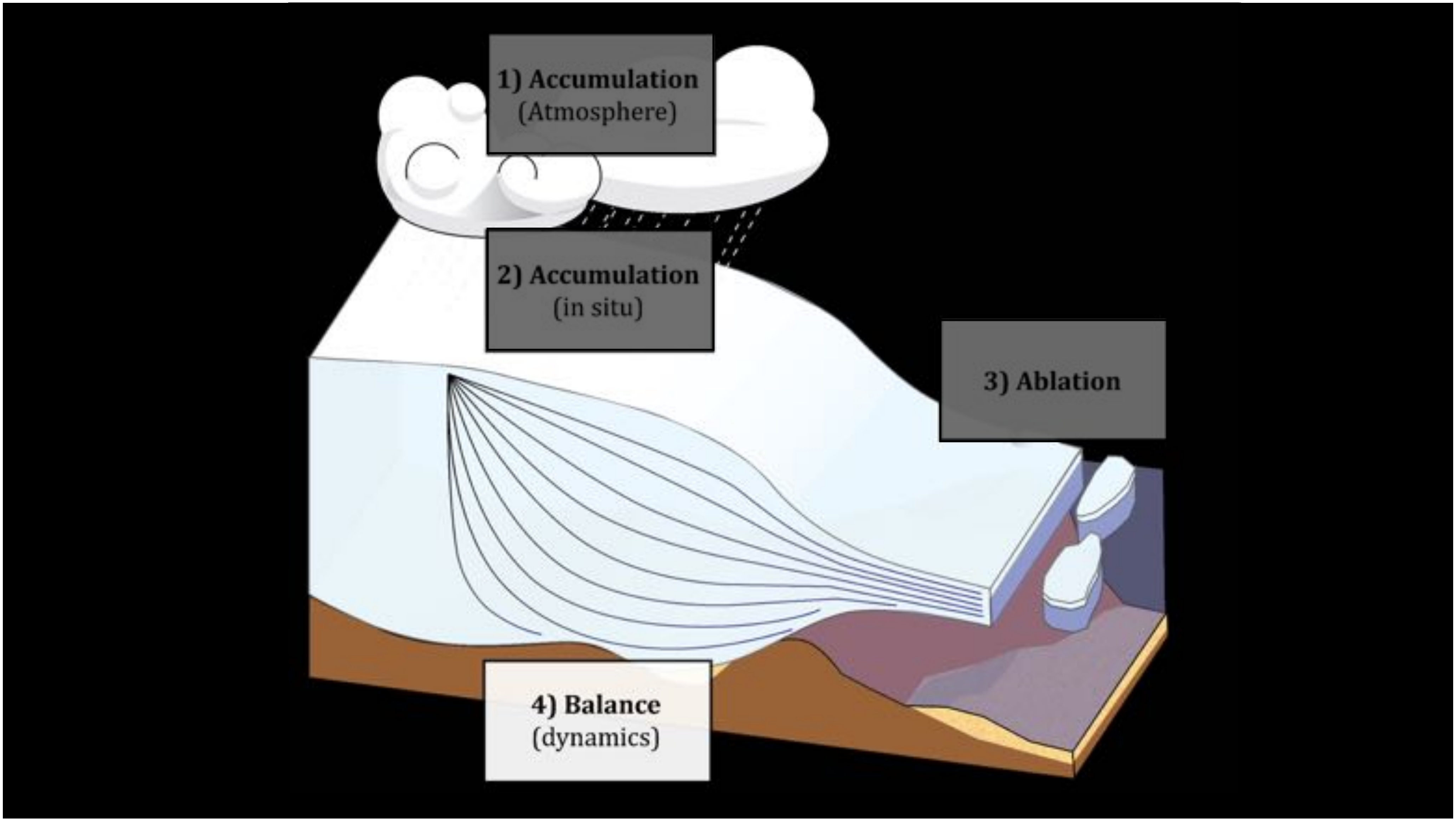
Ice Sheets and Ice Shelves: Characteristics and Processes in Antarctica and Greenland

