Using *in situ* ^{10}Be as a sediment source tracer in Greenland's paraglacial environment

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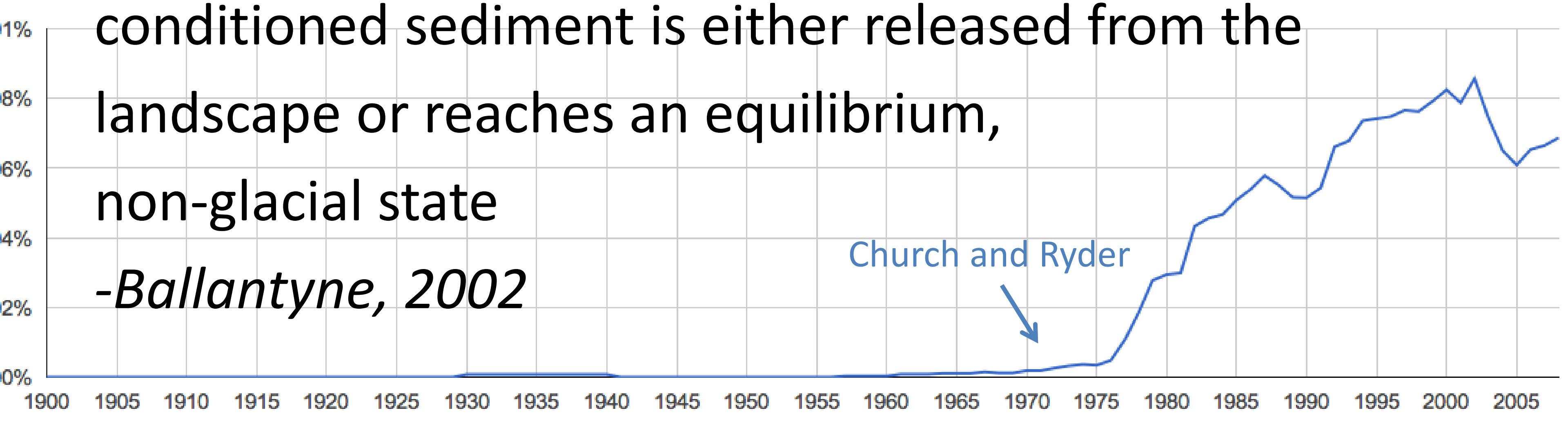
the *paraglacial* environment

An exposed landscape subject to rapid change by glacial and non-glacial processes acting upon a landscape conditioned by glaciation

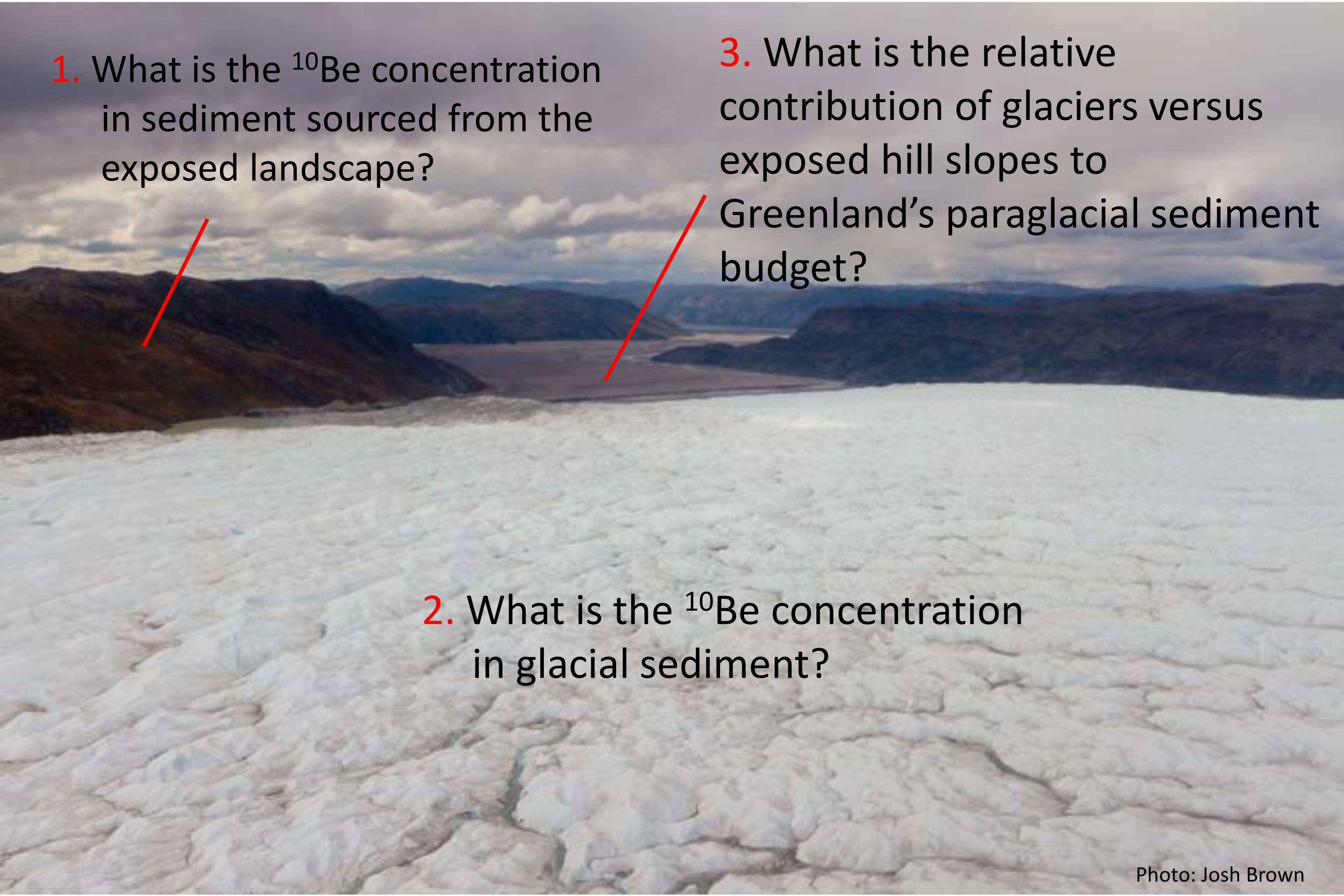
-Church and Ryder, 1972

…existing within a timeframe over which glacially conditioned sediment is either released from the landscape or reaches an equilibrium, non-glacial state

-Ballantyne, 2002



Research Goals



1. What is the ^{10}Be concentration in sediment sourced from the exposed landscape?

3. What is the relative contribution of glaciers versus exposed hill slopes to Greenland's paraglacial sediment budget?

2. What is the ^{10}Be concentration in glacial sediment?

Photo: Josh Brown

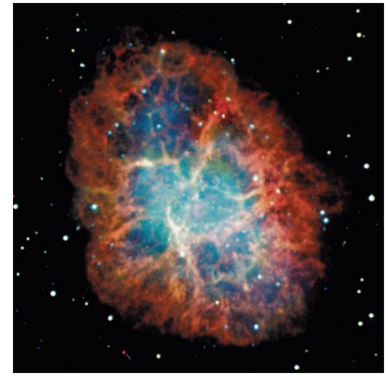
Talk Outline

- Background
  - *In situ* produced cosmogenic ^{10}Be
  - Glacial history of Greenland
  - Sediment sources on Greenland
- Methods
  - Field sites
  - Sample collection and processing
- Data analysis/Results
  - Part I: ^{10}Be as a source tracer
  - Part II: ^{10}Be as a dosimeter of exposure
- Interpretations
- Conclusions
- Implications for future research

Background: *in situ* cosmogenic ^{10}Be

What are cosmic rays?

High speed particles (mostly protons) that originate in super novas



Nasa.gov

As they approach the earth they collide with one another – creating a shower of *protons*, *neutrons*, and *muons*

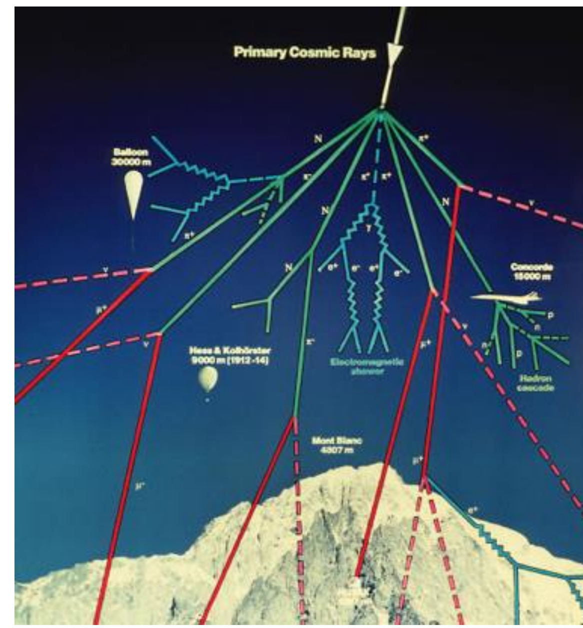
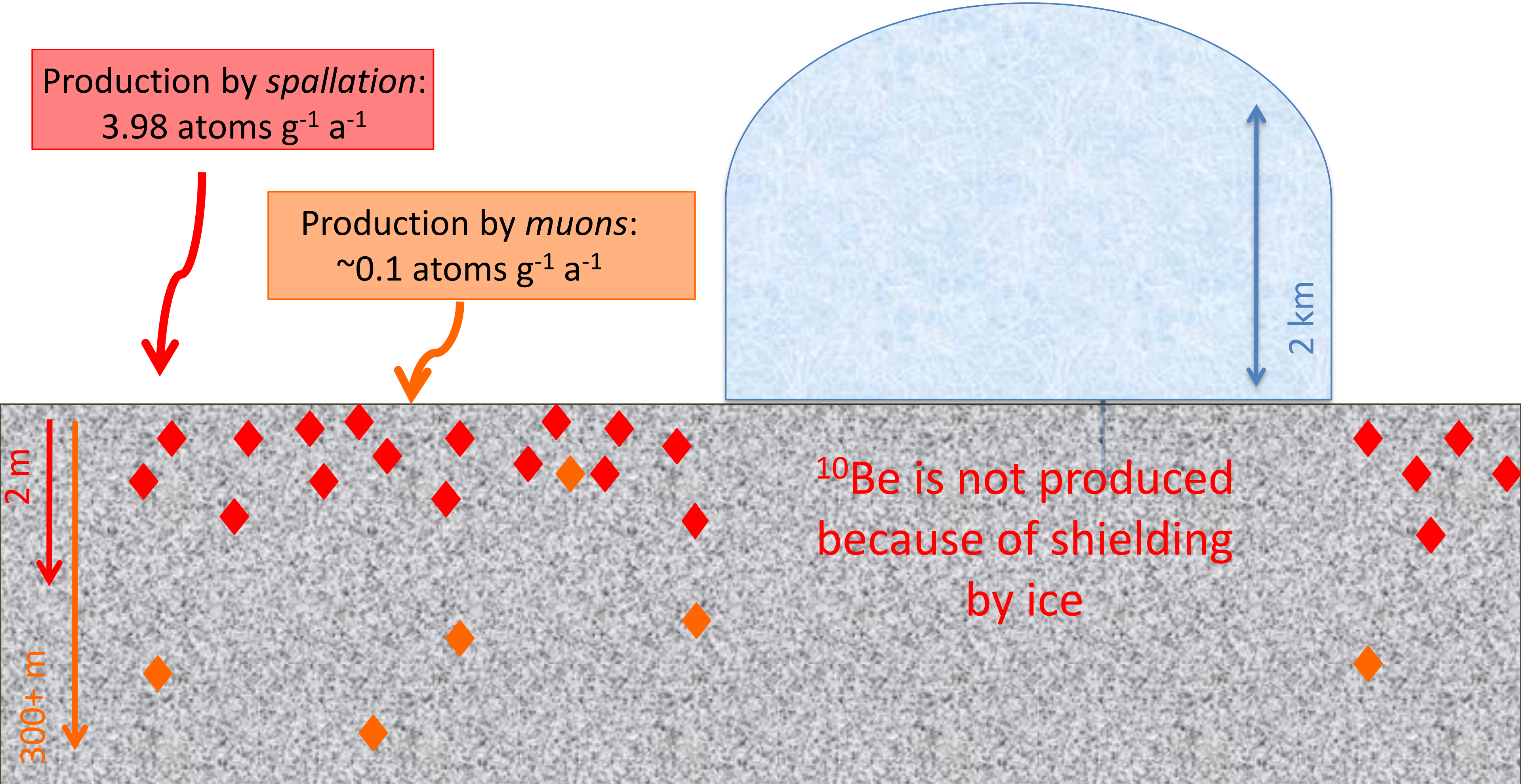


