters
Landmark feature
Horizontal control point
Astronomic position
Glacier
Glacial moraine
Rocks: Awash; Sunken
Wrecks: Exposed; Sunken
Limit of danger; Reef
Foreshore flats
Depth curves in fathoms

GLOSSARY

Fjord, Fjorden	fjord	Isstrøm	glacier
Haven	harbor	Ø, Ødn	island
Isbræ	glacier	Øerne	islands
Isfjord	fjord		

Scale 1:250,000
5 0 5 10 15 20 Statute Miles
5 0 5 10 15 20 25 30 Kilometers
5 0 5 10 Nautical Miles

CONTOUR INTERVAL 200 METERS
RELIEF PARTIALLY SHOWN BY FORM LINES AND HACHURES
TRANSVERSE MERCATOR PROJECTION
BLUE NUMBERED LINES INDICATE THE 10,000 METER UNIVERSAL TRANSVERSE MERCATOR GRID, ZONES 21 AND 22, INTERNATIONAL SPHEROID.

LOCATION DIAGRAM FOR NS 21, 22-11

RELIABILITY DIAGRAM

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Site #2: *Upernavik, 73 °N*

Site #2: *Upernavik, 73°N*

Site #2: *Upernavik, 73°N*

Recap

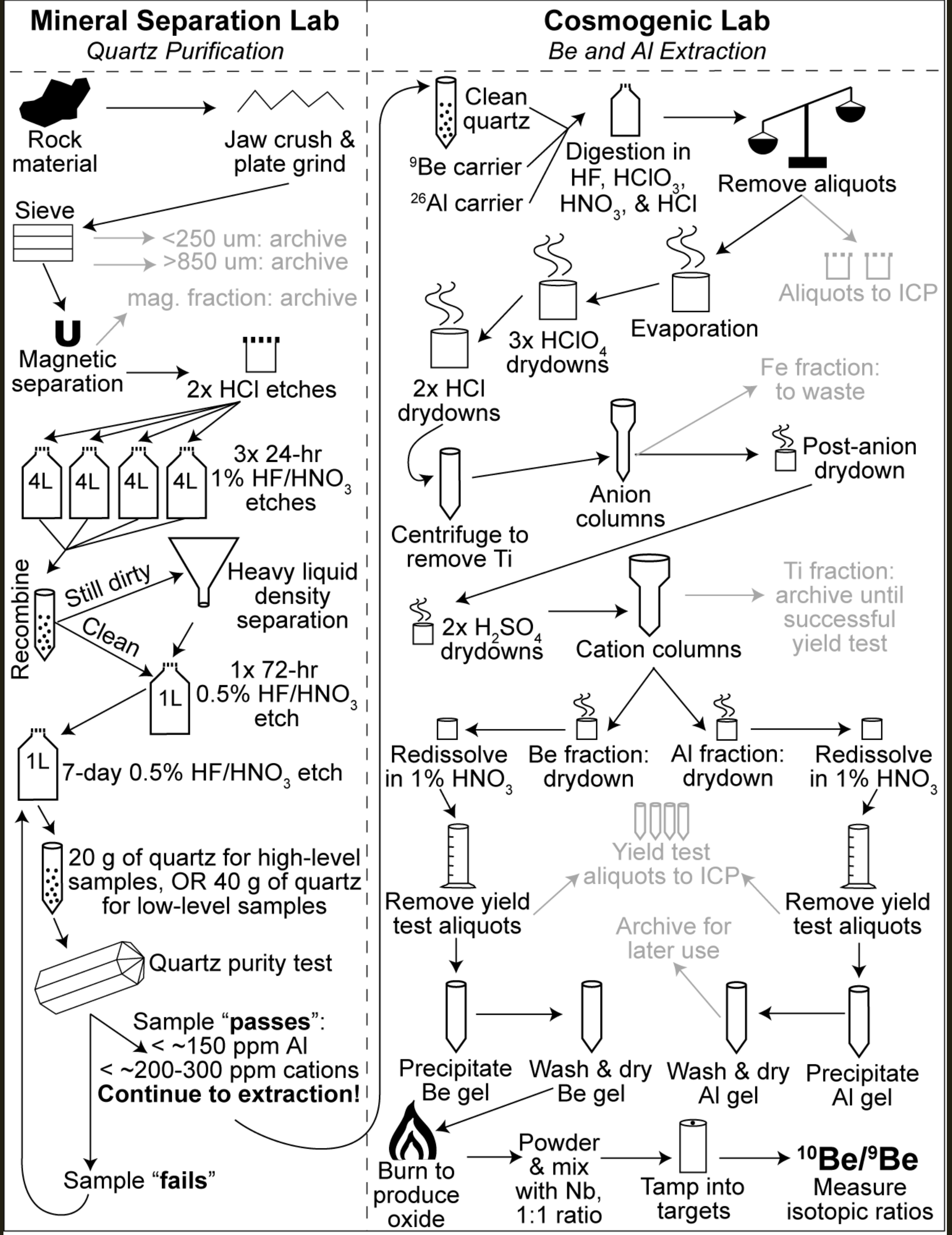
- ^{10}Be and ^{26}Al are radioactive isotopes formed when cosmic rays interact with quartz
- Use the production rate and concentration to calculate an exposure age
- Two study sites in western Greenland: Ilulissat (69°N) and Upernavik (73°N)
- Samples collected in "dipsticks"
- Goal: to understand subglacial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