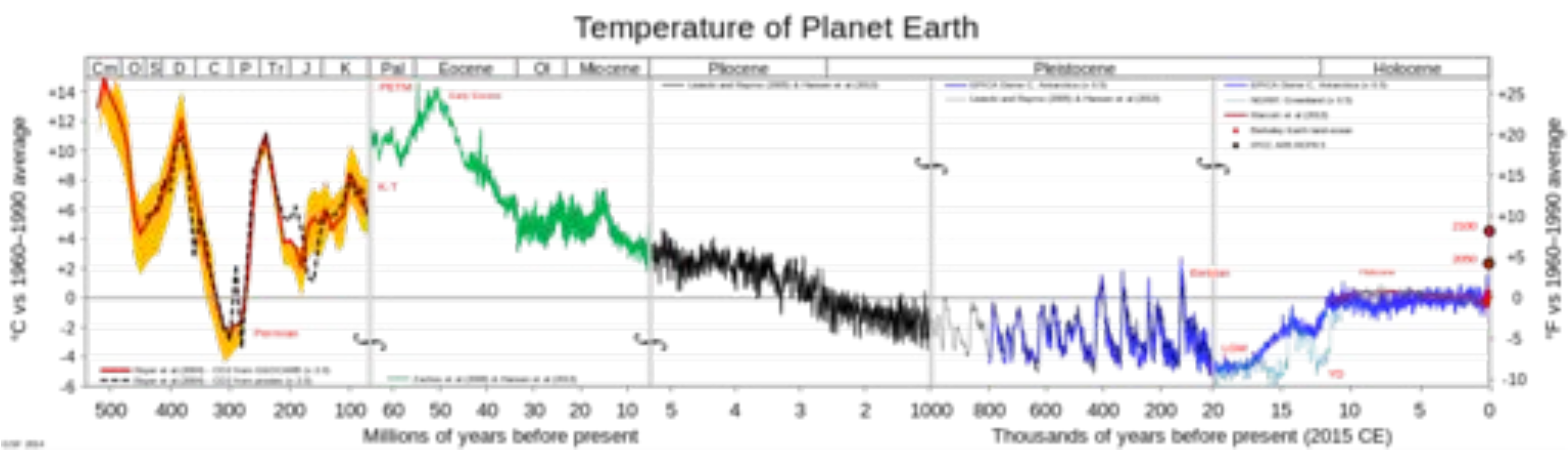
ESS431: Principles of Glaciology

ESS505: The Cryosphere

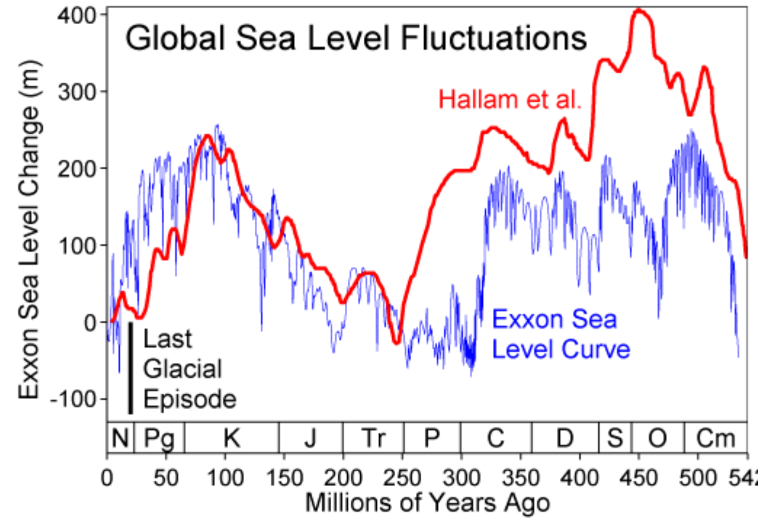
Wednesday, 10/31 – Knut Christianson

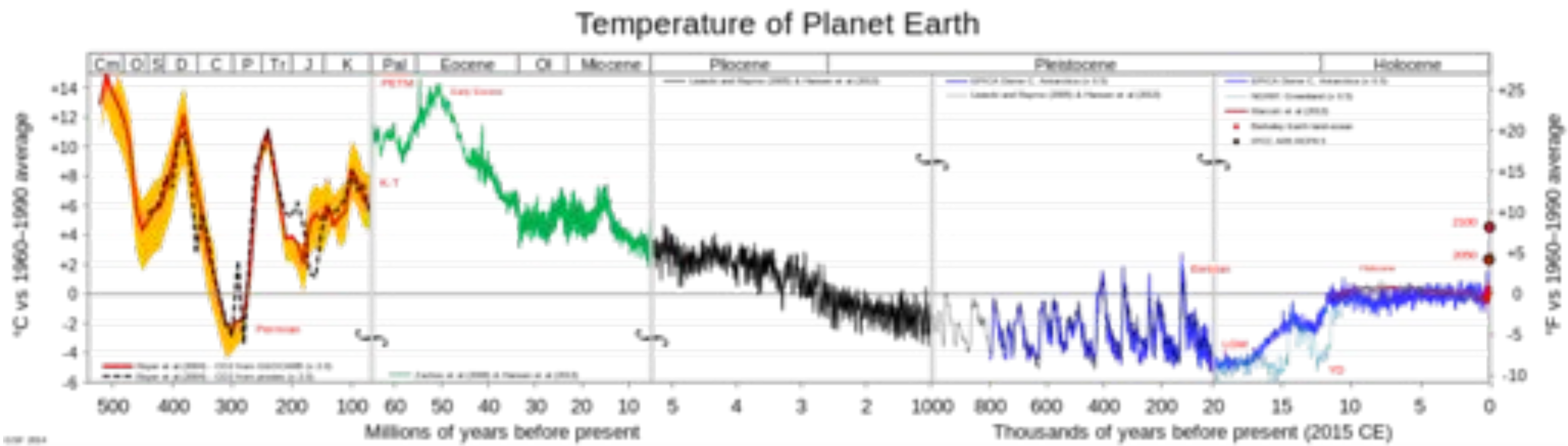

1) Accumulation
(Atmosphere)
2) Accumulation
(in situ)
3) Ablation
4) Balance
(dynamics)