Diagram from CERN

Many are attenuated in Earth's atmosphere, some reach the Earth where they change matter isotopically

Background: *in situ* cosmogenic ^{10}Be

^{10}Be is produced in near surface rocks and sediments because of terrestrial exposure to cosmic rays



Background: *in situ* cosmogenic ^{10}Be

In bedrock and boulders

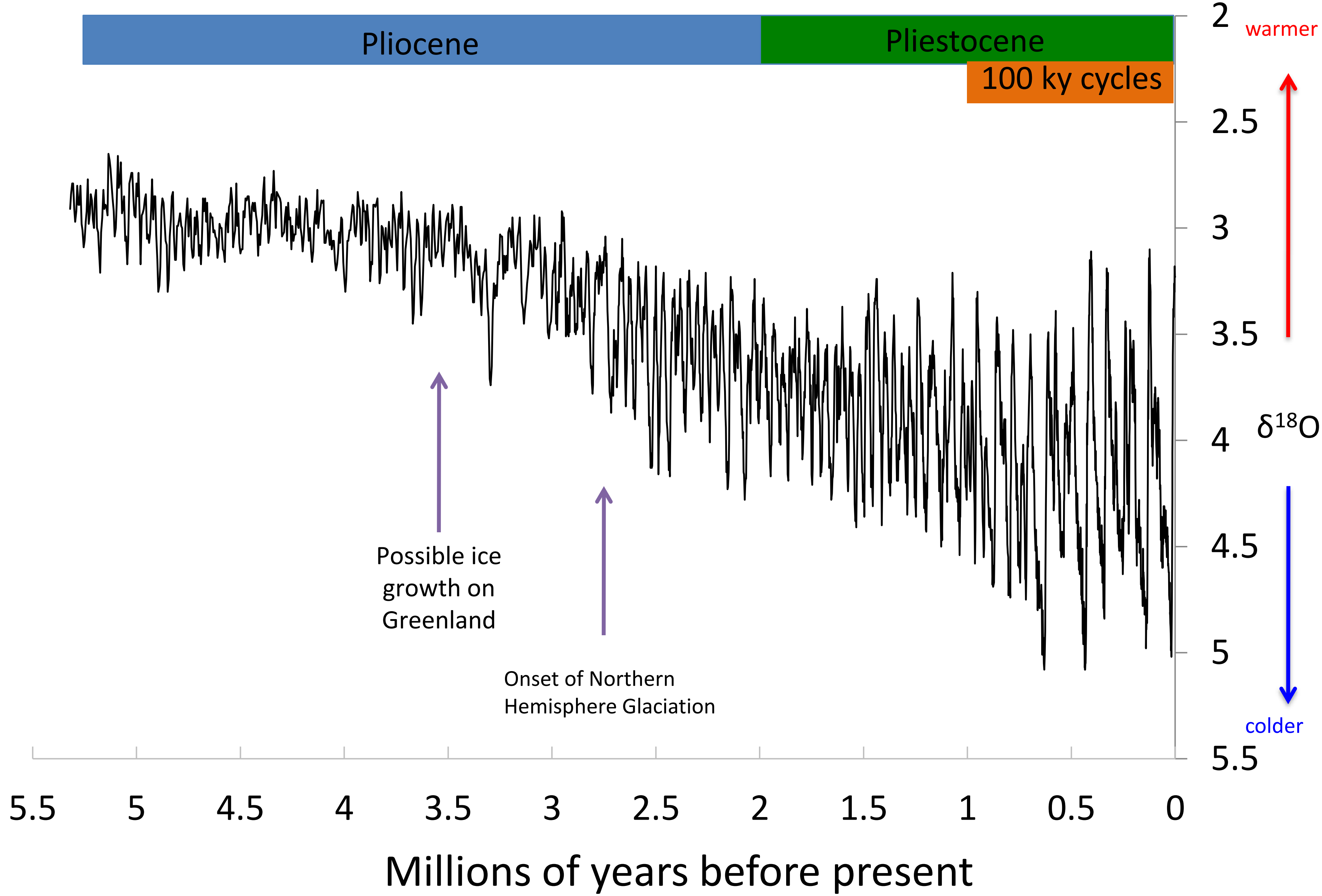
^{10}Be concentration can be used to date ice retreat

Background: *in situ* cosmogenic ^{10}Be

In sediment

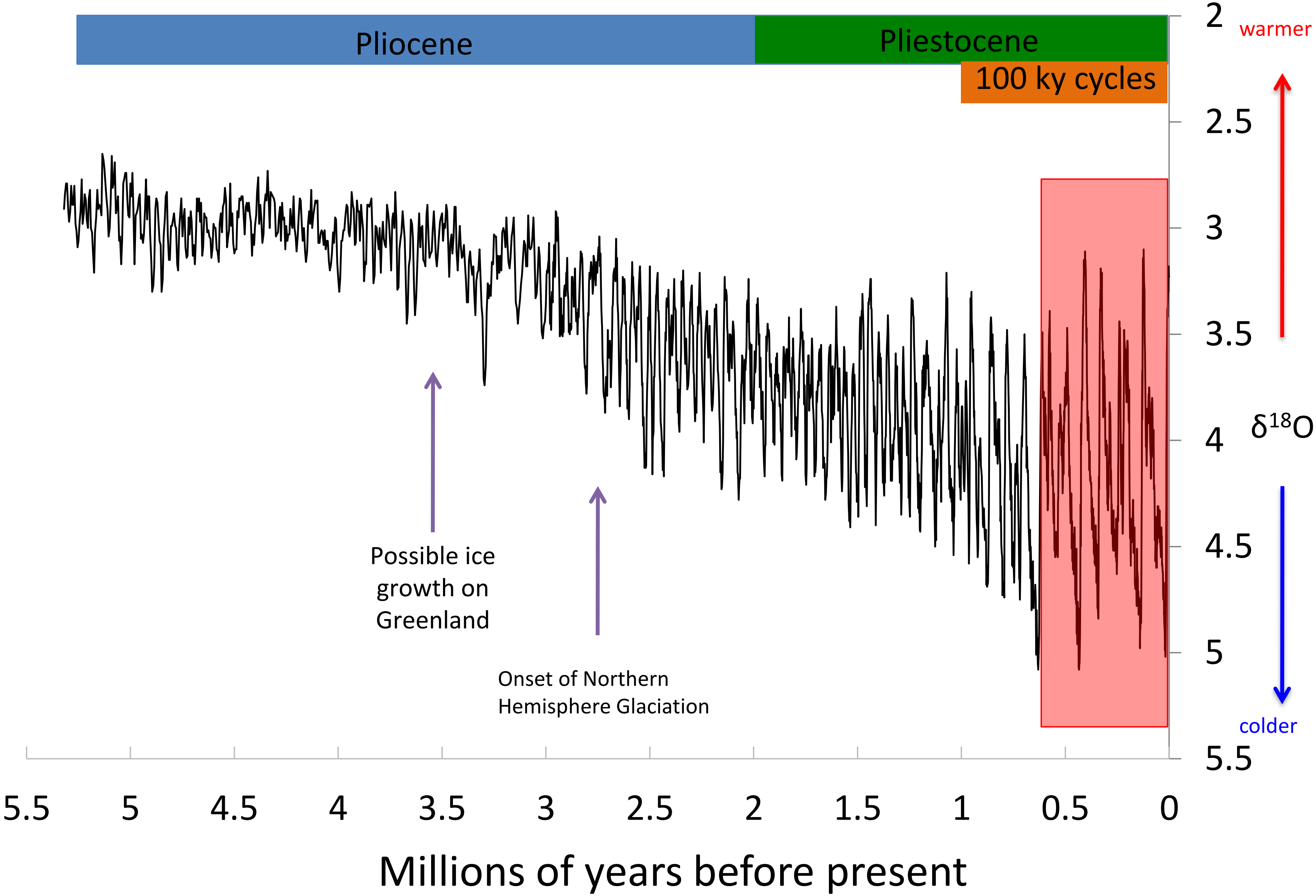
^{10}Be concentration is a cosmic ray dosimeter - if different sediment sources have different characteristic concentrations of ^{10}Be, isotope concentration can be used as a *tracer*