Thesis Part I: Methodological Development

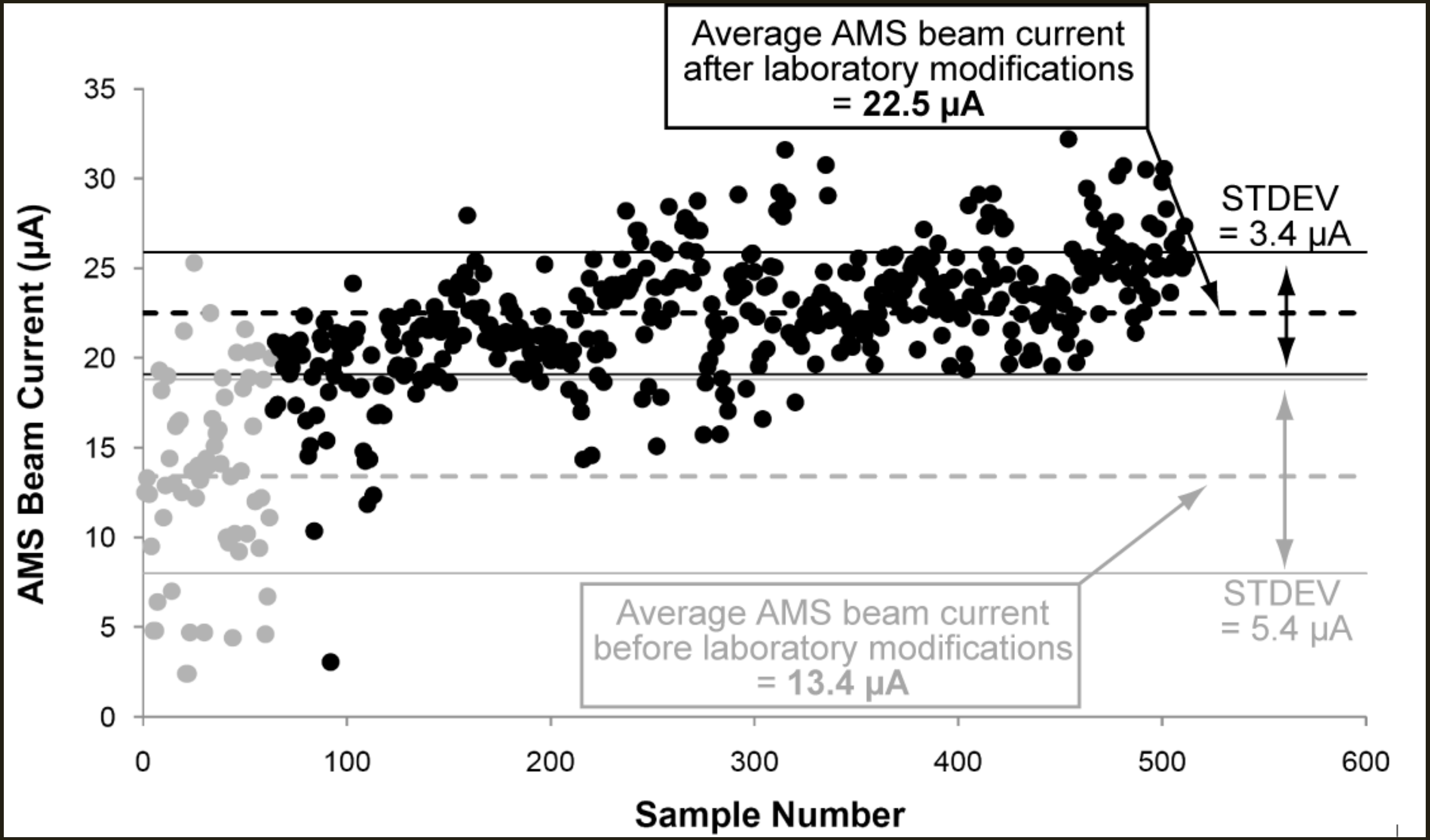
Methodological Limitations

- 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

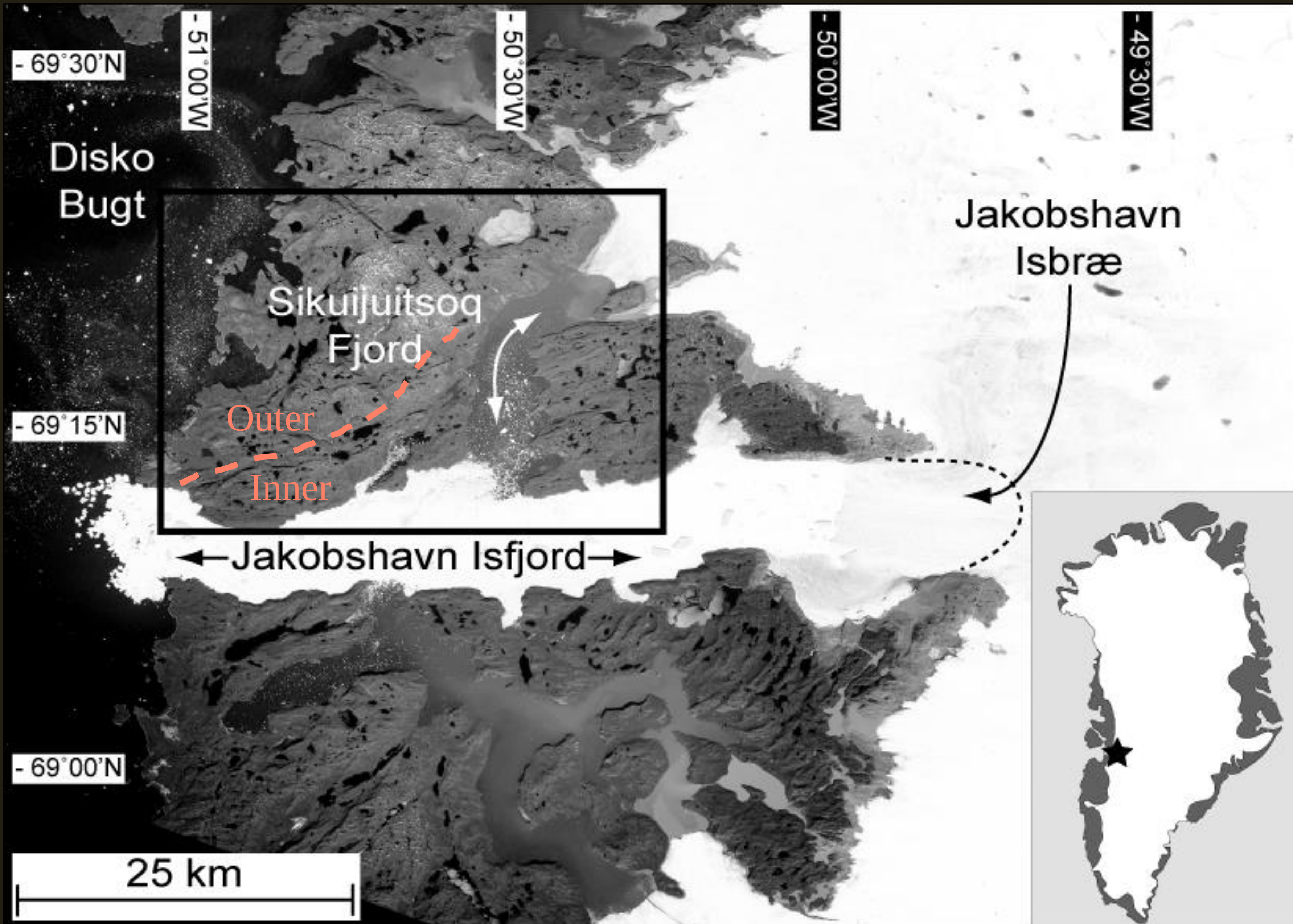
Laboratory Methods



Methodological Optimization

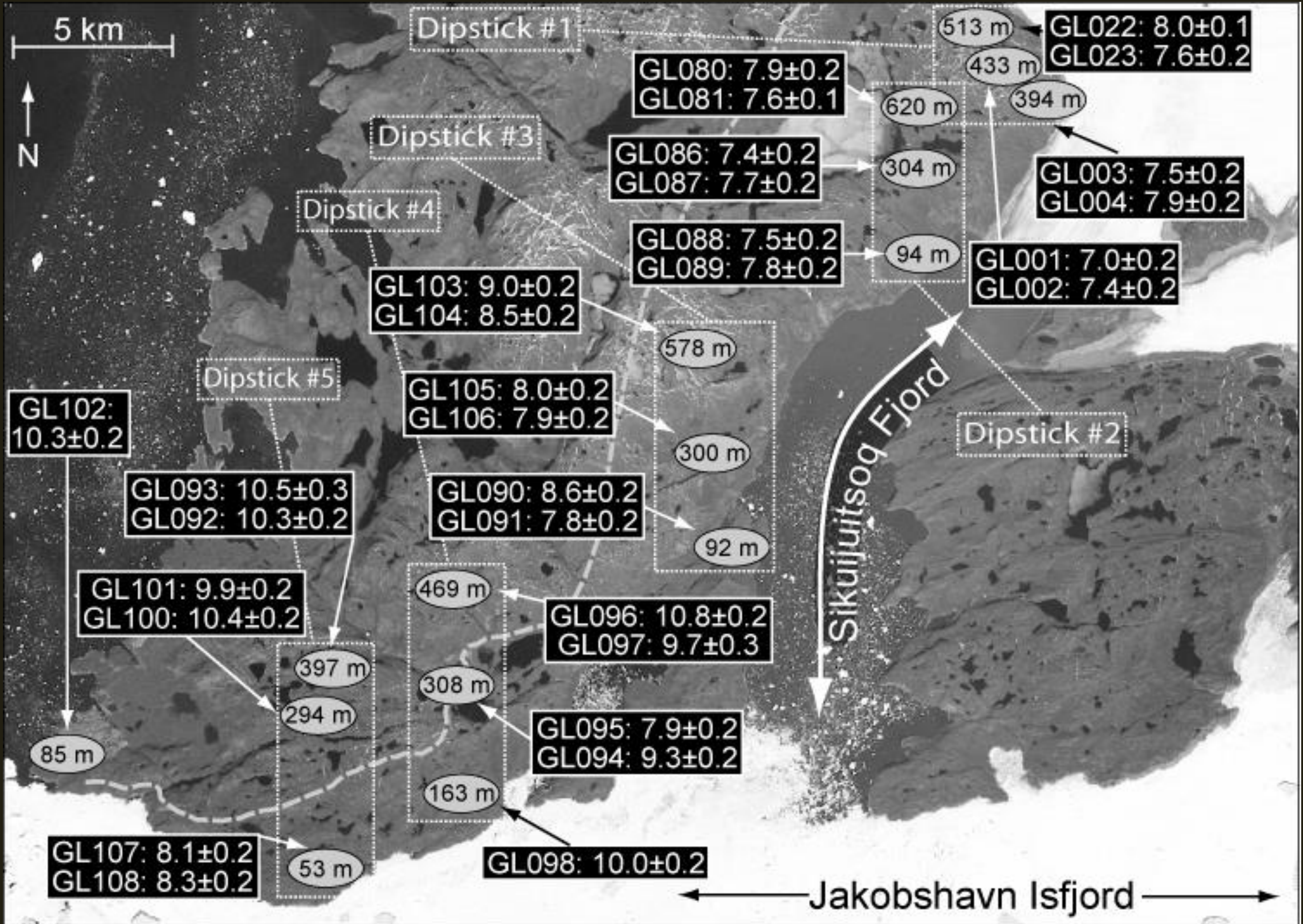


Thesis Part II: Ilulissat, Greenland



(Image courtesy of Landsat, 2000)

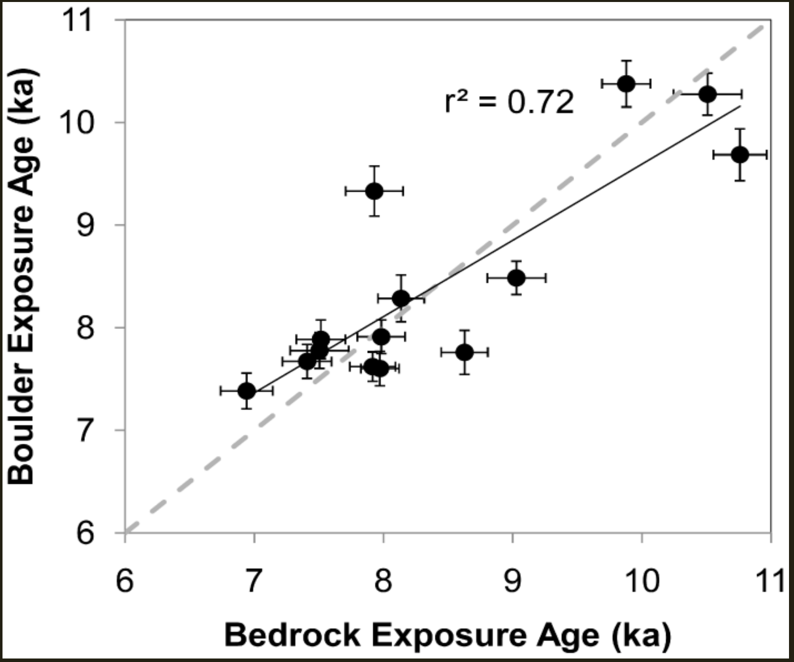
Fjord Stade Moraine



(Image courtesy of Landsat, 2000)