Global Balance

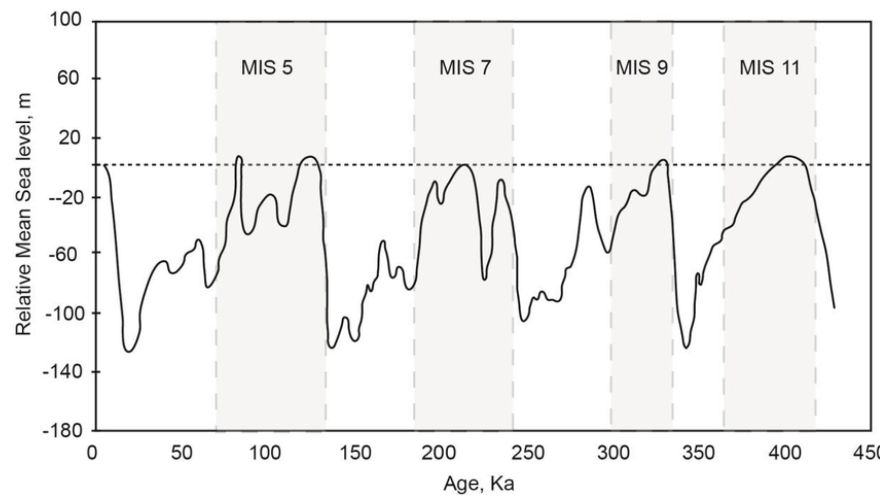


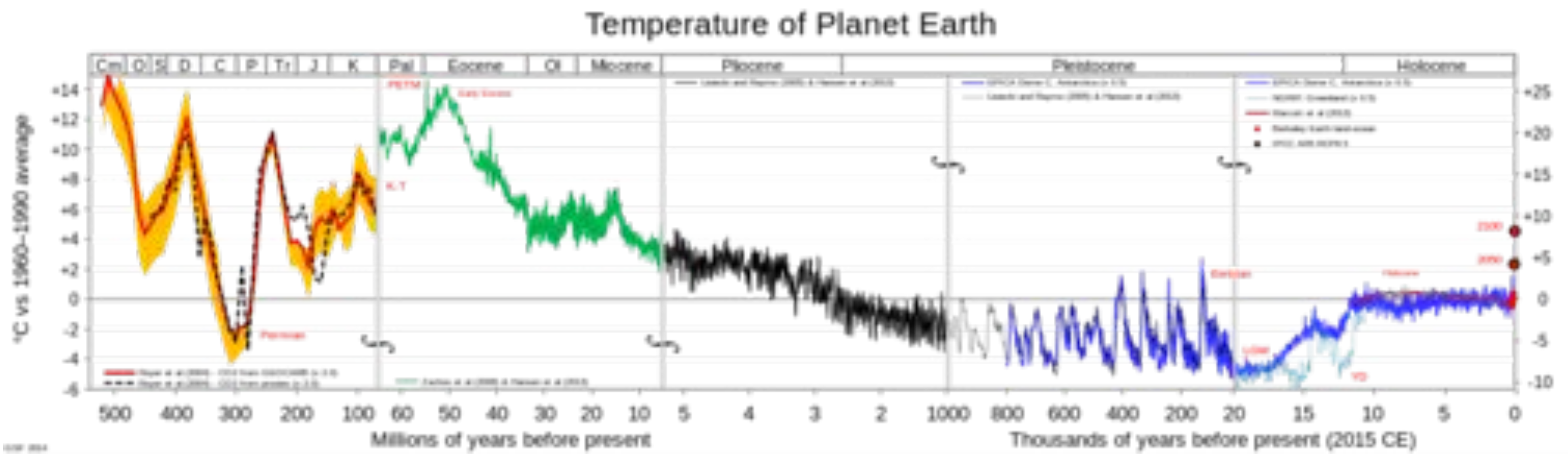
Global Balance

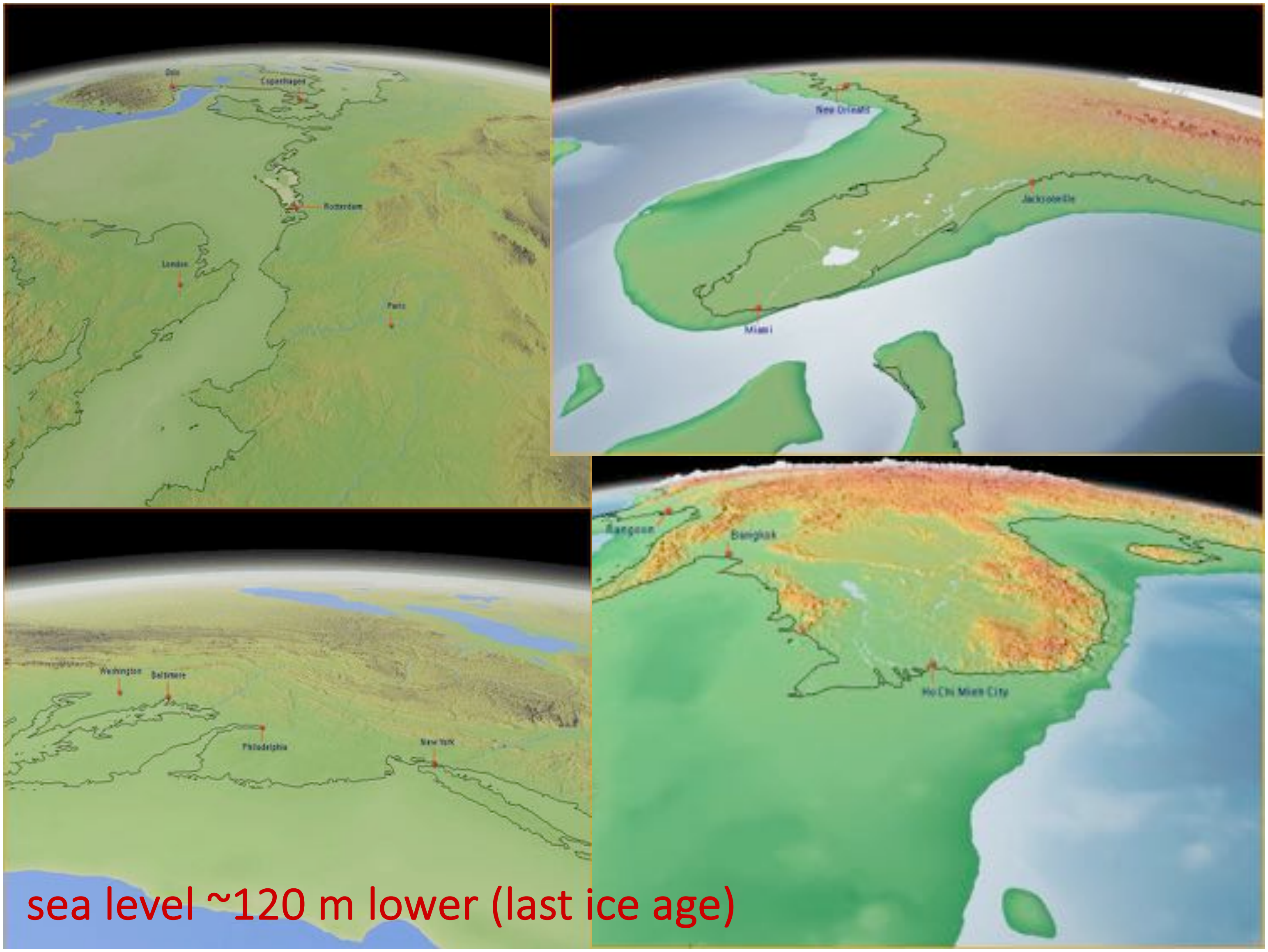




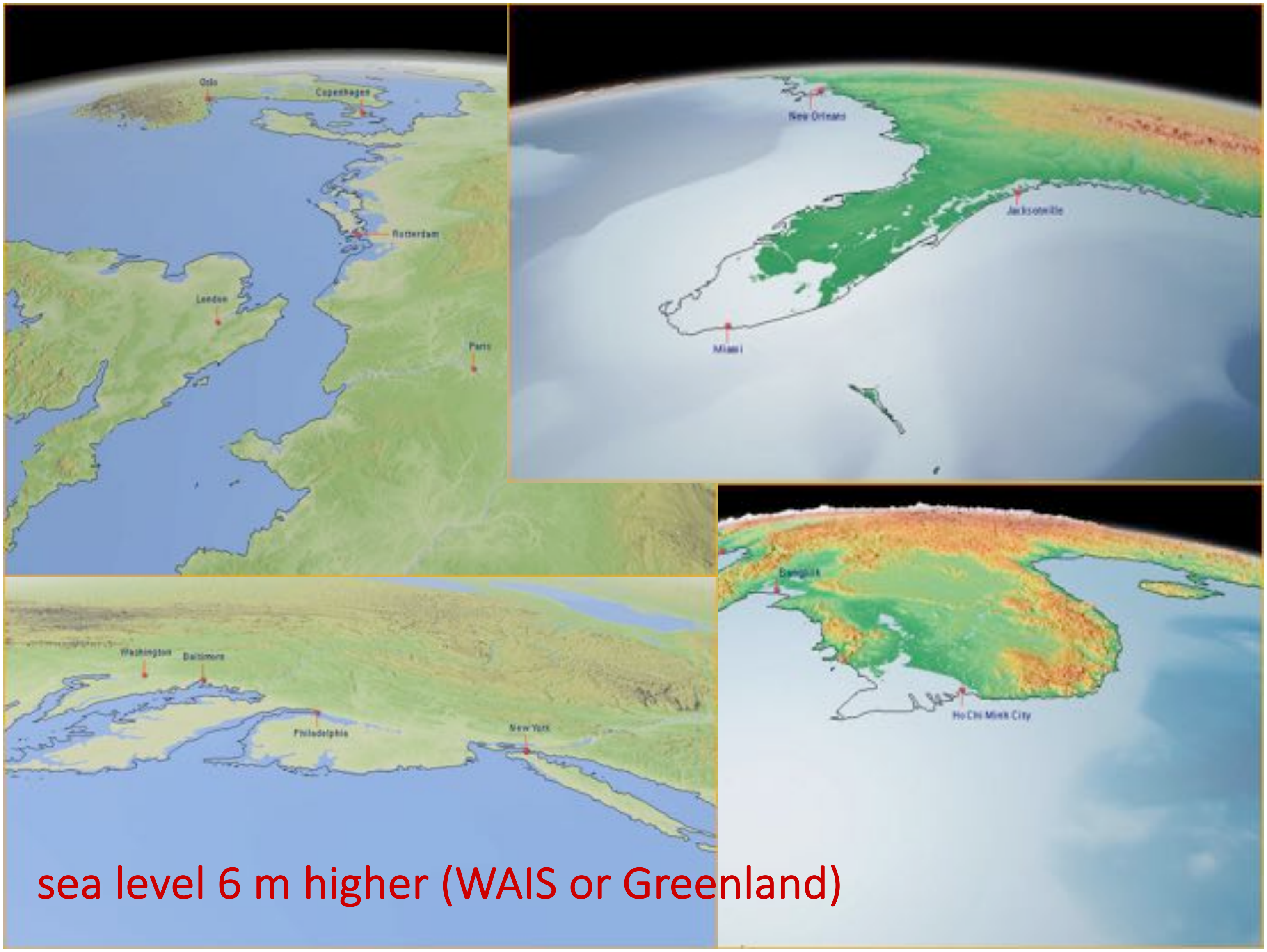