Background: *Glacial history of Greenland*



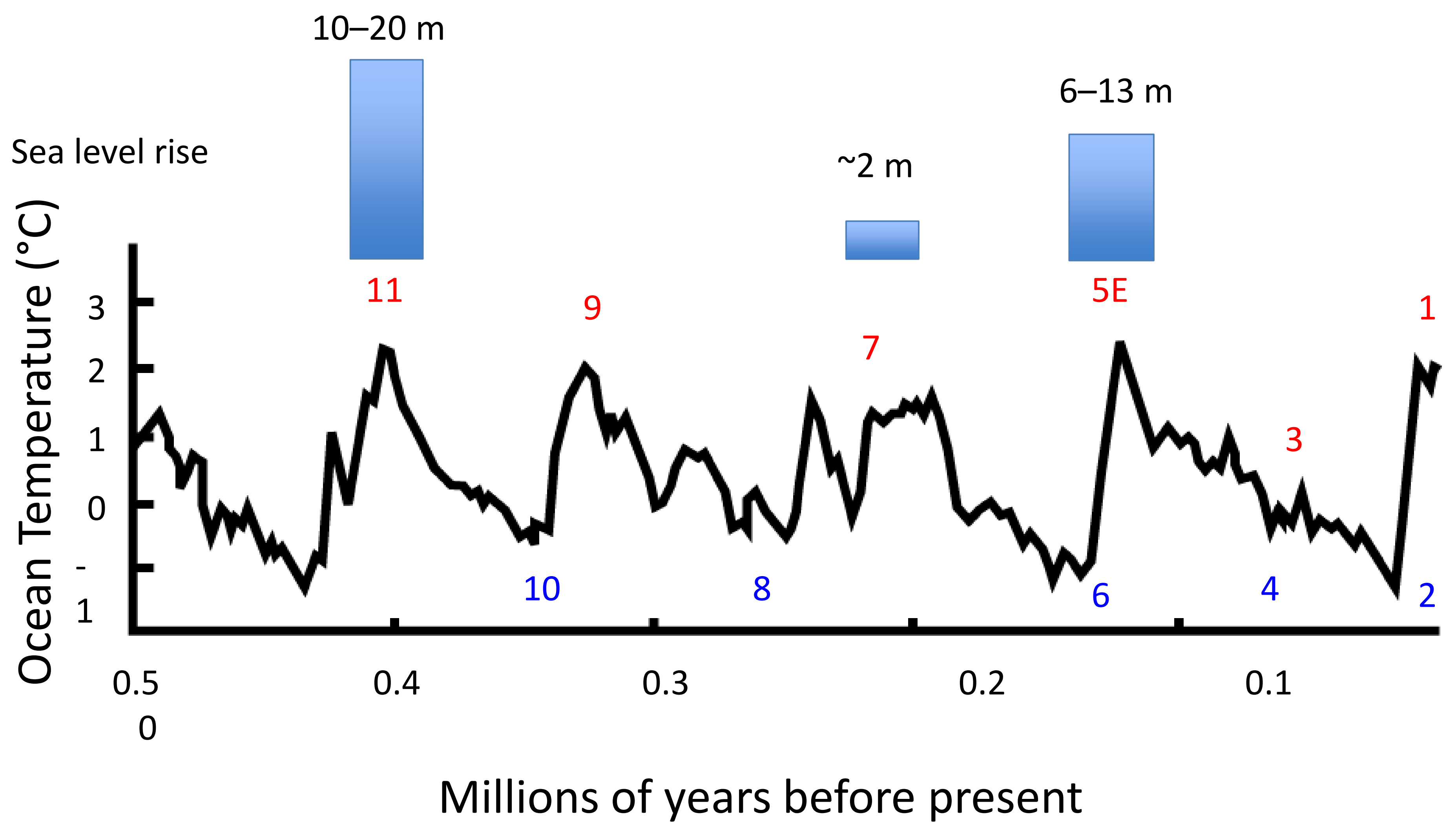
Data from (Lisiecki and Raymo, 2005)

Background: *Glacial history of Greenland*

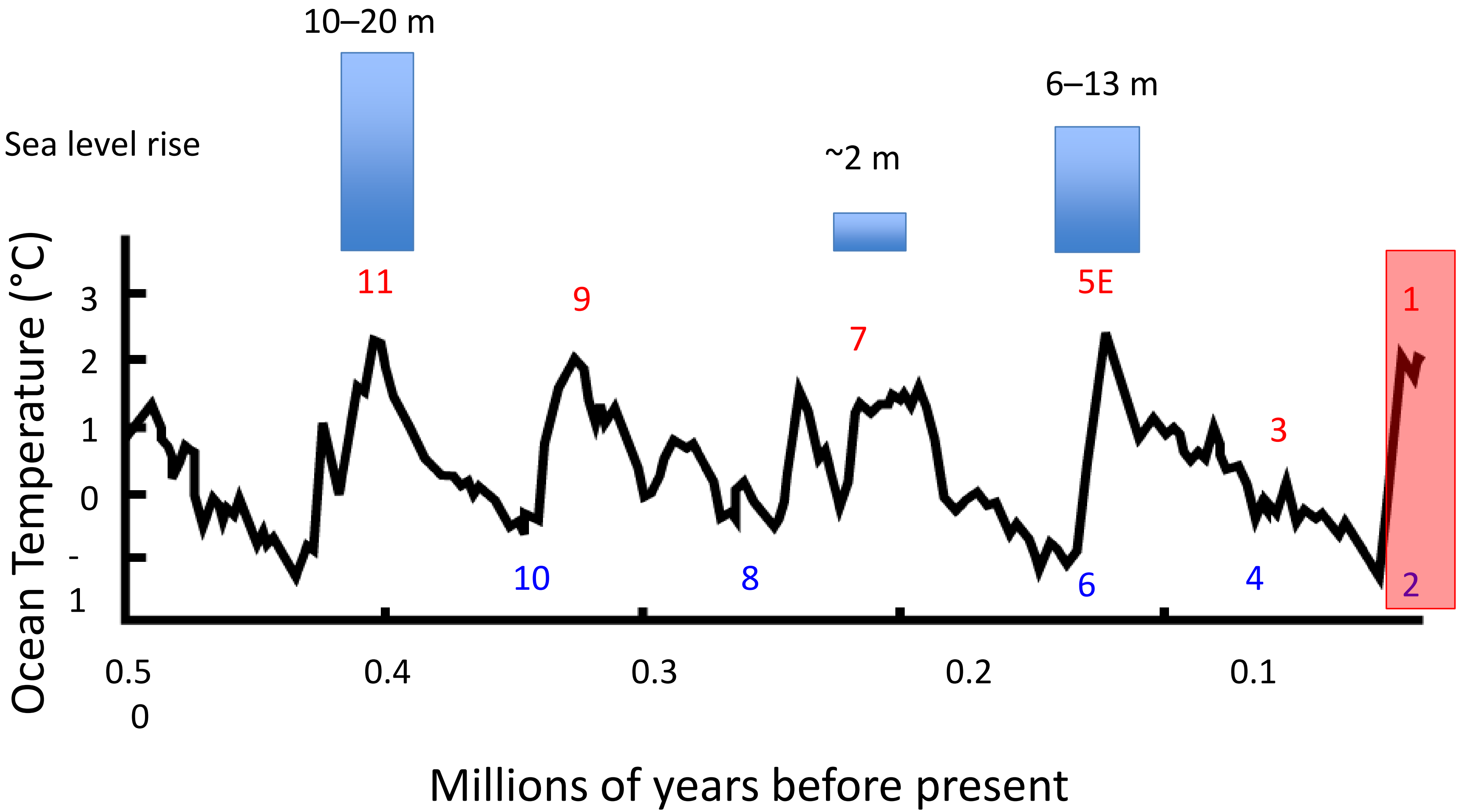


Data from (Lisiecki and Raymo, 2005)