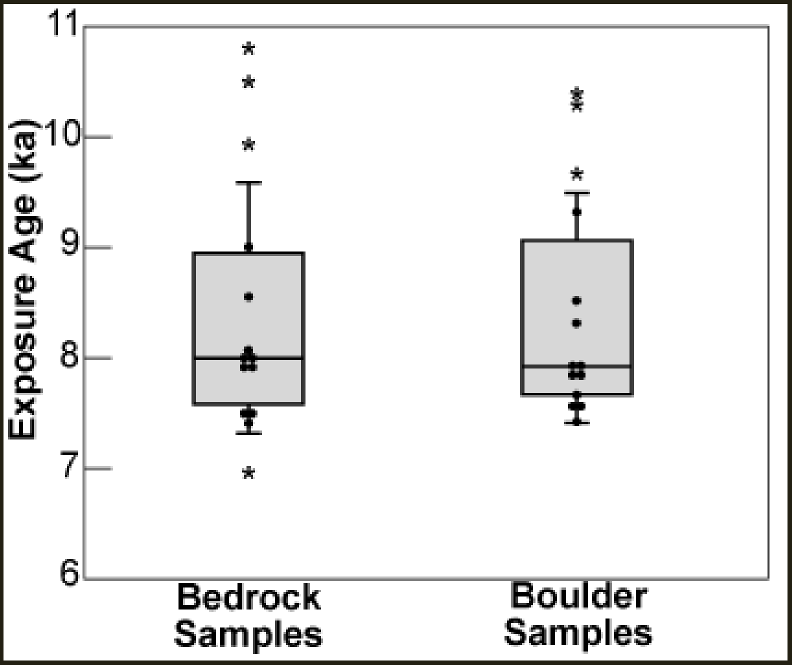
All ages are Holocene

Bedrock/Boulder Comparison

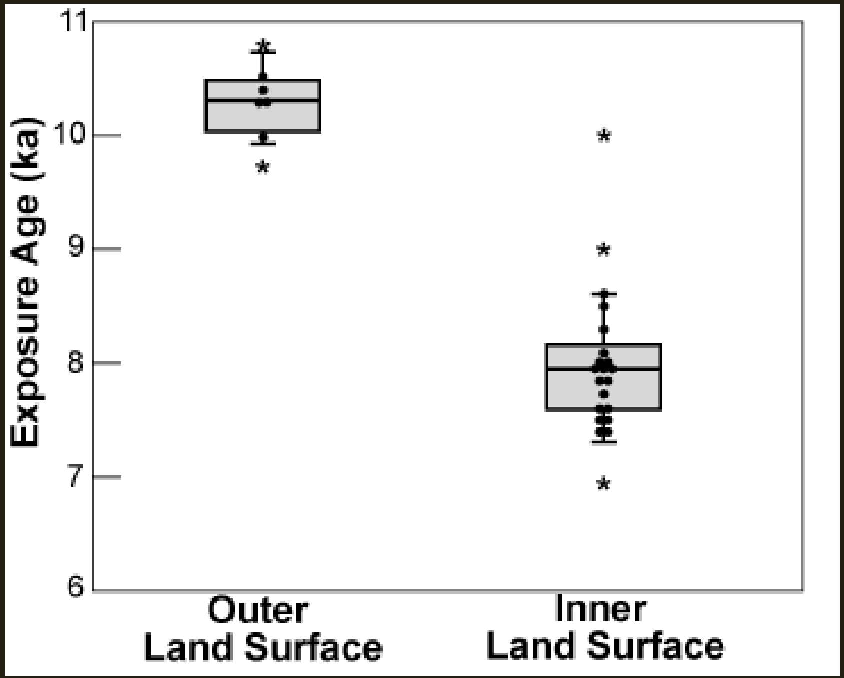


Bedrock and boulder samples are in close agreement

Little or no inheritance
Erosive glacial ice



Complicated Deglaciation Pattern



Age of outer land surface:10.3 ± 0.4 ka (n = 7)

Age of inner land surface: 8.0 ± 0.7 ka (n = 21)

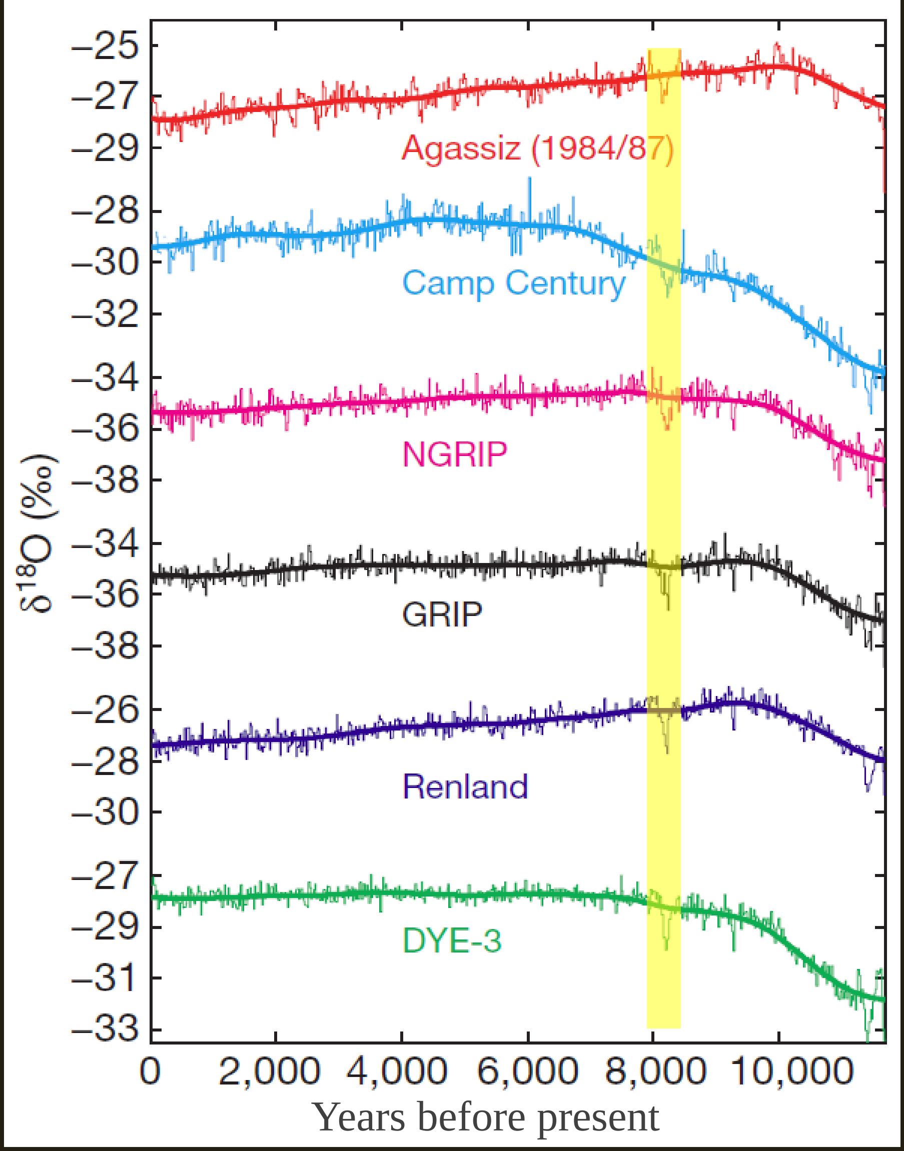
Just inside moraine: 8.2 ± 0.1 ka (n = 2)

Complicated deglaciation pattern!

Age of the Fjord Stade moraine is ~8.2 ka

Part II: Ilulissat, Greenland

Formation of the Fjord Stade Moraine



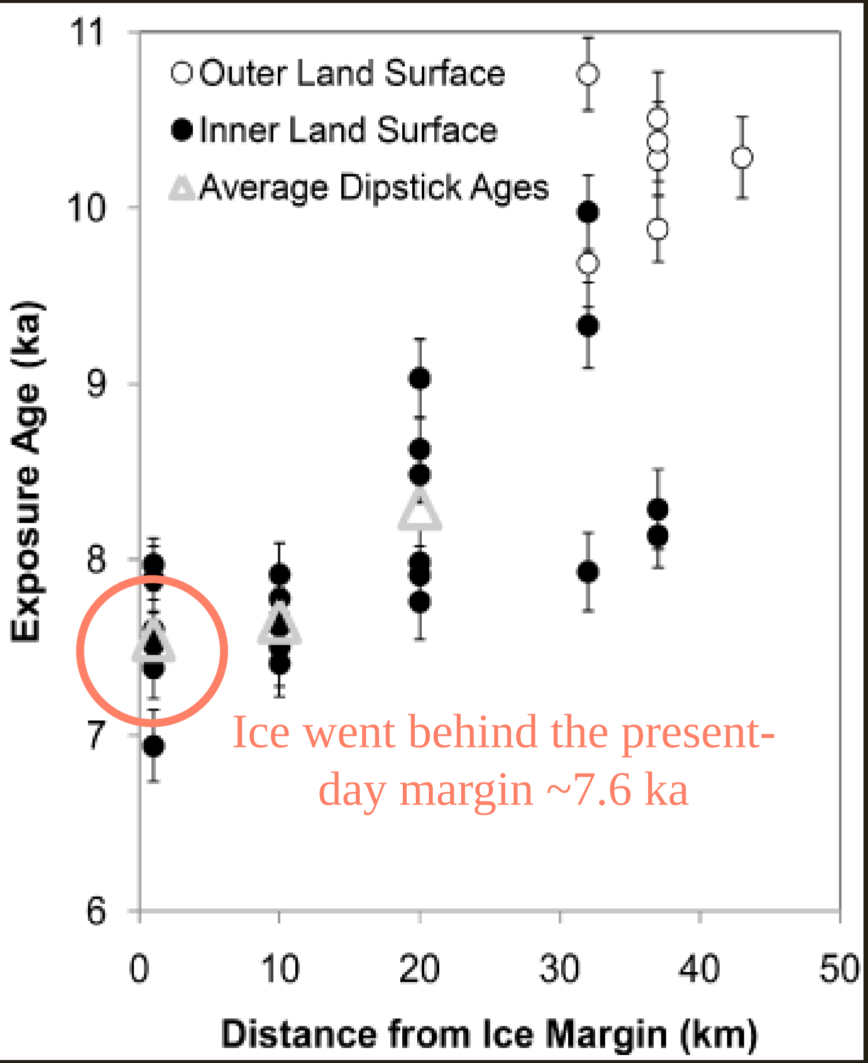
Fjord Stade moraine formed due to an ice margin re-advance in association with the "8200 Event"