Global Balance



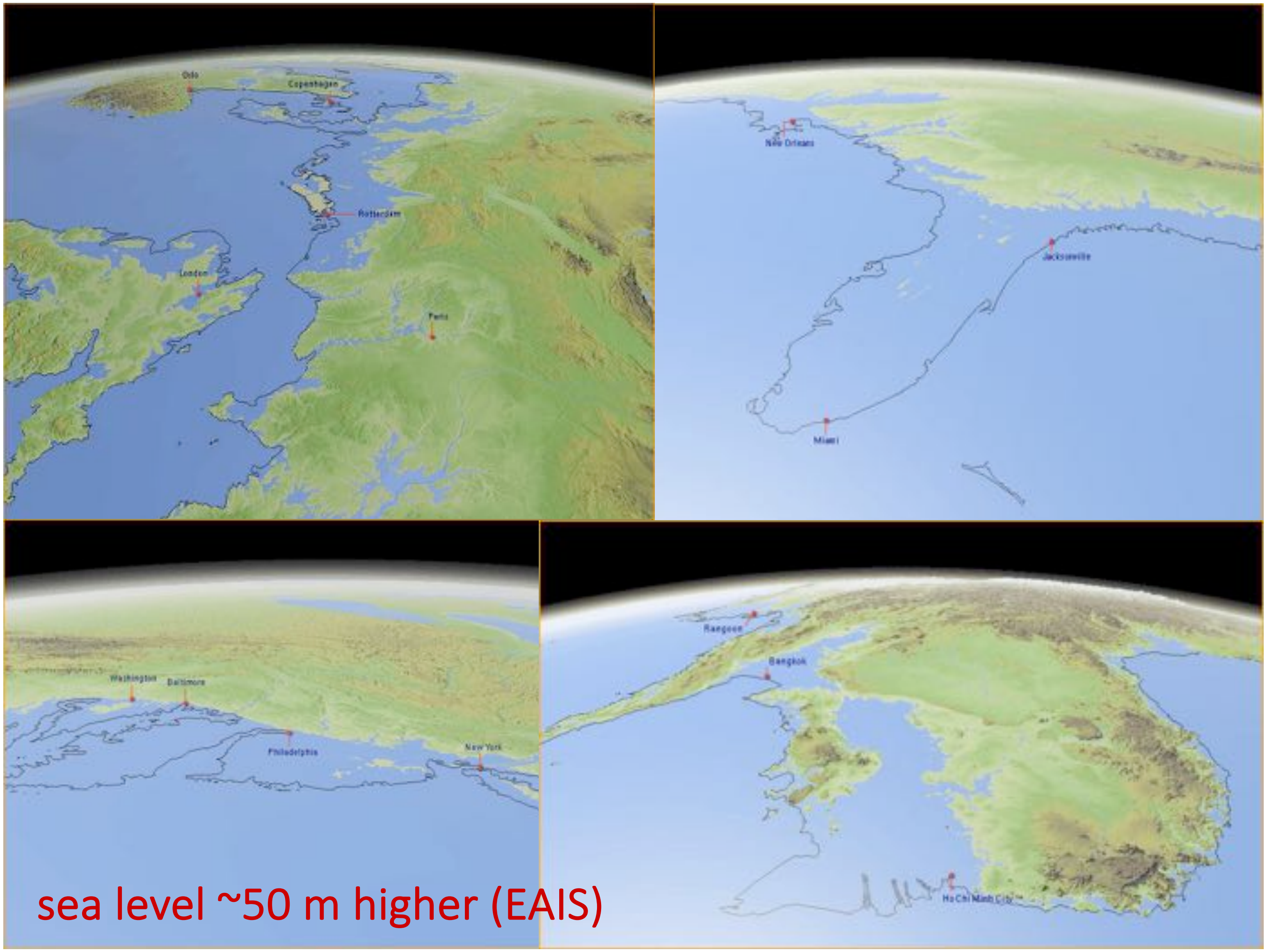




sea level ~120 m lower (last ice age)



sea level 6 m higher (WAIS or Greenland)


Oslo
Copenhagen
Rotterdam
London
Paris
New Orleans
Jacksonville
Miami