Background: *Glacial history of Greenland*

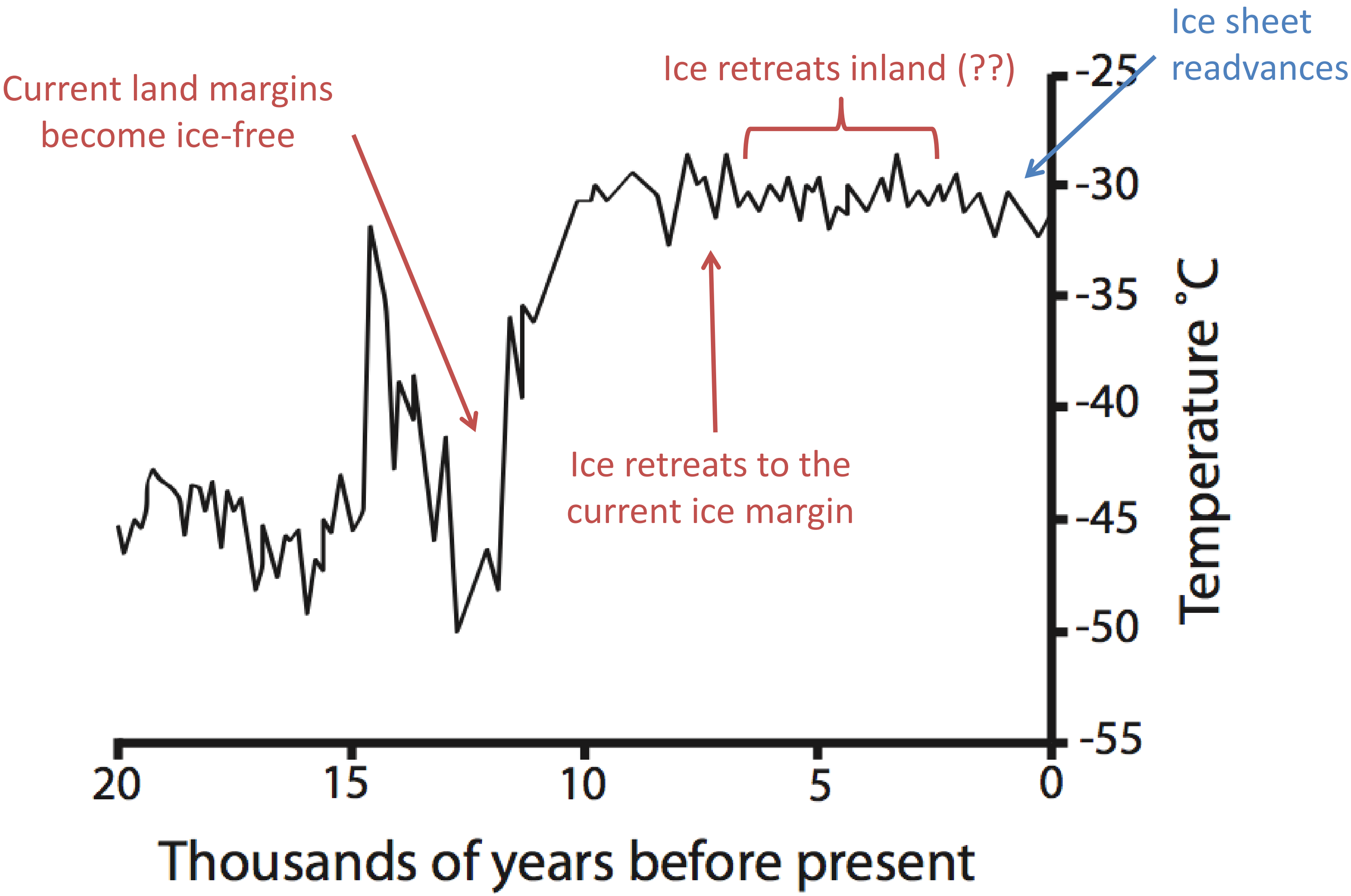


Background: *Glacial history of Greenland*

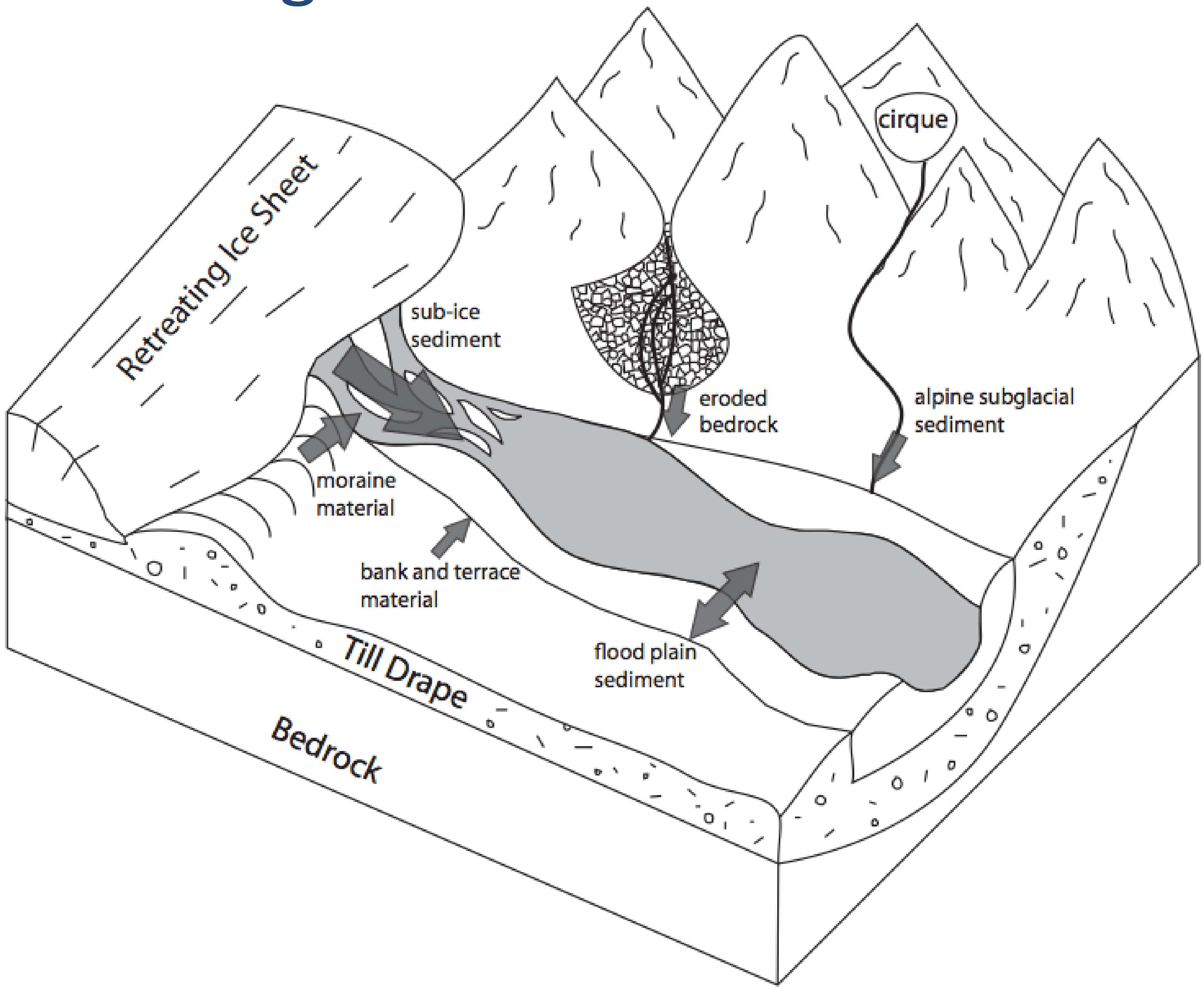


Background: *Glacial history of Greenland*

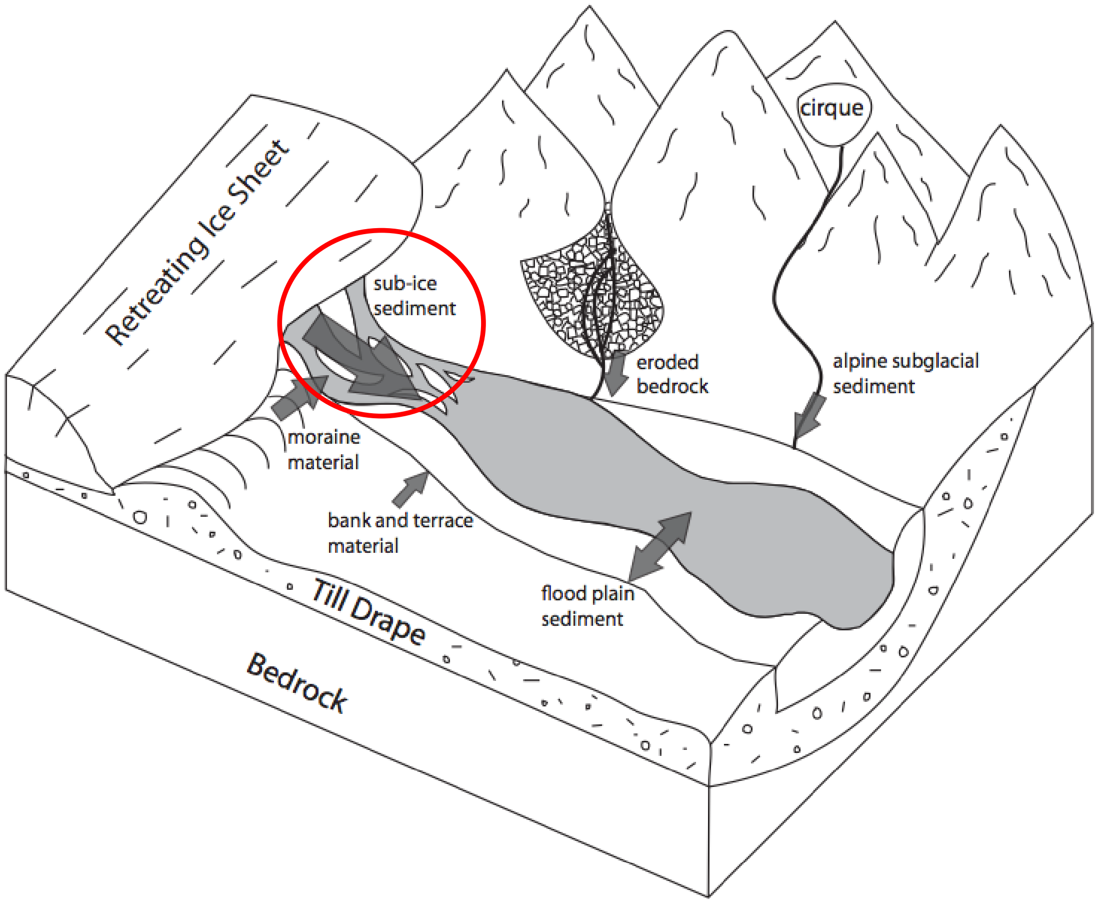
The Holocene (~12 ka to present)