Spatial Variability of Exposure Ages

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

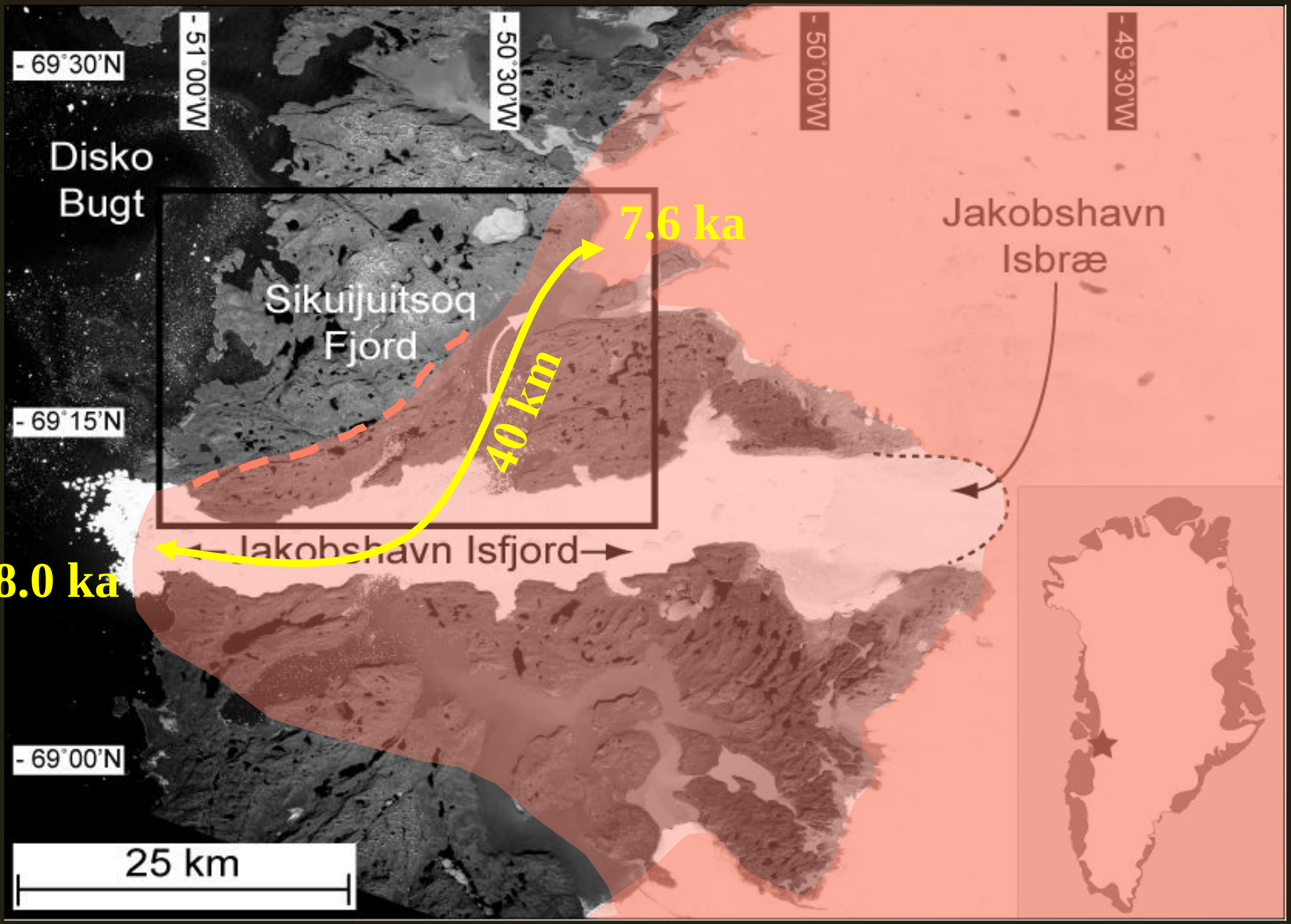
The ice sheet thinned rapidly, at rates greater than what we can detect within the uncertainties associated with ^{10}Be dating.

Spatial Variability of Exposure Ages



How do we quantify ice margin retreat rates?

Ice Margin Retreat



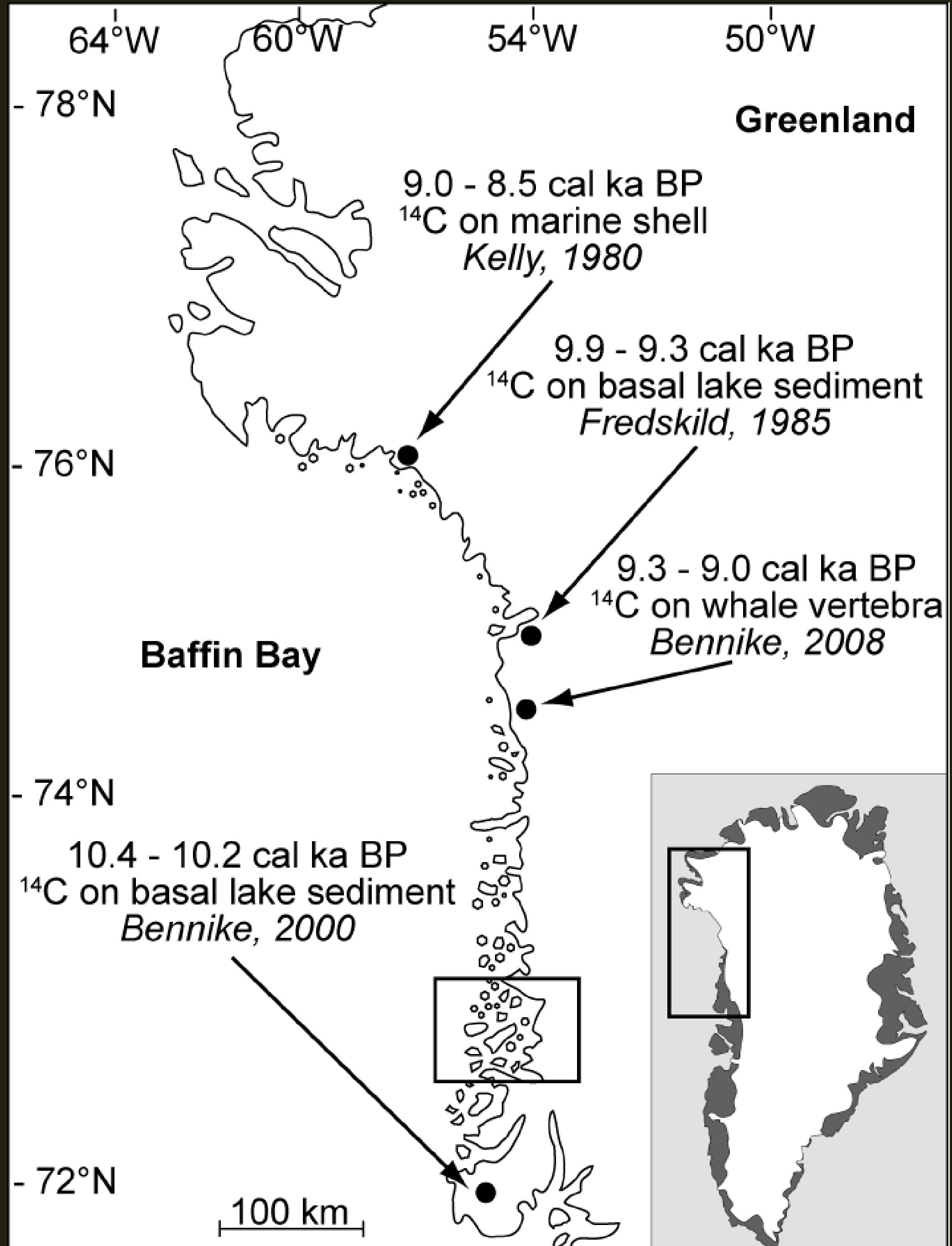
Retreat rate estimate:

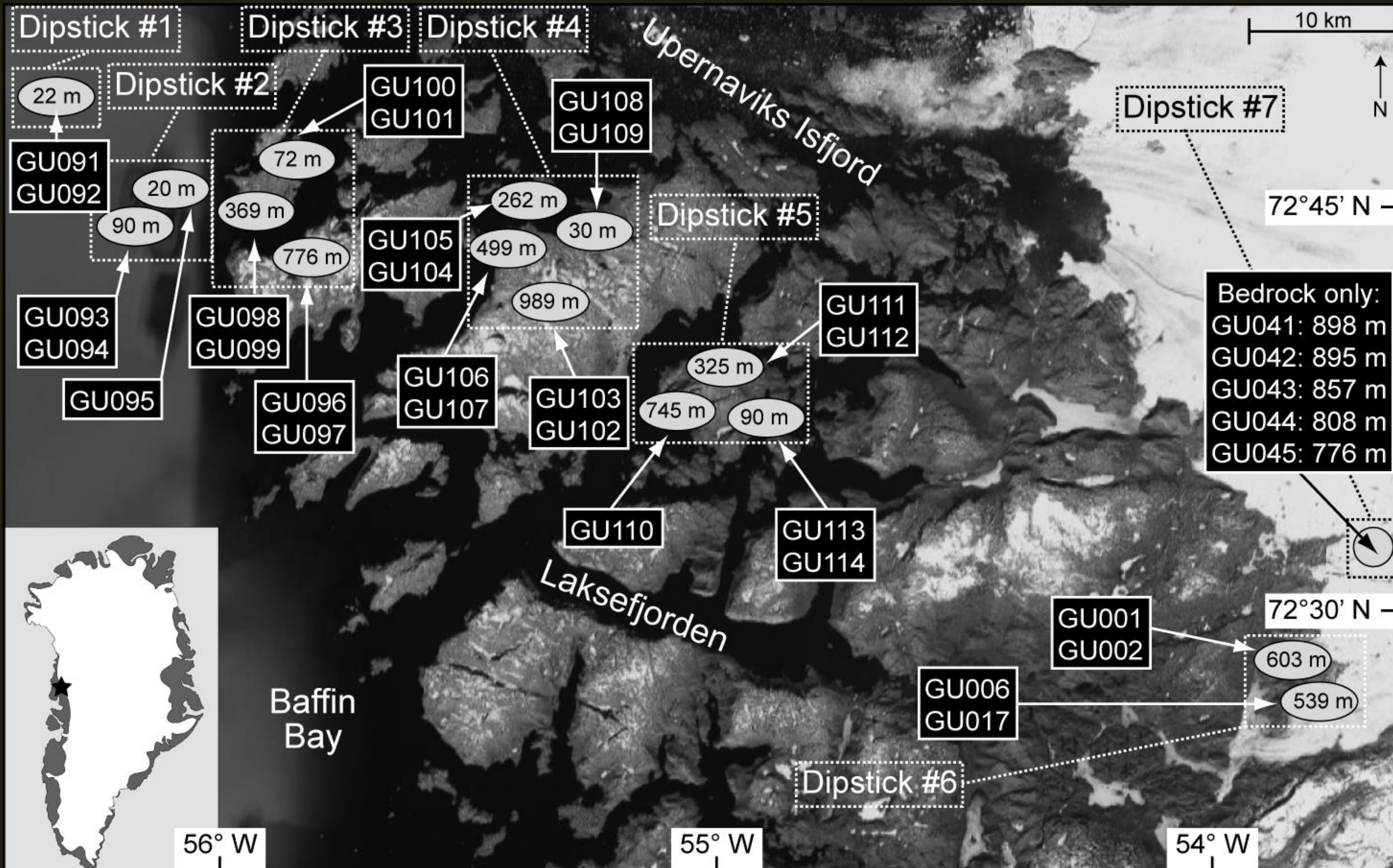
40 km of retreat in 400 yrs ≈ 100 m/yr

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

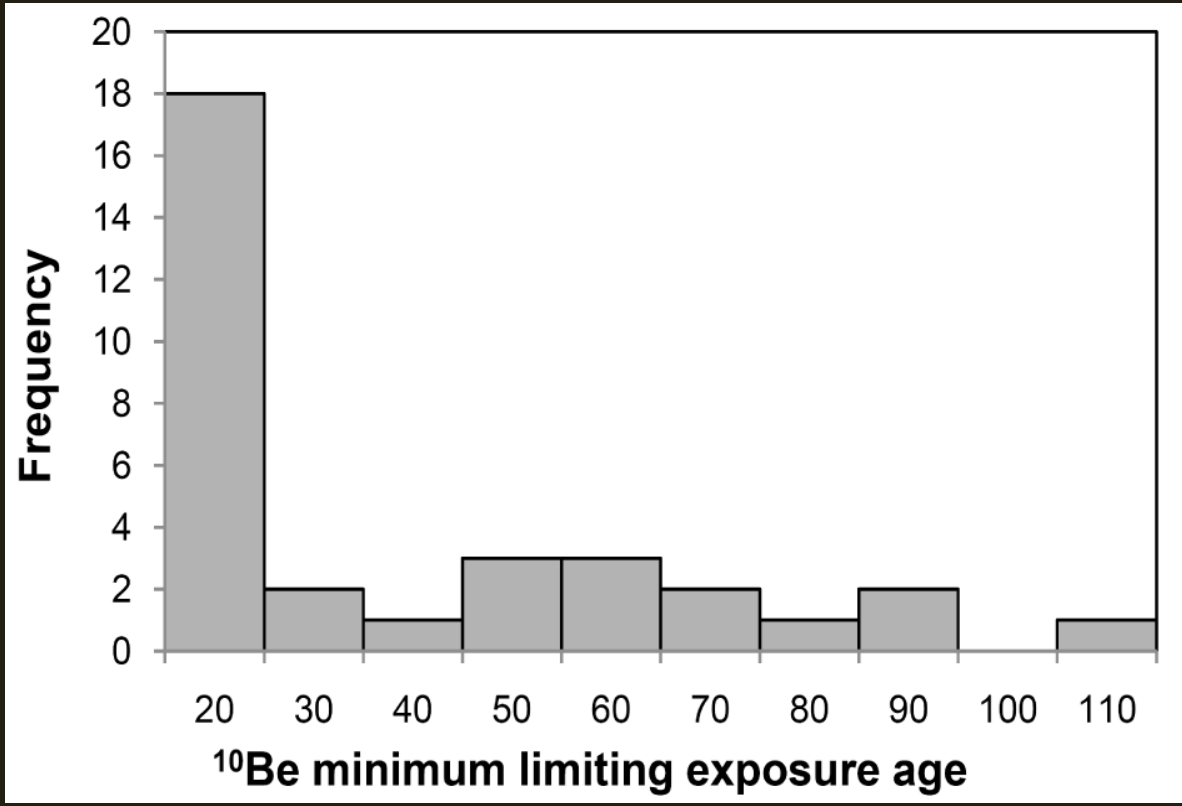
Thesis Part III: Upernavik, Greenland


64°W
60°W
54°W
50°W
78°N
76°N
74°N
72°N
Greenland
9.0 - 8.5 cal ka BP
14C on marine shell
Kelly, 1980
9.9 - 9.3 cal ka BP
14C on basal lake sediment
Fredskild, 1985
9.3 - 9.0 cal ka BP
14C on whale vertebra
Bennike, 2008
Baffin Bay
10.4 - 10.2 cal ka BP
14C on basal lake sediment
Bennike, 2000
100 km



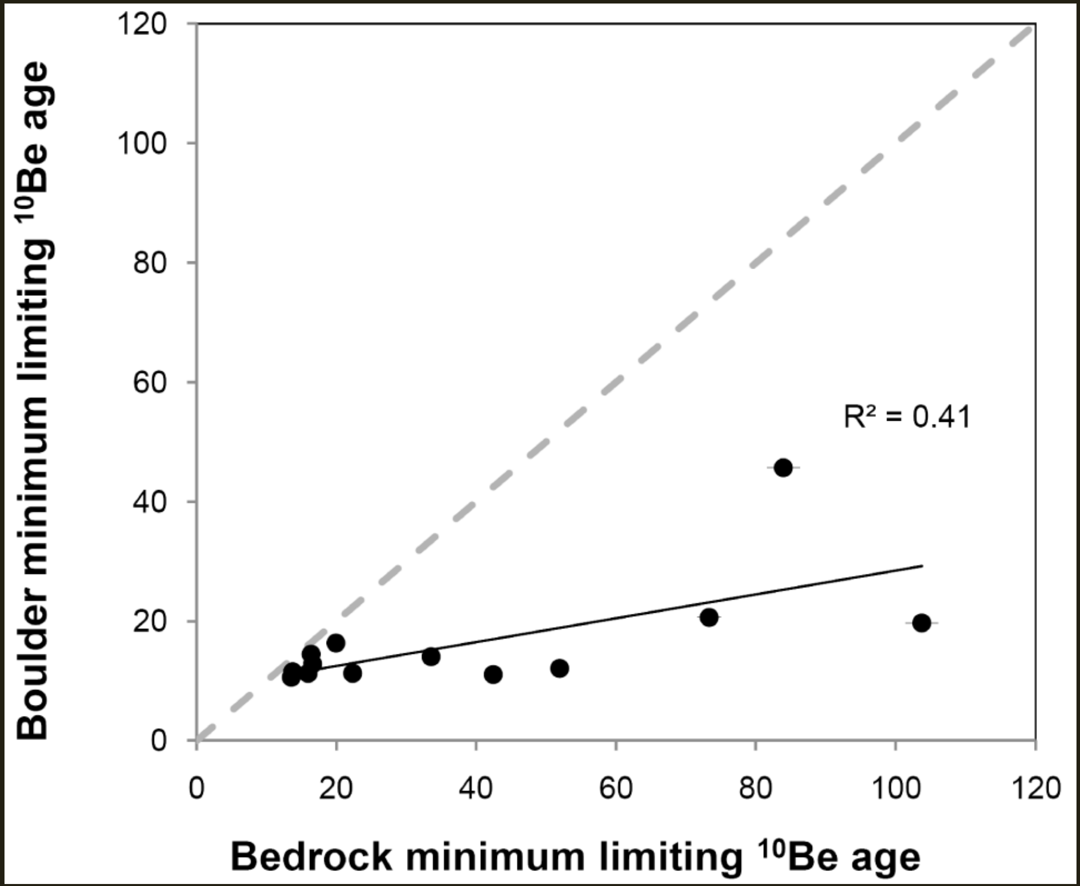
Dipstick #1
22 m
GU091
GU092
Dipstick #2
20 m
90 m
GU093
GU094
GU095
Dipstick #3
GU100
GU101
72 m
369 m
776 m
GU098
GU099
GU096
GU097
Dipstick #4
GU108
GU109
262 m
30 m
GU105
GU104
499 m
989 m
GU106
GU107
GU103
GU102
Upernaviks Isfjord
Dipstick #5
GU111
GU112
325 m
745 m
90 m
GU110
GU113
GU114
Laksefjorden
Baffin
Bay
10 km
N
Dipstick #7
72°45' N
Bedrock only:
GU041: 898 m
GU042: 895 m
GU043: 857 m
GU044: 808 m
GU045: 776 m
72°30' N
GU001
GU002
603 m
GU006
GU017
539 m
Dipstick #6
56° W
55° W
54° W

Sample Ages



Something is going on here… why do we have such old exposure ages?