Washington
Baltimore
Philadelphia
New York
Rangoon
Bangkok
Ho Chi Minh City
sea level ~50 m higher (EAIS)

Today's focus -

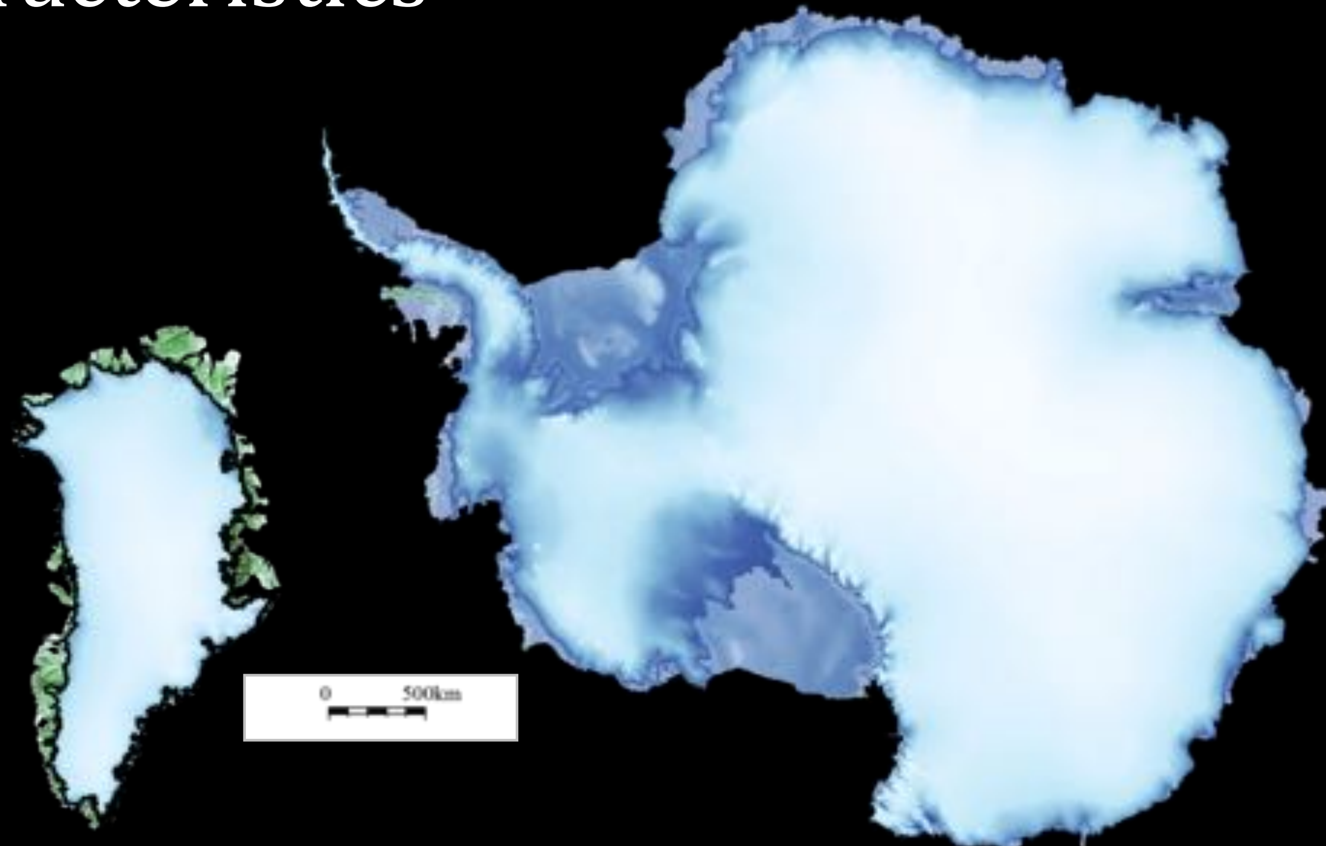
Characteristics of the Modern Ice Sheets