Background: *sediment sources*

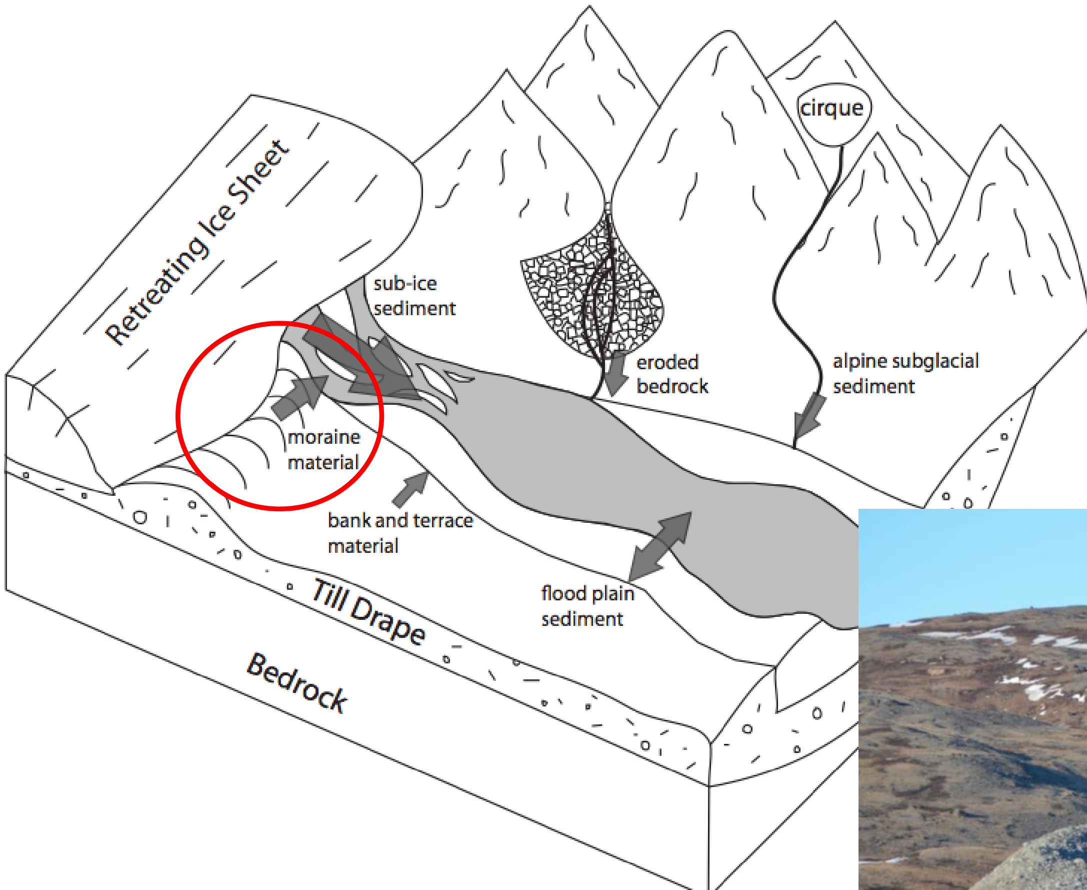


Background: *sediment sources*



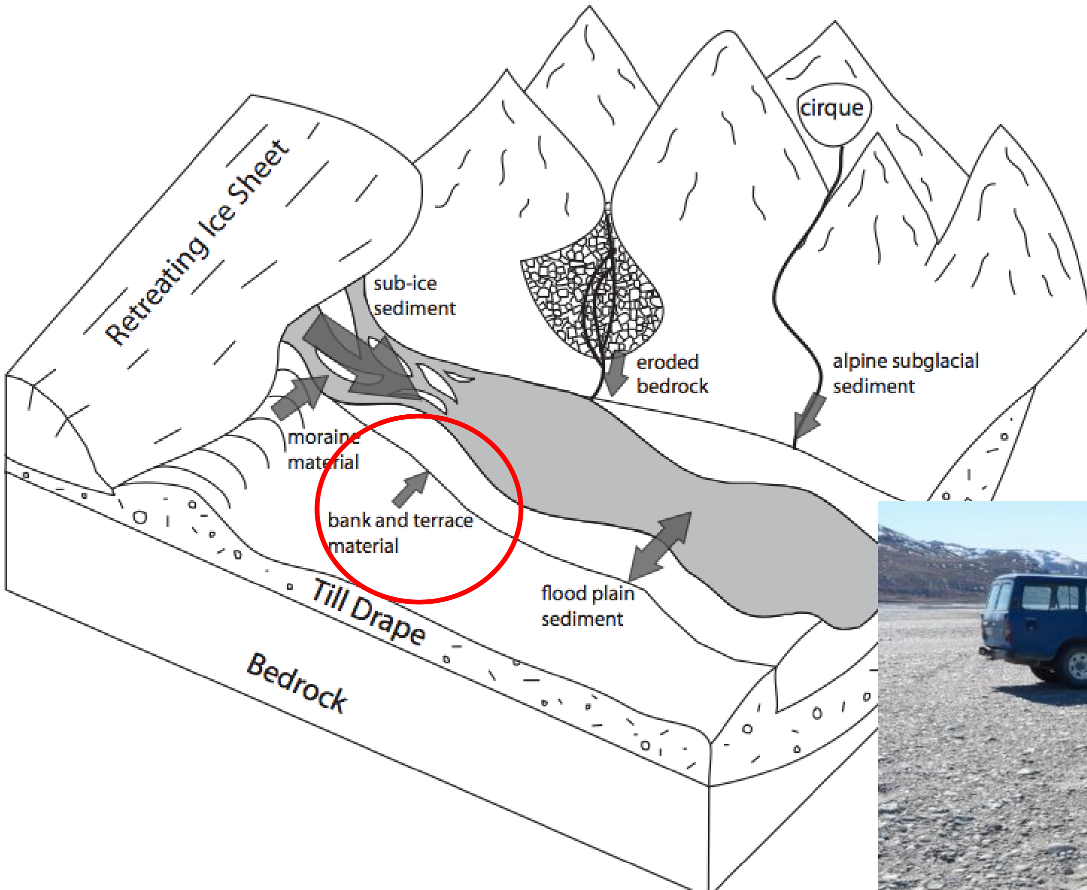
from beneath the ice

Background: *sediment sources*



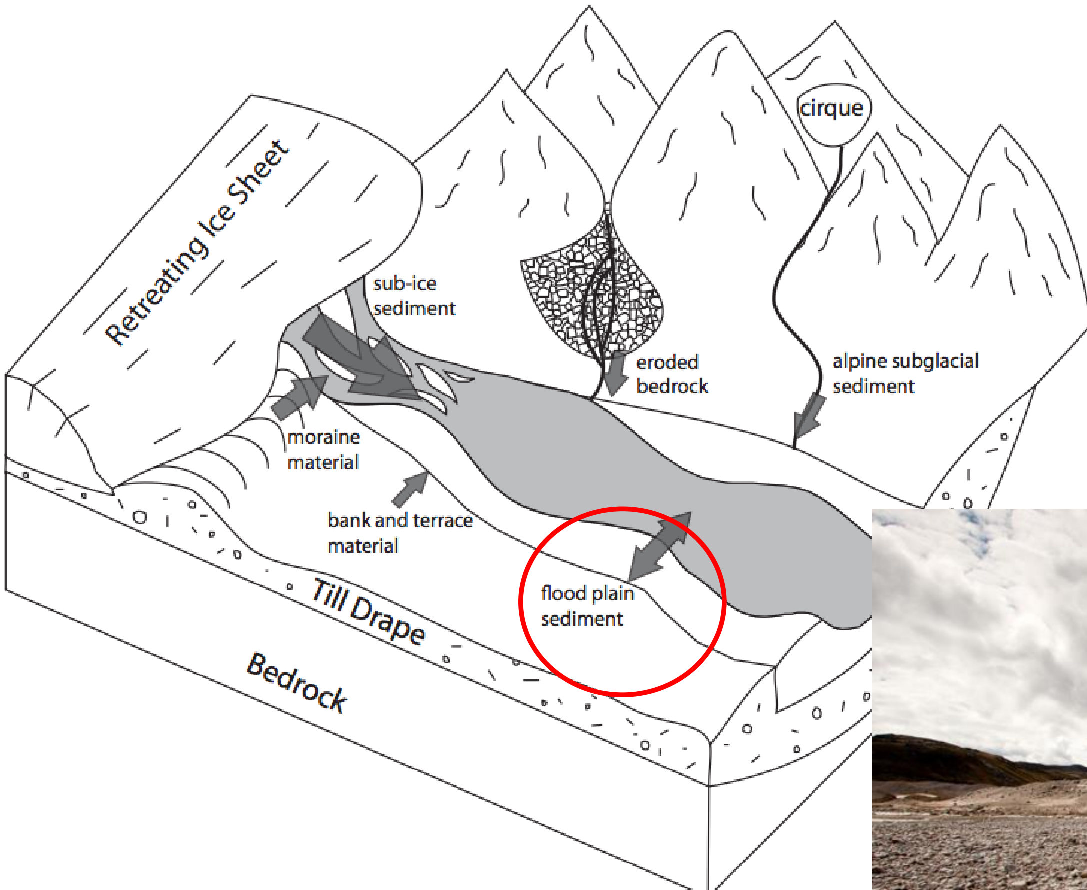
mobilized from moraines

Background: *sediment sources*



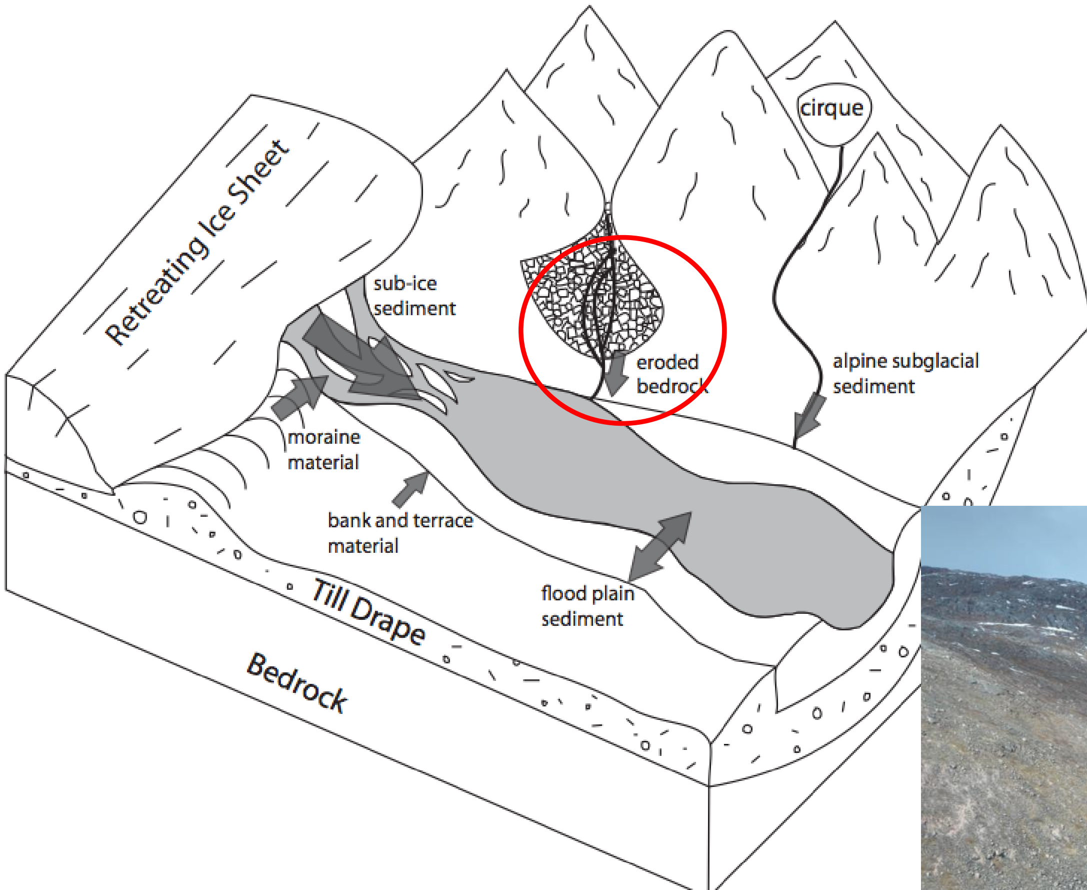
long-term storage in terraces

Background: *sediment sources*



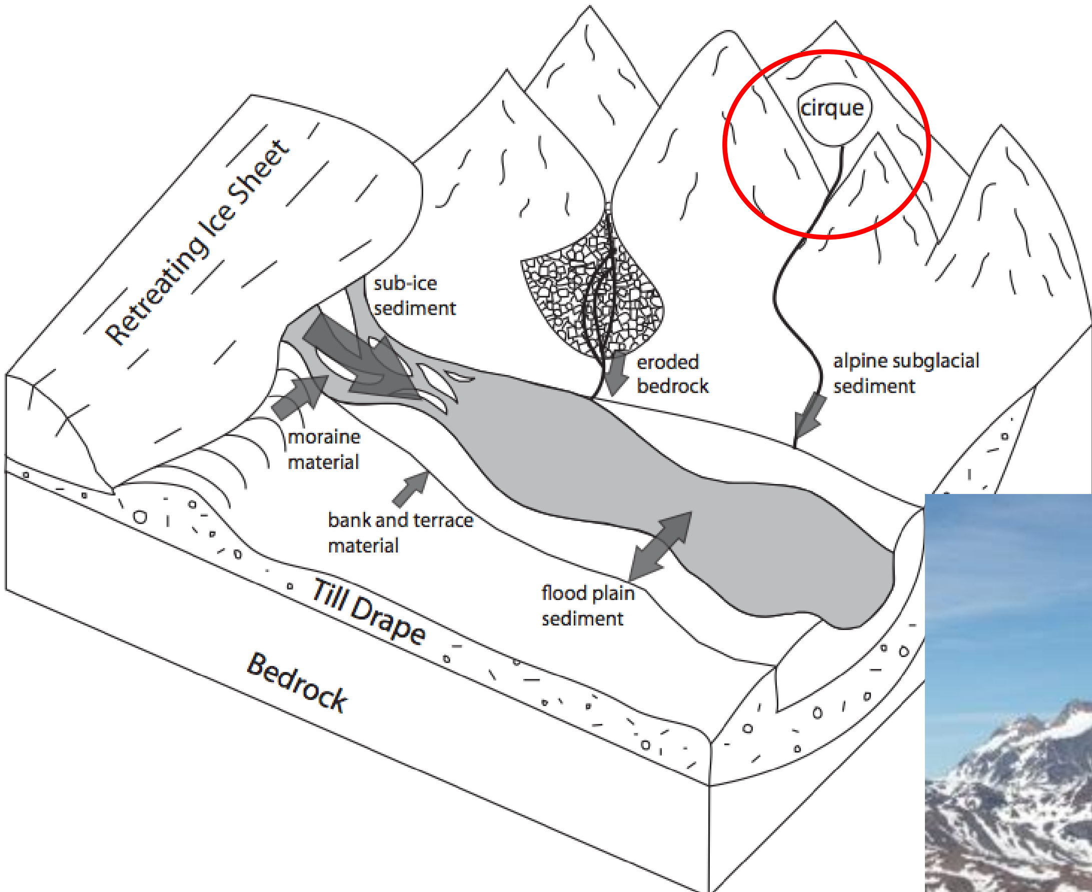
temporary storage in flood plains

Background: *sediment sources*



eroded from exposed slopes