Bedrock/Boulder Comparison



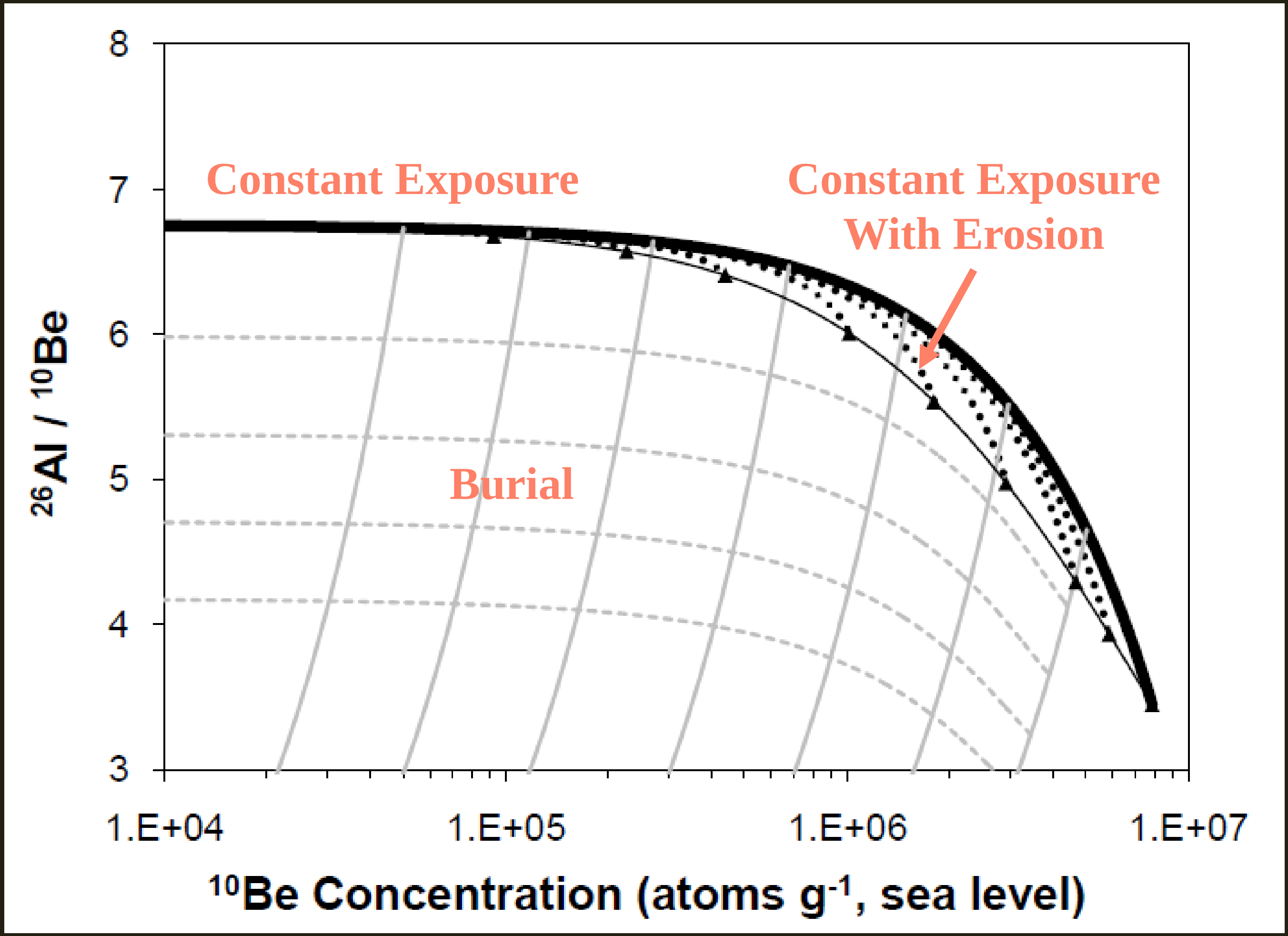
Bedrock samples are much older than paired boulder samples; inheritance is present. Glacial ice is non-erosive or weakly erosive.

Using Cosmogenic ^{26}Al

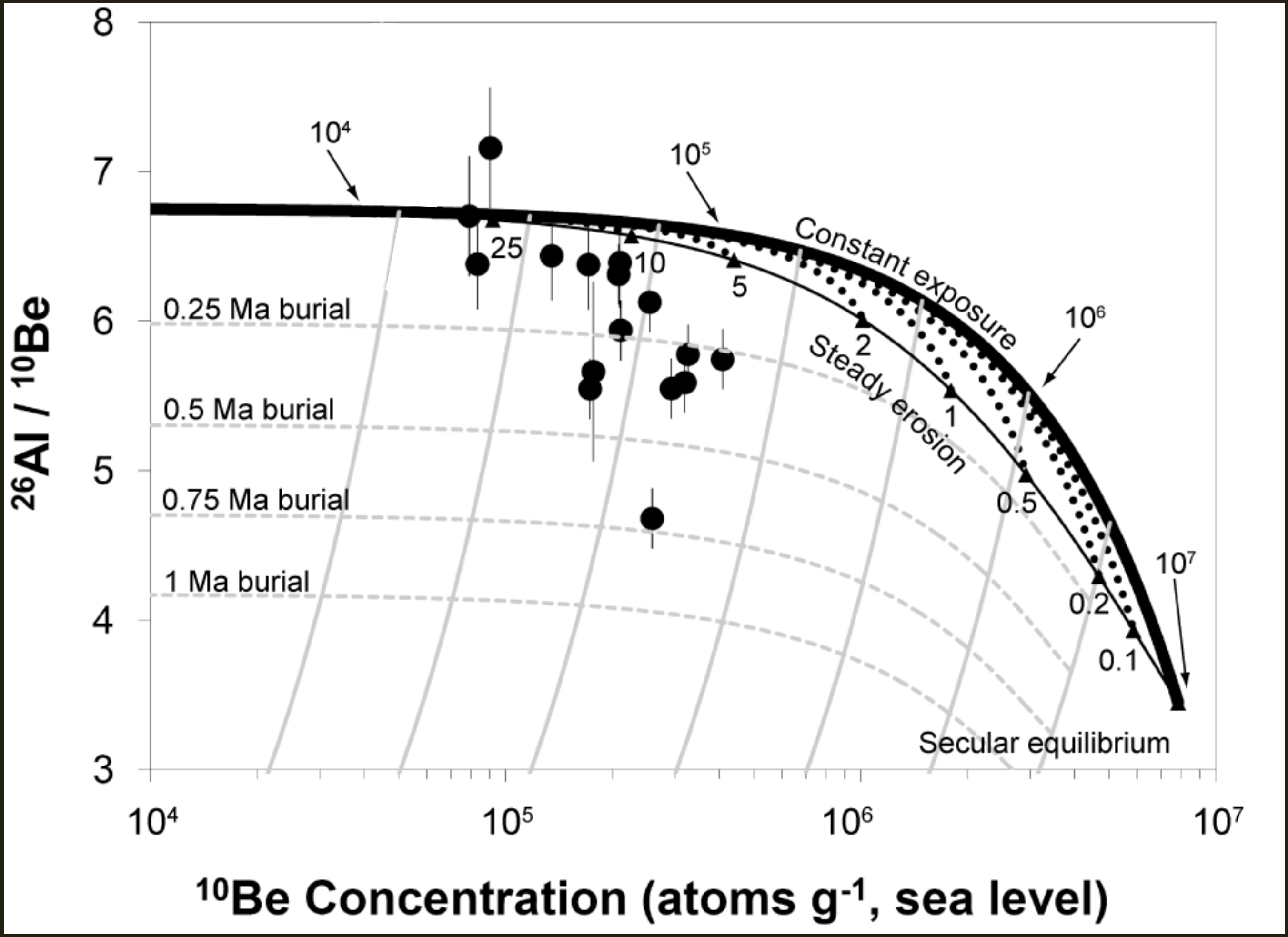
- Higher production rate than ^{10}Be
- Shorter half-life than ^{10}Be
- The two isotopes behave differently when burial occurs and production ceases

Part III: Upernavik, Greenland

The Two-Isotope Plot



The Two-Isotope Plot



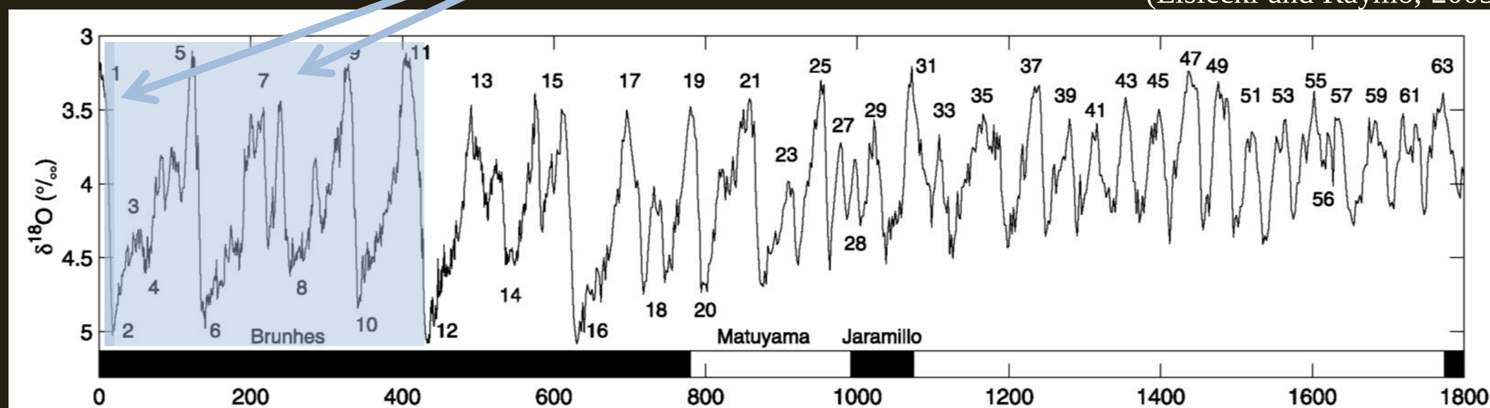
Samples have experienced both exposure and burial. They have long total histories.