- Their Substrate
- Their Ice Flow Structure

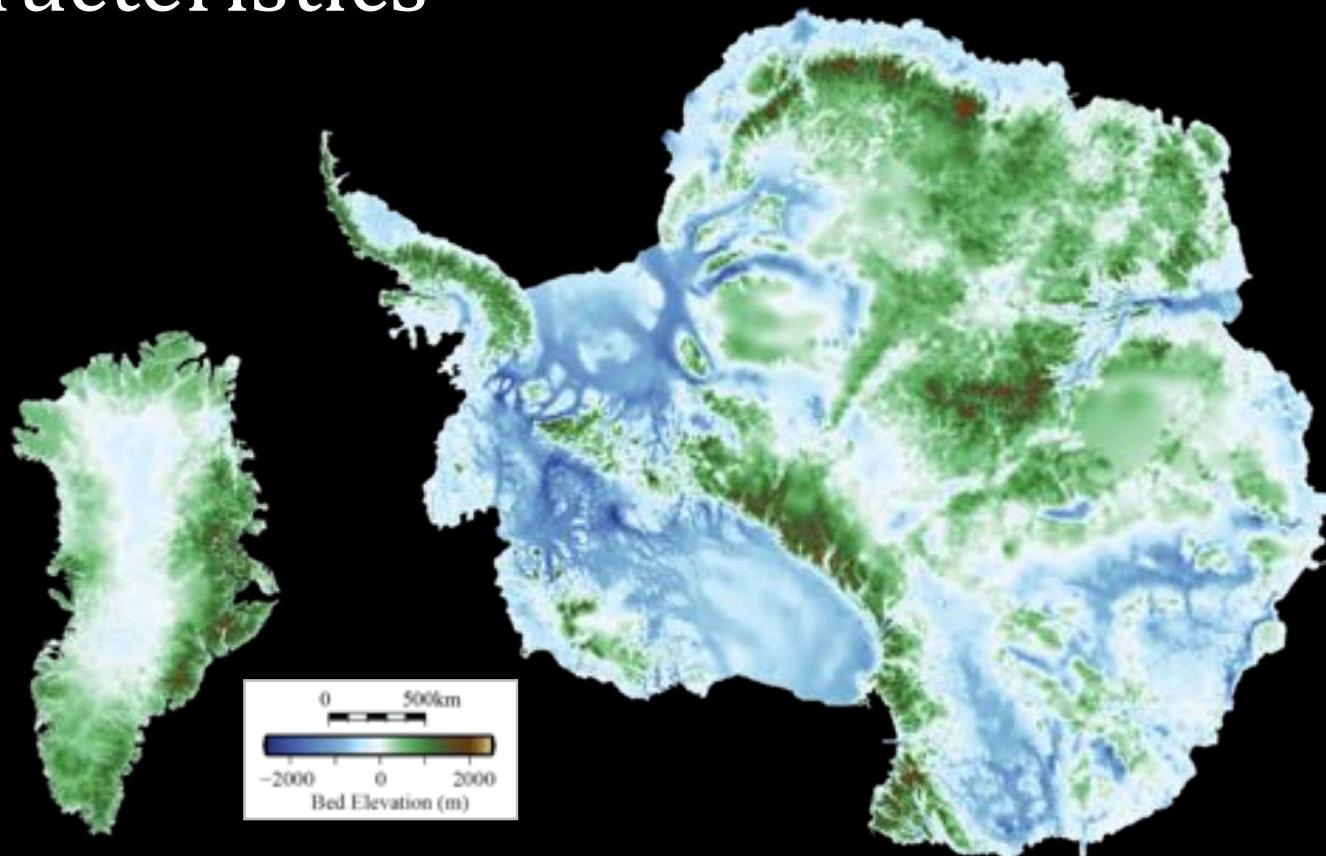
Processes that control their stability

- Ice Shelf Melt
- Marine Ice Sheet Instability

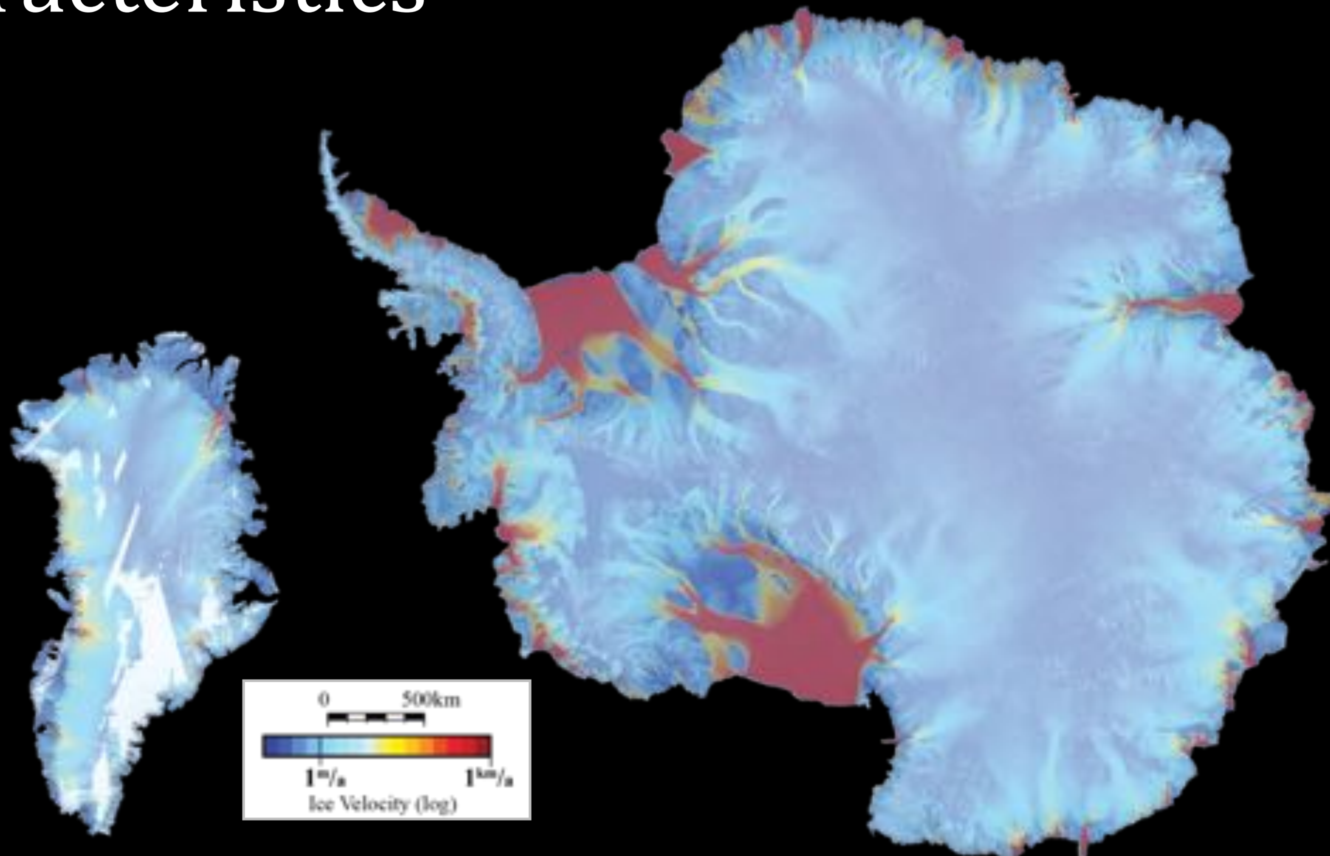
Modern Characteristics



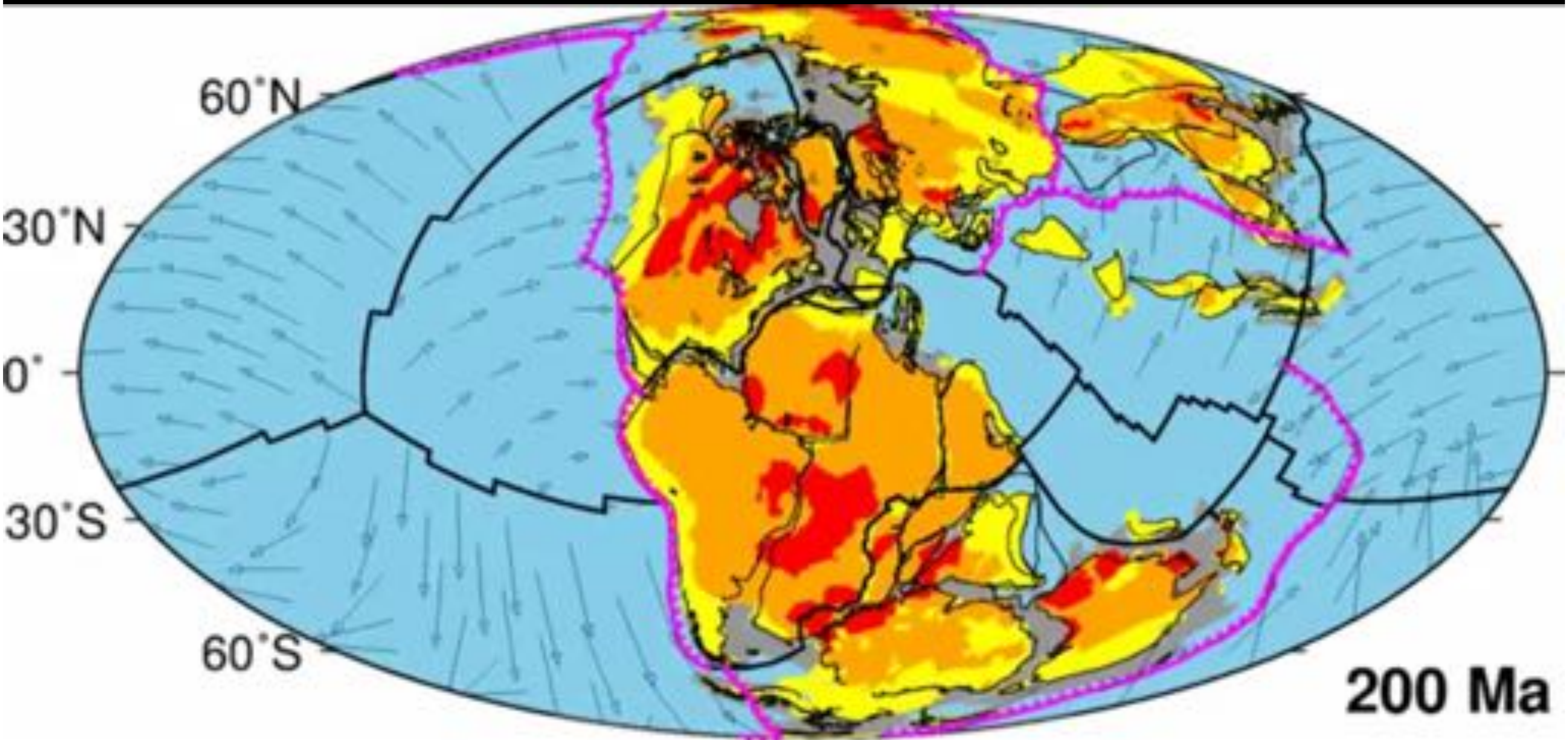