Background: *sediment sources*



sourced from alpine glaciers

Methods: *Field Sites*

Kangerlussuaq

2011, 2012

Tasiilaq

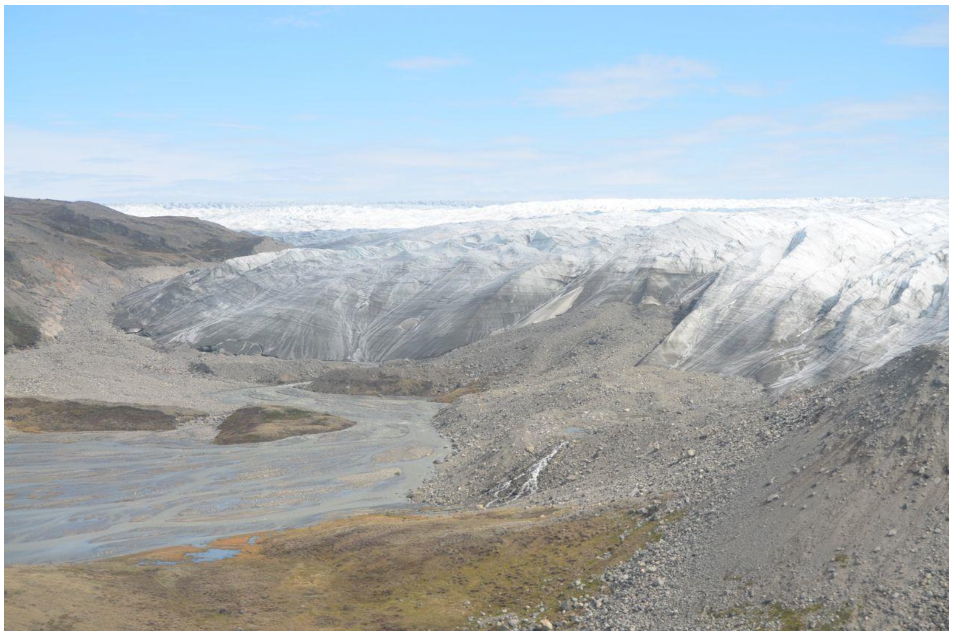
2012

Narsarsuaq

2011

Methods: *Field Sites*

Kangerlussuaq



Ice margin is at low elevations
~180 km inland of the coast

Methods: *Field Sites*

Kangerlussuaq

Outwash flows through wide valleys, ~20 km to the fjord head

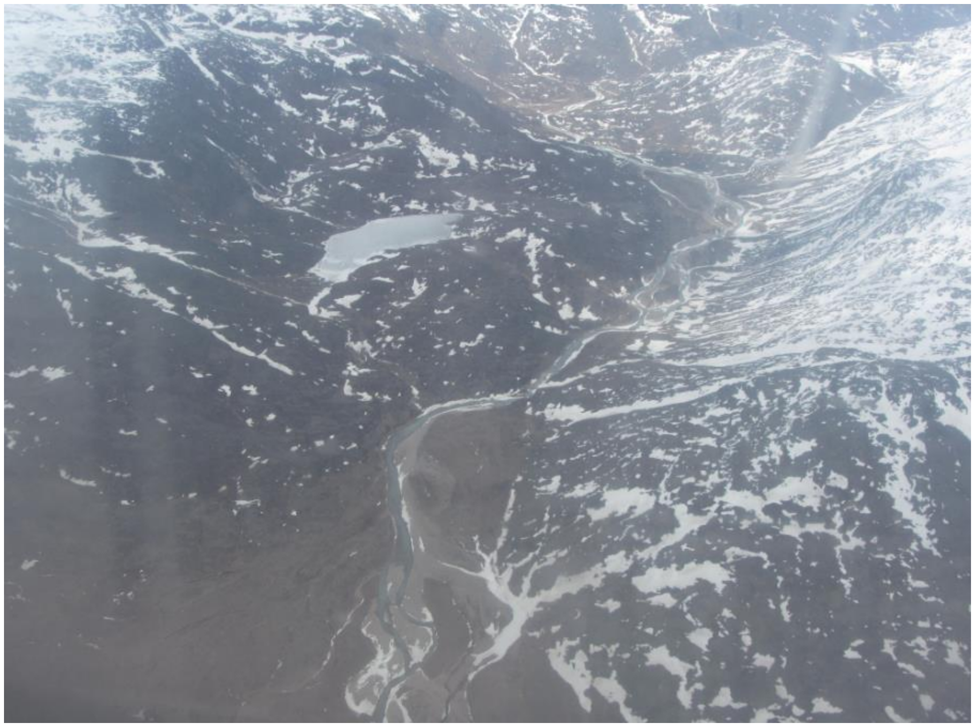
Methods: *Field Sites*

Narsarsuaq

Ice margin is mostly at high elevations (500 to 800 m above sea level)