Landscape History

Landscape history represented
by Upernavik samples
by Ilulissat samples

Warmer

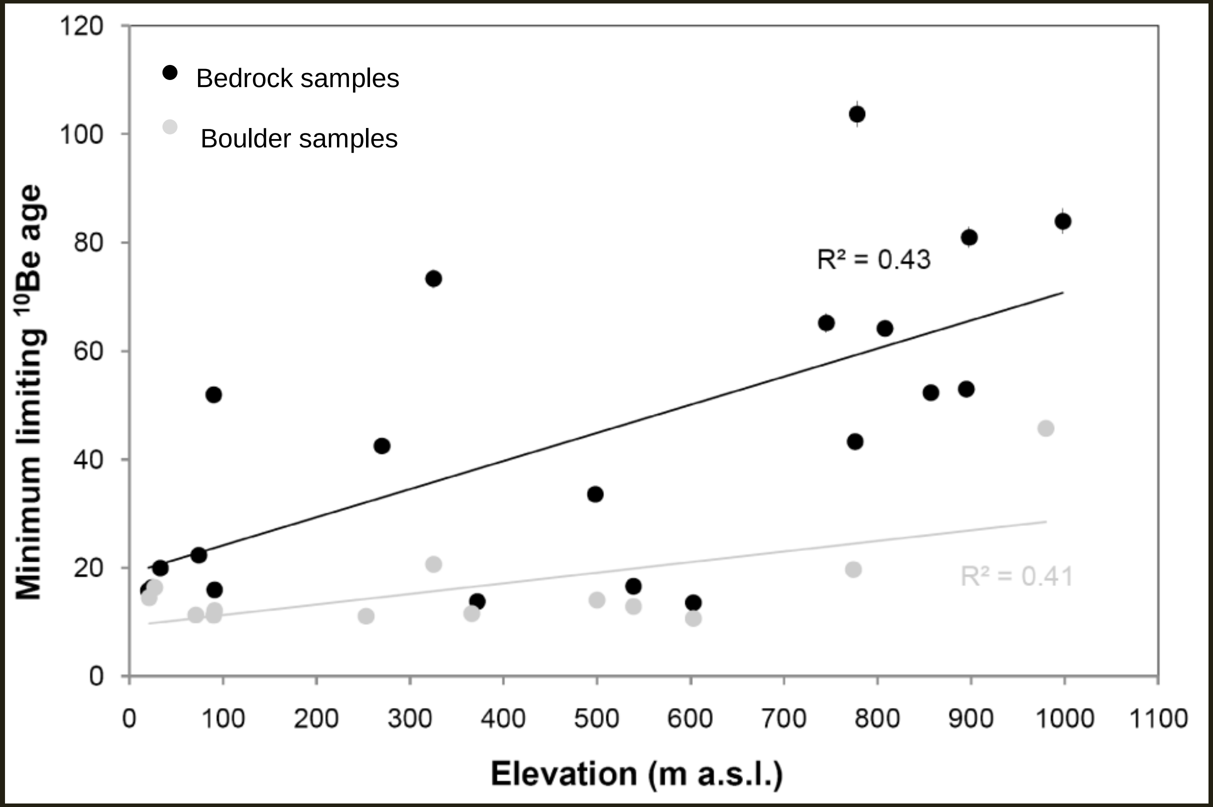
(Lisiecki and Raymo, 2005)



Colder

Part III: Upernavik, Greenland

Inheritance and Elevation

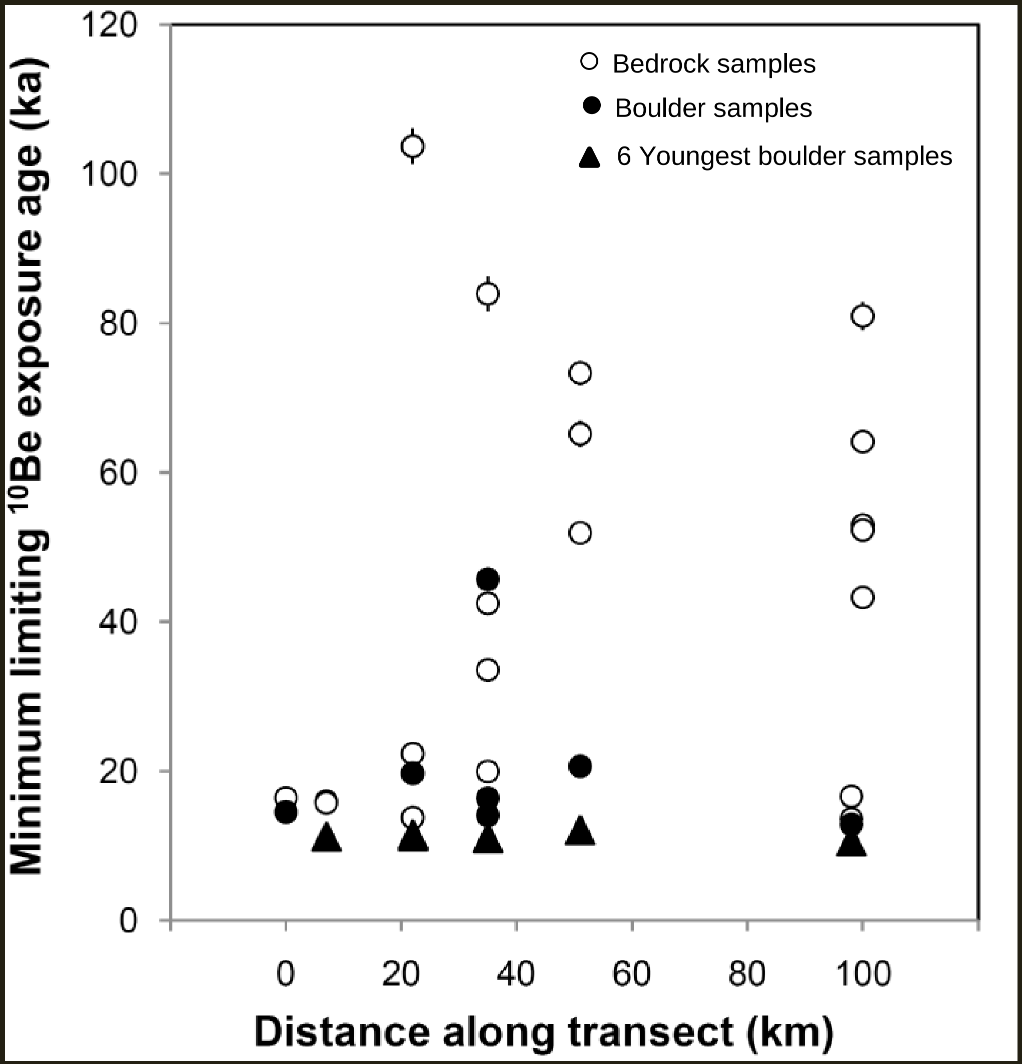


There is more inheritance at higher elevations. High-elevation ice is less erosive.