Modern Characteristics



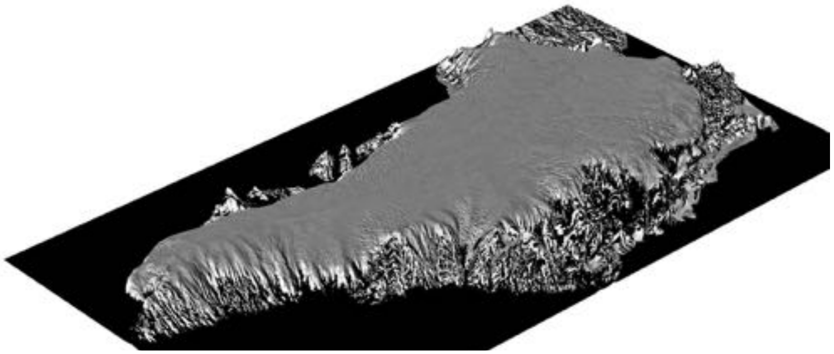
Modern Characteristics

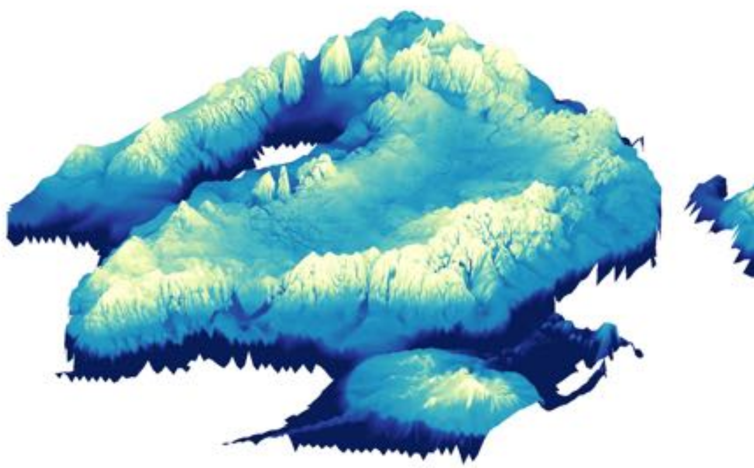


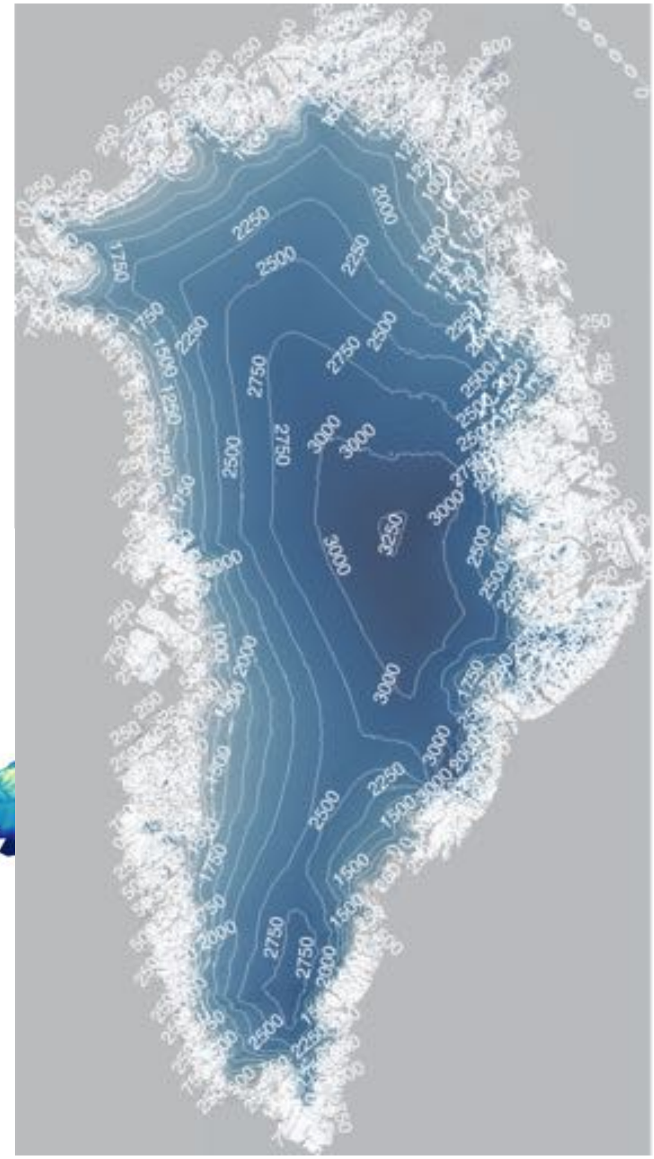
What Controls the Subglacial Topography in Greenland and Antarctica?