Methods: *Field Sites*

Narsarsuaq



Ice-free landscape has high relief, and outwash flows through narrow channels

Methods: *Field Sites*

Tasiilaq

Ice margin is relatively close to the coast

Methods: *Field Sites*

Tasiilaq

Glaciers on coastal islands are not attached to the mainland ice sheet

Methods: *Field Work*

Getting to the sample sites

Collecting elevation data

Sampling bedrock

Sampling moraine material

Taking field notes

Sampling outwash

Photos: Josh Brown

Methods: *Lab Work*

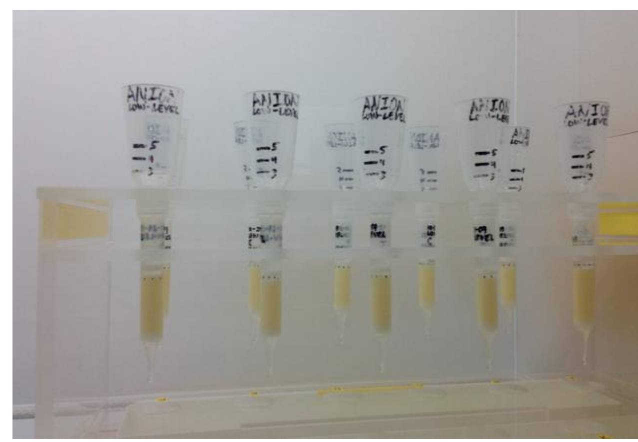
sieving

magnetic separation

labeling

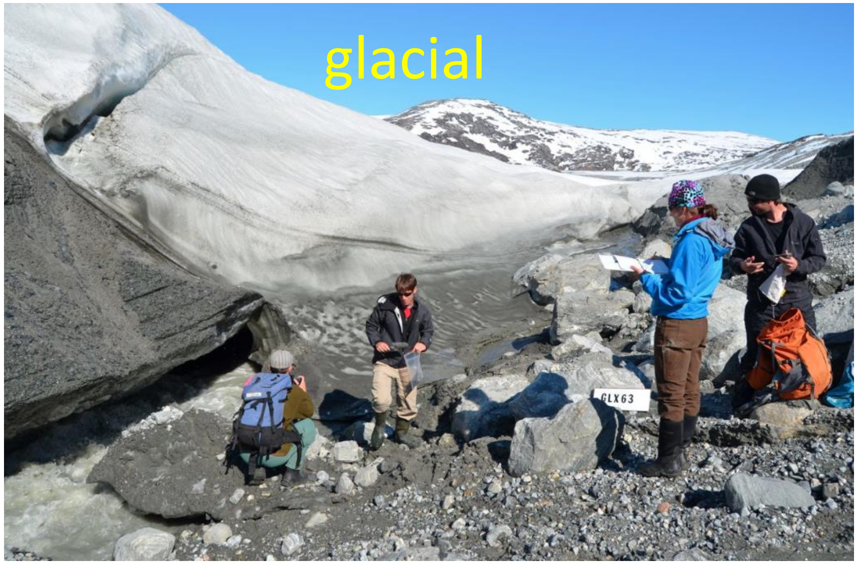
acid etches

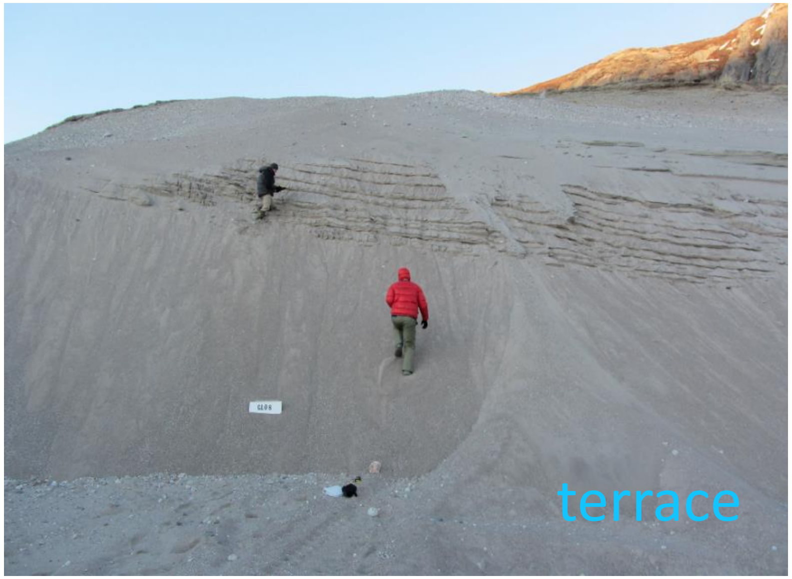
density separation

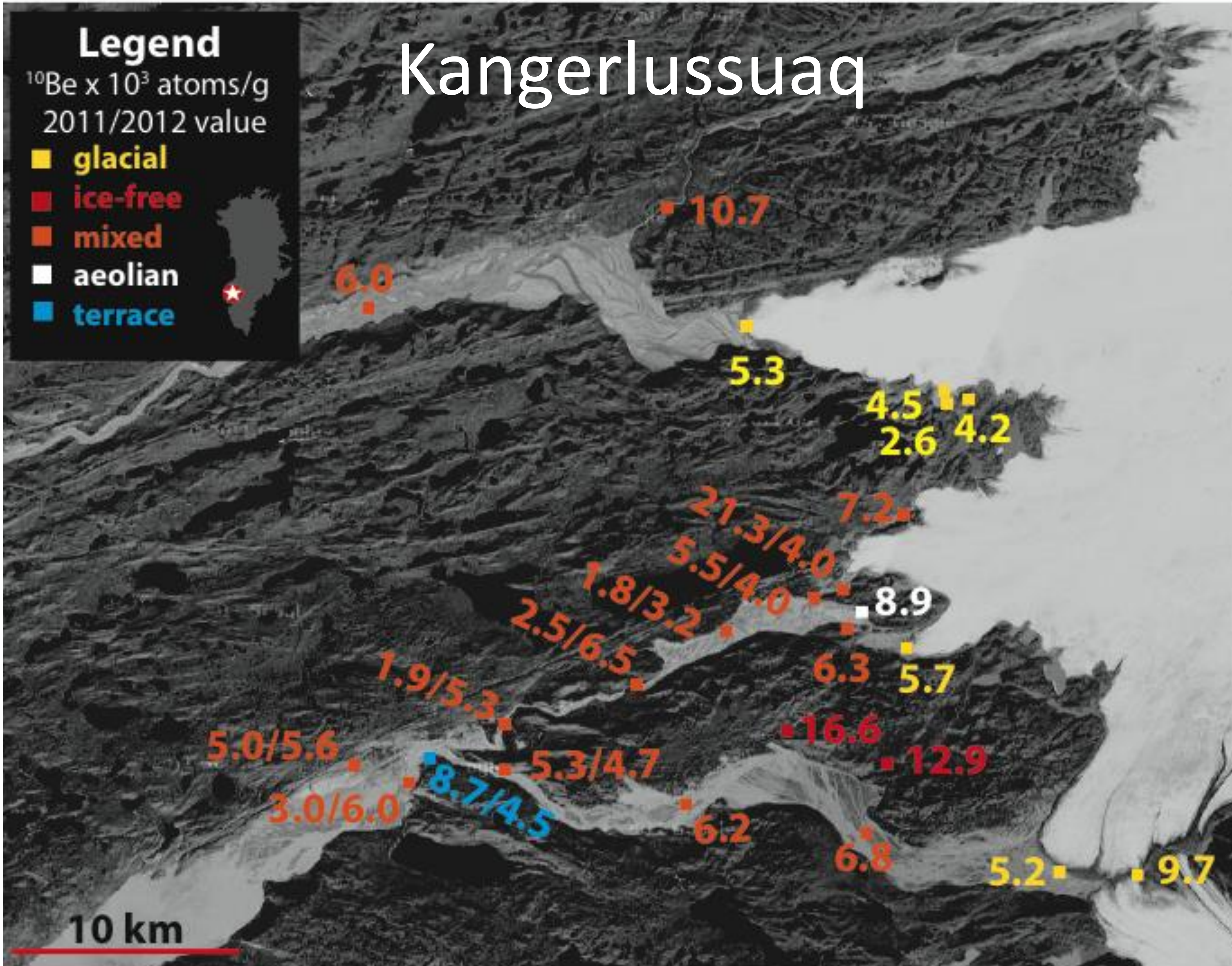


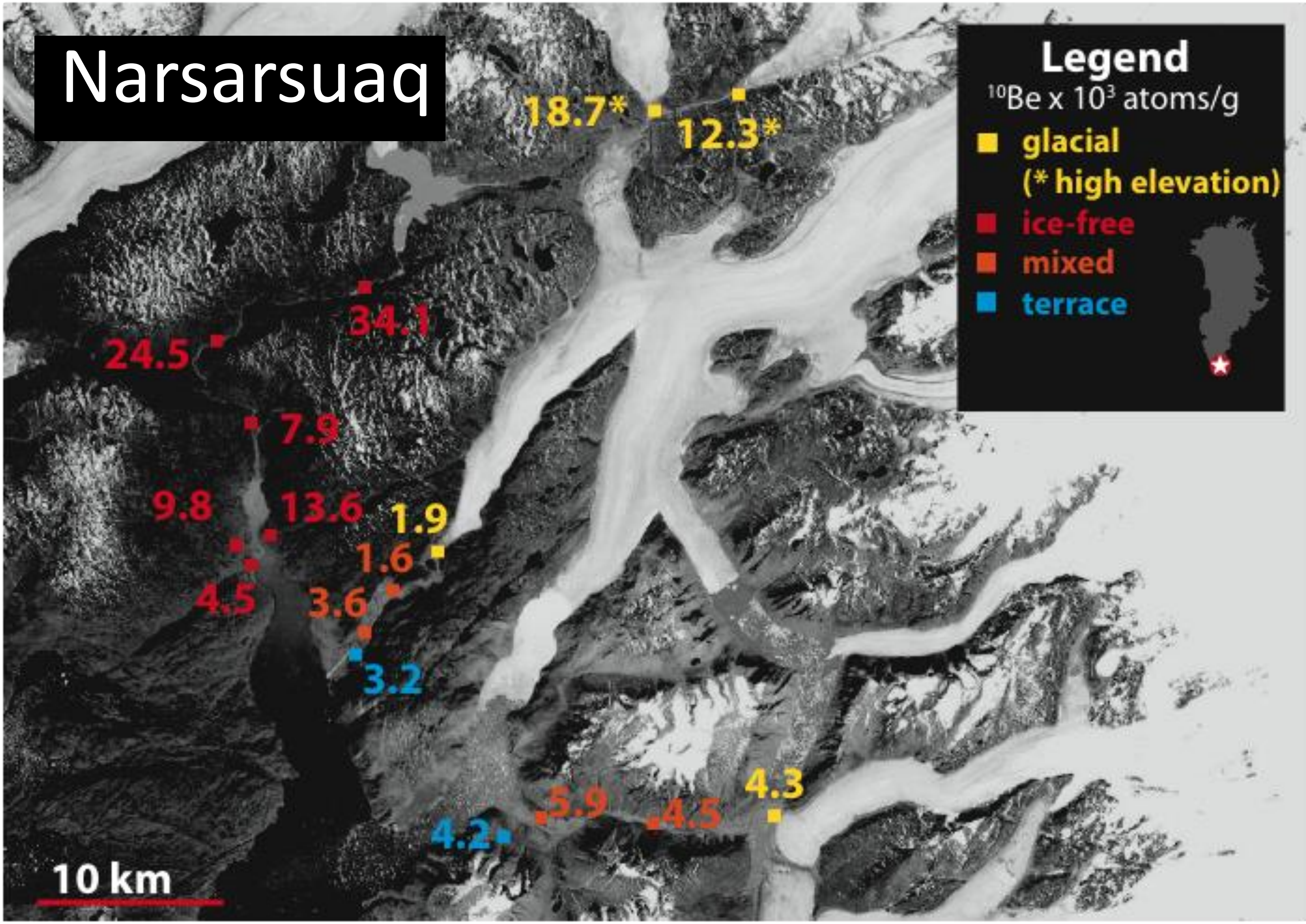
^{10}Be extraction

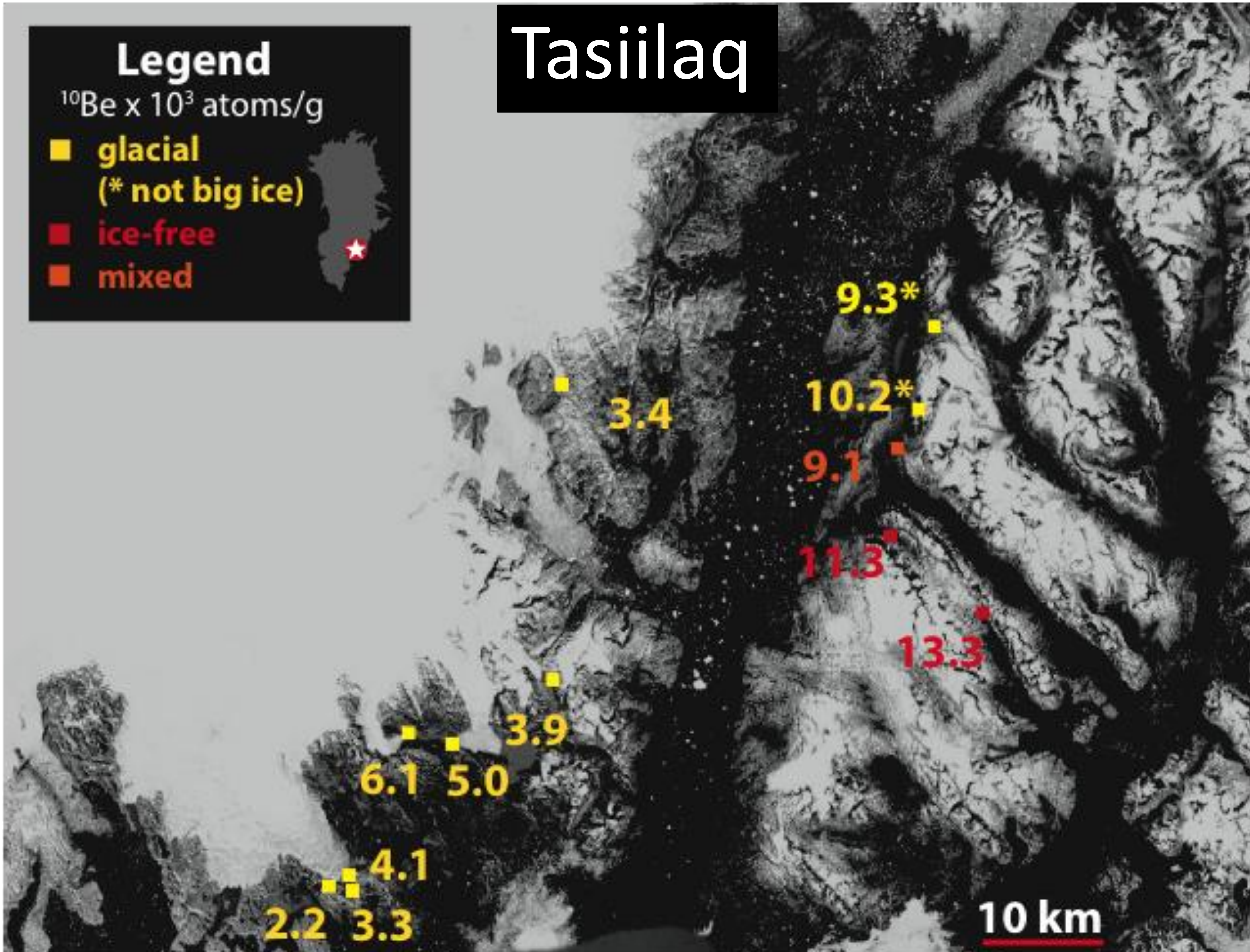
Methods: *Data Analysis*






Kangerlussuaq
Legend
¹⁰Be x 10³ atoms/g
2011/2012 value
glacial
ice-free
mixed
aeolian
terrace
10.7
6.0
5.3
4.5
4.2
2.6
7.2
21.3/4.0
5.5/4.0
8.9
1.8/3.2
2.5/6.5
6.3
5.7
1.9/5.3
16.6
12.9
5.0/5.6
5.3/4.7
8.7/4.5
3.0/6.0
6.2
6.8
5.2
9.7
10 km


Narsarsuaq
Legend
10Be x 10³ atoms/g
glacial
(* high elevation)
ice-free
mixed
terrace
18.7*
12.3*
34.1
24.5
7.9
9.8
13.6
1.9
1.6
4.5
3.6
3.2
4.3
5.9
4.5
4.2
10 km


Tasiilaq
Legend
$^{10}Be \times 10^3$ atoms/g
glacial
(* not big ice)
ice-free
mixed
9.3*
10.2*
9.1
11.3
13.3
3.4
3.9
6.1
5.0
4.1
2.2
3.3
10 km

Results

^{10}Be concentration x 10^3 atoms per gram

Region	Ice-free	Glacial	Mixed	Terrace	Aeolian	Median
K	14.8 ± 2.6 *n=2*	5.2 ± 2.0 *n=7*	5.9 ± 1.8 *n=14*	6.6 ± 3.0 *n=1*	8.9 *n=1*	**5.9** ***n=26***
N	15.7 ± 11.3 *n=6*	11.7 ± 7.2 *n=3*	3.5 ± 1.8 *n= 5*	3.7 ± 0.7 *n=2*		**5.2** ***n=16***
T	12.3 ± 1.4 *n=2*	5.3 ± 2.8 *n=9*	9.1 *n=1*			**5.6** ***n=12***
All	14.9 ± 8.6 (13.1) *n=10*	6.5 ± 4.1 (5.2) *n=19*	5.5 ± 2.2 (5.3) *n=20*	5.2 ± 2.4 (4.4) *n=3*	8.9 *n=1*	**5.9** ***n=54***