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

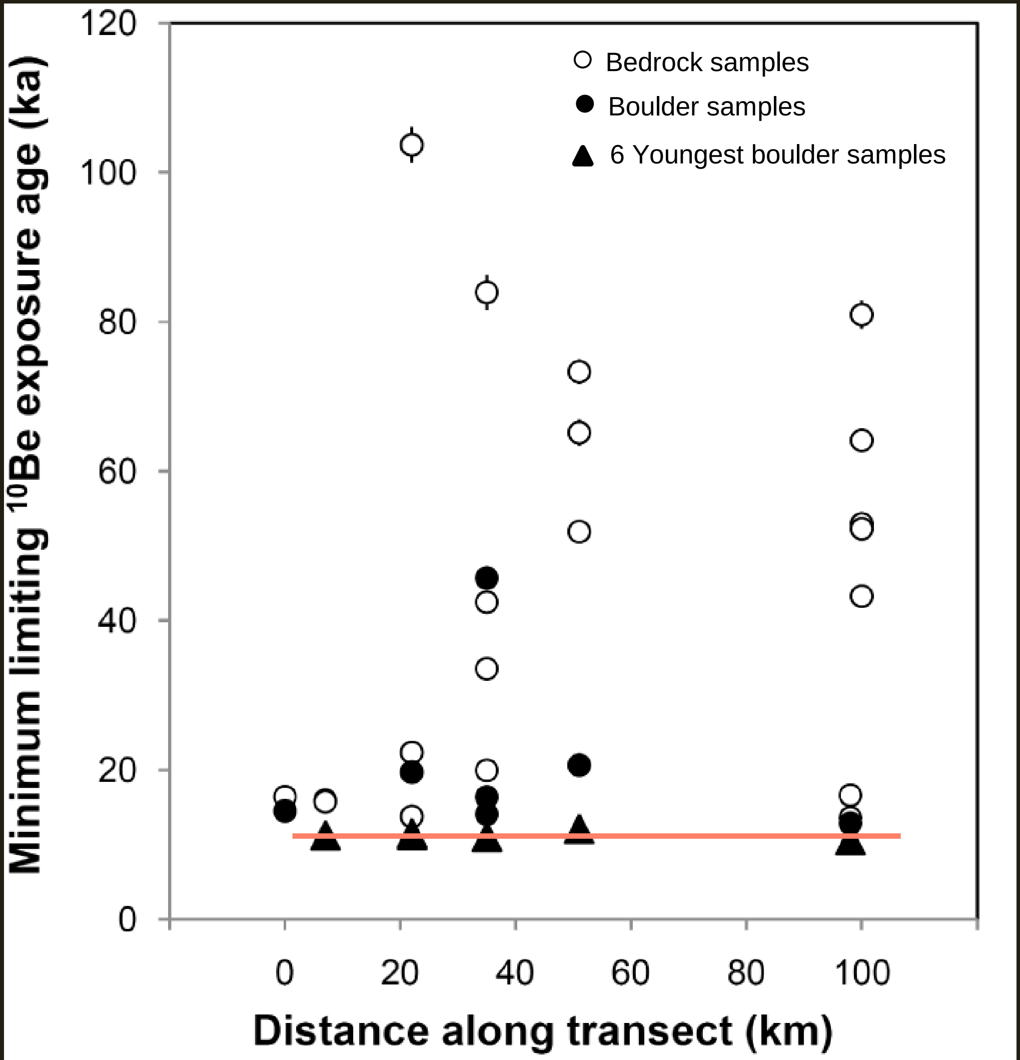
Spatial Variability of Exposure Ages



How do we quantify ice margin retreat rates?

Part III: Upernavik, Greenland

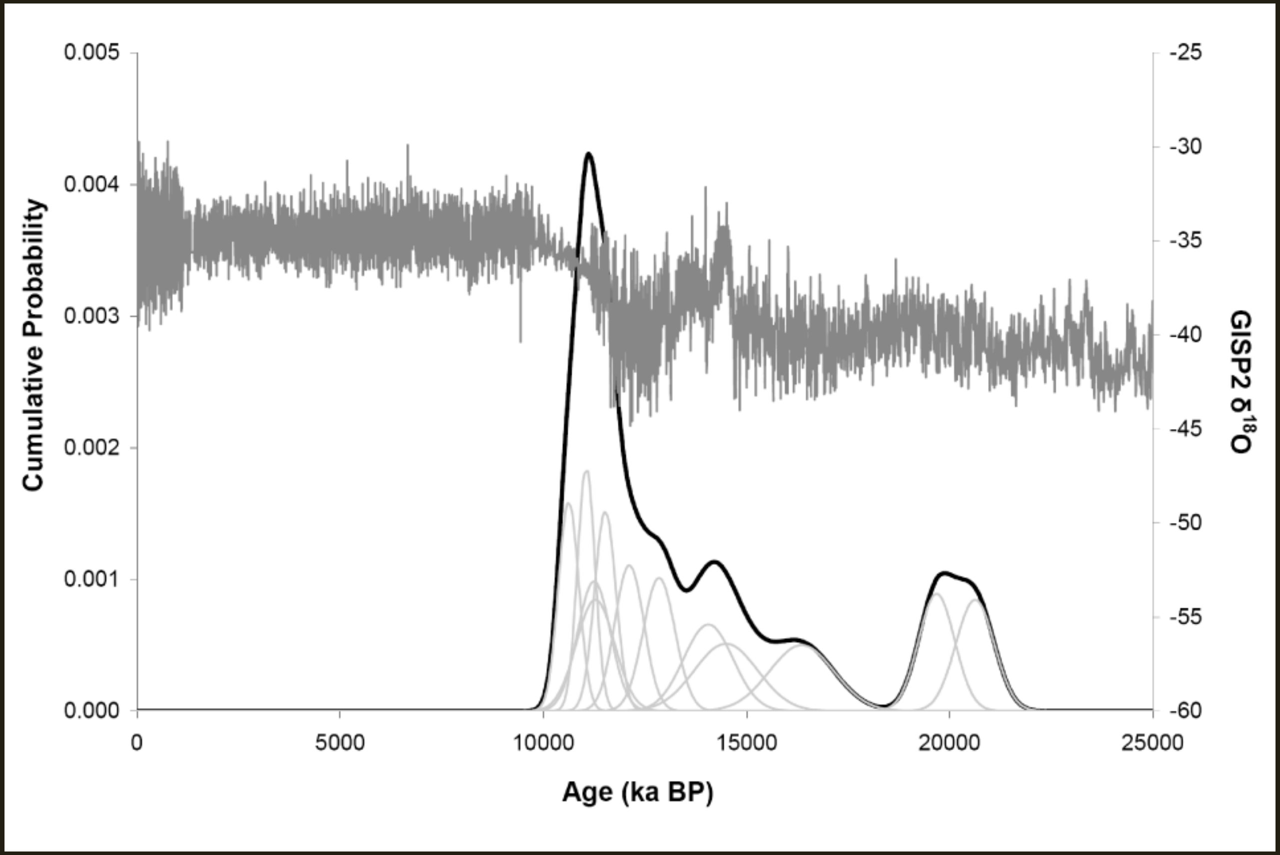
Spatial Variability of Exposure Ages



6 youngest samples have statistically indistinguishable ages of 11.3 ± 0.5 ka

Numerical modeling yields a statistically most likely retreat rate of ~170 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 ~11.3 ± 0.5 ka
- Ice retreated at ~170 m/yr
- Rapid ice retreat may have coincided with warming after the Younger Dryas

Conclusions
&
The Big Picture

Comparisons Between Sites

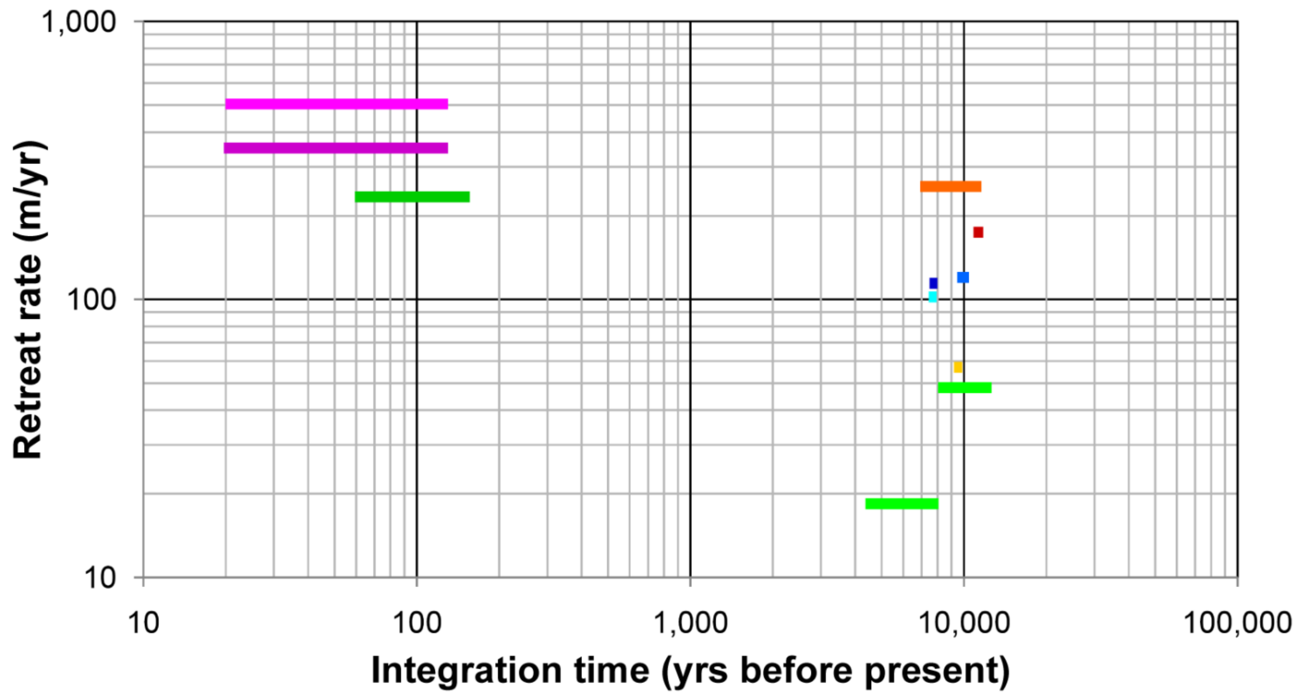
ILULISSAT	UPERNAVIK

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



= Sikuijuitsoq 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

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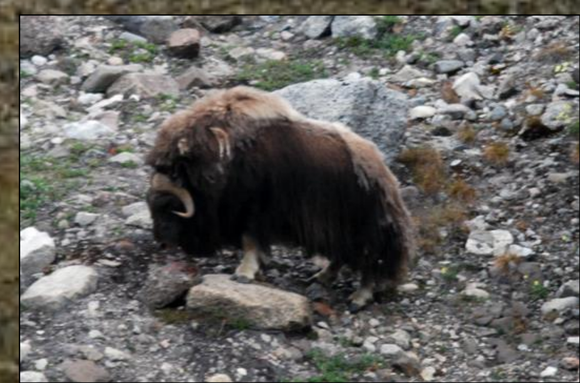

Burial Scenarios