Results

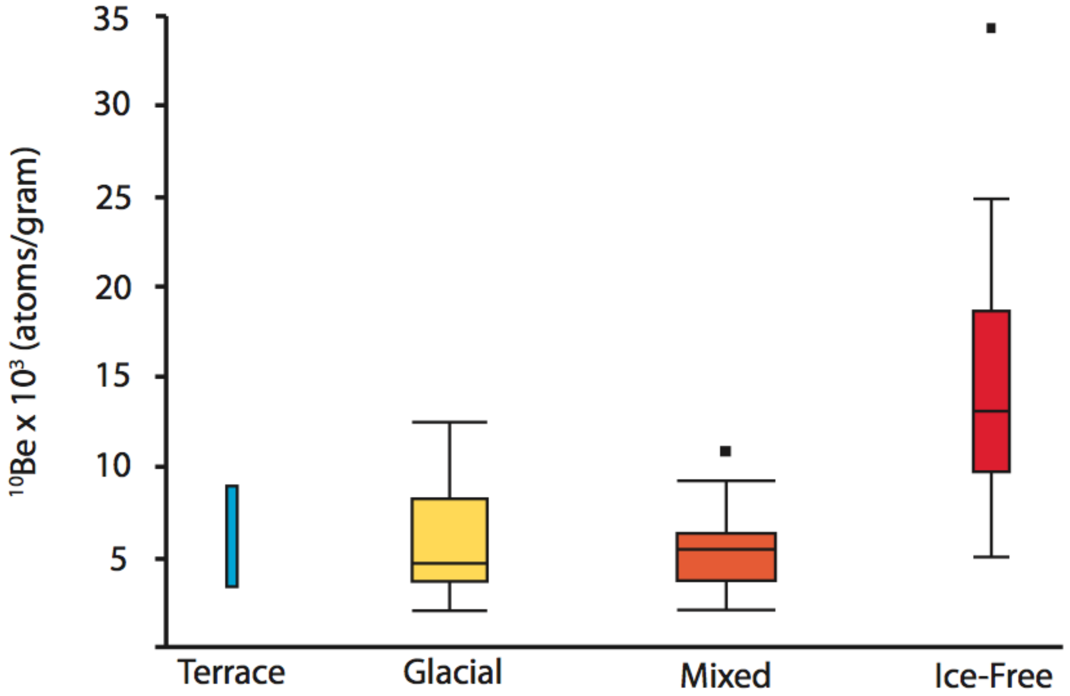
^{10}Be concentration x 10^3 atoms per gram

Region	Ice-free	Glacial	Mixed	Terrace	Aeolian	Median
K	14.8 ± 2.6 *n=2*	5.2 ± 2.0 *n=7*	5.9 ± 1.8 *n=14*	6.6 ± 3.0 *n=1*	8.9 *n=1*	5.9 *n=26*
N	15.7 ± 11.3 *n=6*	11.7 ± 7.2 *n=3*	3.5 ± 1.8 *n= 5*	3.7 ± 0.7 *n=2*		5.2 *n=16*
T	12.3 ± 1.4 *n=2*	5.3 ± 2.8 *n=9*	9.1 *n=1*			5.6 *n=12*
All	**14.9 ± 8.6** **(13.1)** ***n=10***	**6.5 ± 4.1** **(5.2)** ***n=19***	**5.5 ± 2.2** **(5.3)** ***n=20***	**5.2 ± 2.4** **(4.4)** ***n=3***	**8.9** ***n=1***	**5.9** ***n=54***

Data Analysis and Results: *Part I*

^{10}Be concentration as a sediment source tracer

Is the concentration of ^{10}Be in sediment from different sources characteristically different?



^{10}Be concentration in ice-free sediment is significantly higher than in glacial sediment

Data Analysis and Results: *Part I*

^{10}Be concentration as a sediment source tracer

What is the relative contribution of sediment from ice-free versus glacial sources?

$$C_{if}X \quad + \quad C_gY \quad = \quad C_m$$

~90% of mixed category sediment in channels is glacial in origin

Implications I: ^{10}*Be as a tracer*

- there isn't enough sediment from ice-free terrain to affect downstream channel concentration
- glacial sediment also dominated the fluvial system in the early Holocene (terrace concentration)
- ice-free slopes in the paraglacial landscape are not as unstable as previous research suggests

Data Analysis and Results: *Part II*

^{10}Be as a dosimeter of cosmic ray exposure

How did relatively high concentrations of ^{10}Be accumulate in ice-free sediment?

$$C = C_i + \frac{P_{s,m} S_e}{\Lambda^{-1}\varepsilon} e^{-\Lambda}\left(1 - e^{-\Lambda^{-1}\varepsilon t}\right)$$

Surficial production on an eroding surface

Data Analysis and Results: *Part II*

^{10}Be as a dosimeter of cosmic ray exposure

Ice-free sediment – glacial sediment exposed on the landscape since Holocene ice retreat

1. Ice-free landscape blanketed by unconsolidated material

2. Inherited ^{10}Be concentration: ~5 x 10^3 atoms per gram (glacial concentration)

3. Additional ~7 to 13 ky of exposure

4. ^{10}Be concentration is consistent with regolith erosion rates from 0.4 to 0.9 mm per year

Data Analysis and Results: *Part II*

^{10}Be as a dosimeter of cosmic ray exposure

Glacial sediment - some prior cosmogenic exposure

Testable hypothesis:

1) mid-Holocene retreat (~7 ka)
2) last interglacial (~115 ka)
3) before ice sheet inception (~3.5 Ma)

Data Analysis and Results: *Part II*

^{10}Be as a dosimeter of cosmic ray exposure

How did low concentrations of ^{10}Be in glacial sediment accumulate?

OR

Recent (Holocene or last interglacial) surficial exposure?

Pre ice sheet, deep production by muons?

$$\frac{1}{b-a}\int_a^b \left(P_{s,m} S_e e^{-\frac{xr}{\Lambda}} \right) dt$$

$$\ln[C] = -\frac{x}{\Lambda_{\mu f}} + \ln\left(\frac{P_{\mu f}}{\frac{\varepsilon}{\Lambda_{\mu f}} + \lambda} \right)$$

Data Analysis and Results: *Part II*

^{10}Be as a dosimeter of cosmic ray exposure

Glacial sediment - some prior cosmogenic exposure:

-mid-Holocene retreat (~7 ka)

-last interglacial (~115 ka)

-before ice sheet inception (~3.5 Ma)

1. During the mid-Holocene, surficial sediment would have accumulated 10×10^3 to 30×10^3 atoms per gram of ^{10}Be

2. Glacial sediment ^{10}Be concentration: ~5×10^3 atoms per gram

3. Terrace sediment, which was not exposed, has the same ^{10}Be concentration as glacial sediment

Data Analysis and Results: *Part II*

^{10}Be as a dosimeter of cosmic ray exposure

Glacial sediment - some prior cosmogenic exposure:

~~-mid-Holocene retreat (~7 ka)~~

-last interglacial (~115 ka)

-before ice sheet inception (~3.5 Ma)

1. Terrace and glacial sediment would have both been exposed (~15 ky)

2. Sediment ^{10}Be concentration of ~5 x 10^3 atoms per gram would have accumulated in the upper 2 m of bedrock

3. This sediment is probably gone – erosion in the last glacial cycle has been > 2 m

Data Analysis and Results: *Part II*

^{10}Be as a dosimeter of cosmic ray exposure

Glacial sediment - some prior cosmogenic exposure:

~~-mid-Holocene retreat (~7 ka)~~

~~-last interglacial (~115 ka)~~

-before ice sheet inception (~3.5 Ma)

1. Glacial sediment must be sourced deeply

2. ^{10}Be must have accumulated by **muogenic** production

3. ^{10}Be in glacial sediment is inherited from long-term exposure before the ice sheet was established

4. Measured concentrations are consistent with steady-state accumulation, 20 to 30 m below the surface

Implications II: ^{10}*Be as a dosimeter*

- Holocene retreat was not great enough or long enough for significant ^{10}Be accumulation in surficial sediment OR
- The volume of sediment sourced deeply, that was not exposed, far exceeds the volume of sediment that was exposed

Conclusions

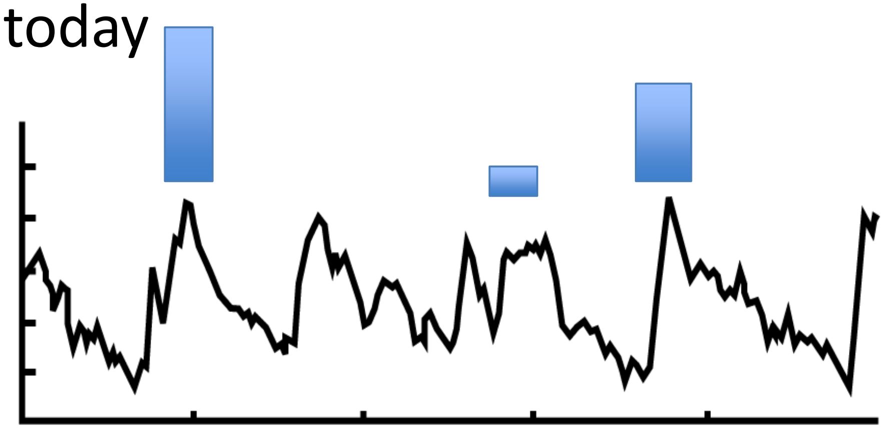
- We can use ^{10}Be concentration as a sediment tracer because concentrations in glacial and ice-free sediment are characteristically different
- ^{10}Be concentration in glacial sediment is LOW - relict of long-term exposure pre Greenland Ice Sheet
- ^{10}Be concentration in ice-free sediment is HIGHER - but there is not enough sediment sourced from ice- free terrain to affect mixed concentration in channels

Future Research

- Fjord sediment gets evacuated to the deep ocean during periods of glacial advance
- Fjord sediment concentration = glacial sediment concentration

Future Research

- ^{10}Be in the off-shore marine record controlled by:
  - efficacy and timing of glacial erosion NOT
  - duration and extent of paraglacial landscape exposure UNLESS
  - past ice sheet retreat was significantly greater then it is today



Acknowledgements

- Andrea and Jason
- NSF Greenland Grant, UVM
- Geology department faculty and staff
- Fellow graduate students
- My family!


Questions?

$$C = C_i + \frac{P_{s,m} S_e}{\Lambda^{-1}\varepsilon} e^{-\Lambda}\left(1 - e^{-\Lambda^{-1}\varepsilon t}\right)$$

Surficial production on an eroding surface

C= concentration (atoms g^{-1})
C_i = inherited concentration
$P_{s,m}$= production rate (3.98 atoms g^{-1} a^{-1})
S_e= scaling factor (elevation)
Λ= attenuation (160 g cm^{-2})
ε= erosion (g cm^{-2} a^{-1})

$$\frac{1}{b-a}\int_{a}^{b}\left(P_{s,m}S_{e}e^{-\frac{x\rho}{\Lambda}}\right)t$$

Spallation production at depth

$P_{s,m}$= production rate (atoms g^{-1} a^{-1})
S_e= scaling factor (elevation)
Λ= attenuation (160 g cm^{-2})
P = density (2.7 g cm^{-3})
t = exposure duration
x = depth (cm)

$$\ln[C] = -\frac{x}{\Lambda_{\mu f}} + \ln\left(\frac{P_{\mu f}}{\frac{\varepsilon}{\Lambda_{\mu f}} + \lambda}\right)$$

steady-state production by muons

C= concentration (atoms g^{-1})

P_{uf}= production rate (0.093 atoms g^{-1} a^{-1})

Λ= attenuation (4,320 g cm^{-2})

ε= erosion (g cm^{-2} a^{-1})

λ = decay constant (4.9867×10^{-7})