60°N
30°N
0°
30°S
60°S
200 Ma

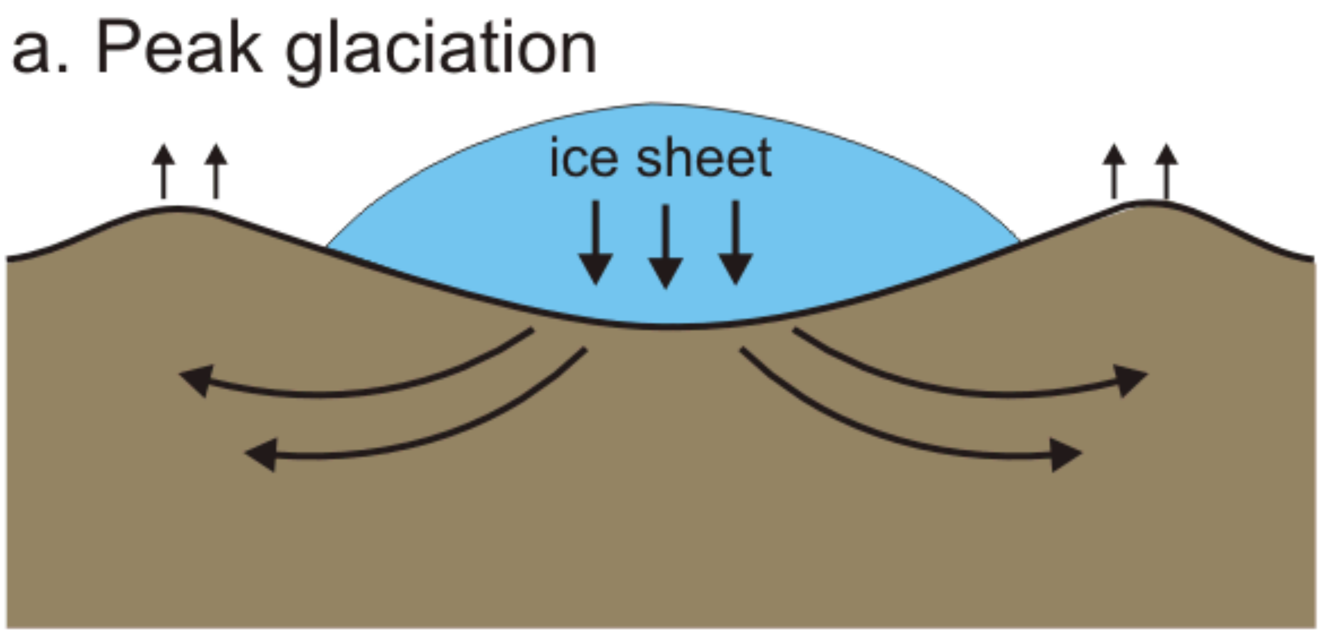
Greenland Surface and Bed Topography







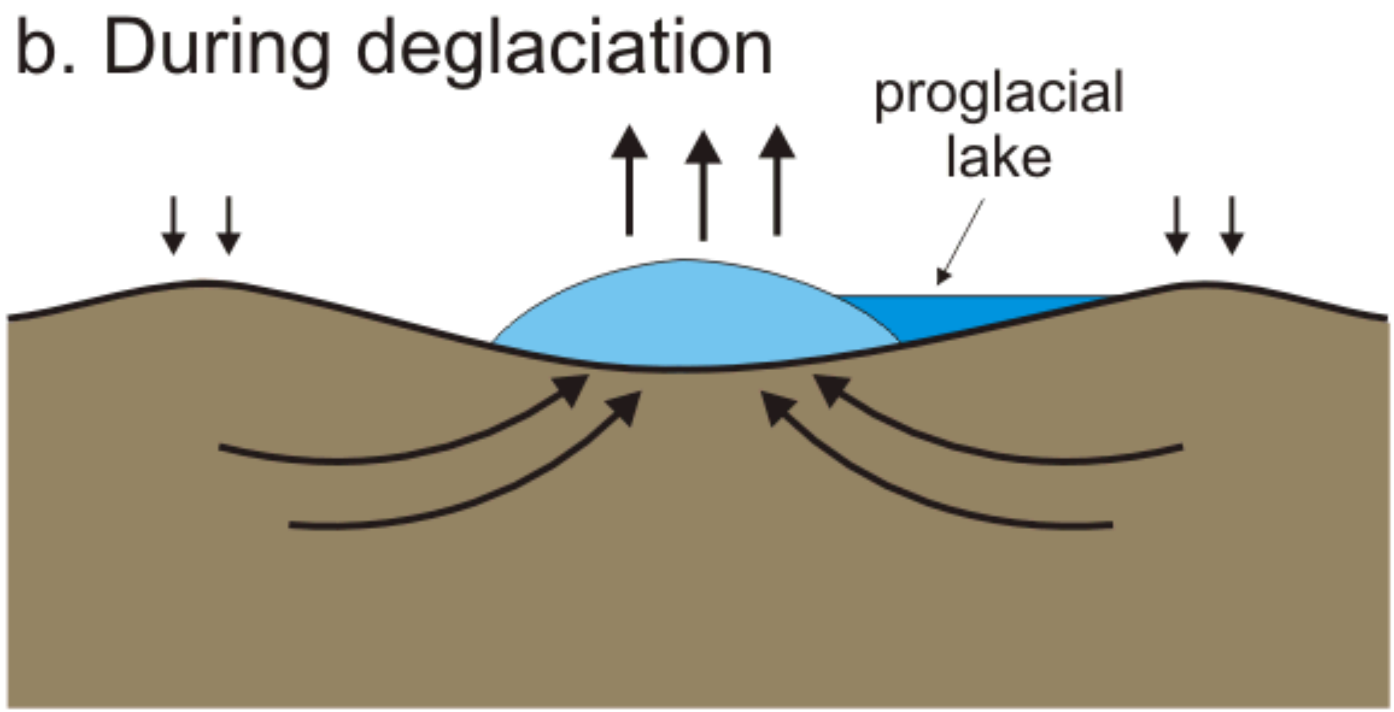
Isostatic Depression



- Soft material in asthenosphere is squeezed out
- Lithosphere bends and sinks
- Fore-bulges rise due to elasticity

http://www.pgc.nrcan.gc.ca/geodyn/docs/rebound/glacial.html

Isostatic Rebound



- Soft material in asthenosphere returns
- Lithosphere rises
- Fore-bulges drop

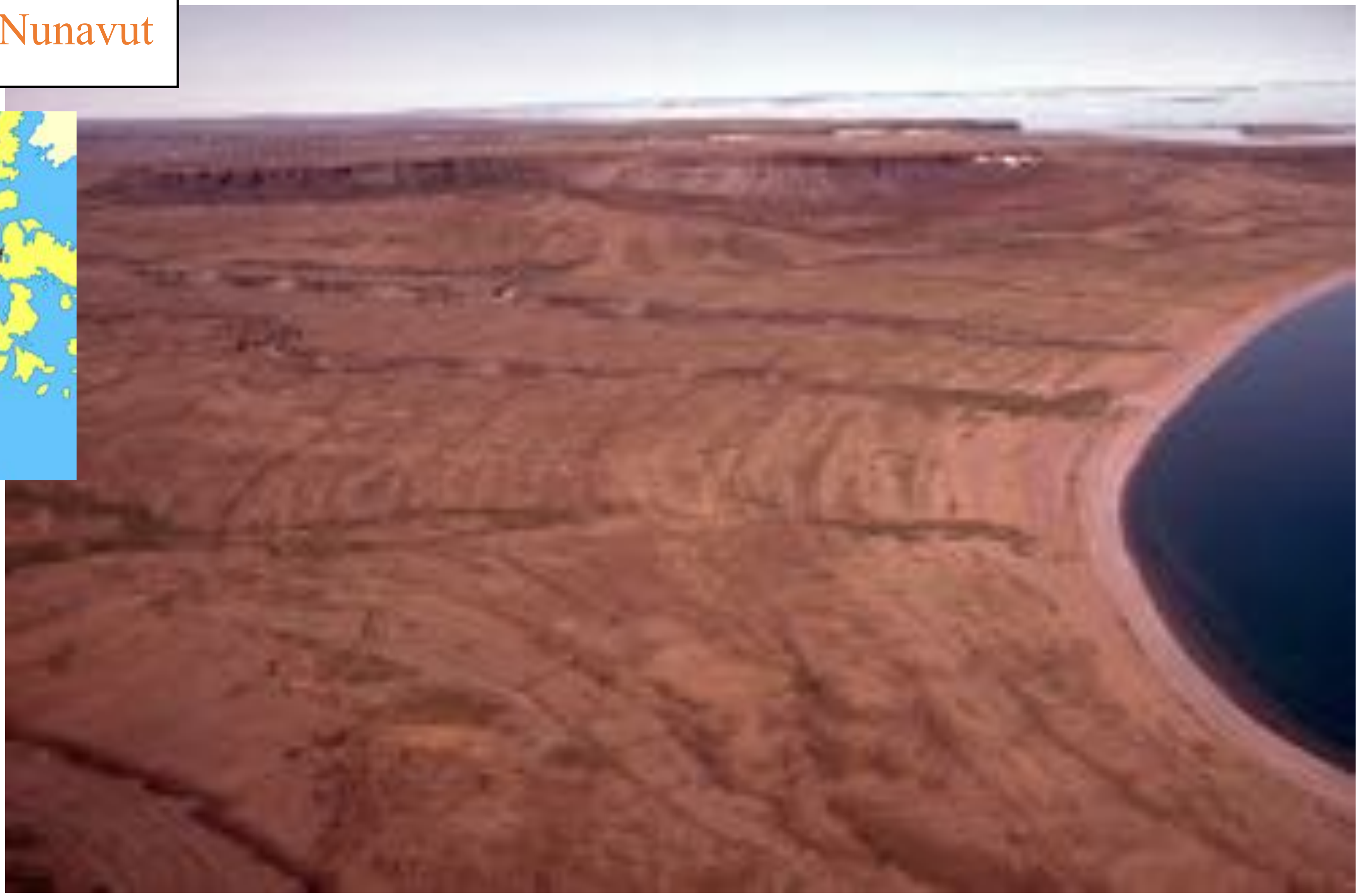
http://www.pgc.nrcan.gc.ca/geodyn/docs/rebound/glacial.html

Uplift in Scandinavia

The lithosphere still remembers that there was an ice age

Postglacial Rebound - Coronation Gulf, Nunavut

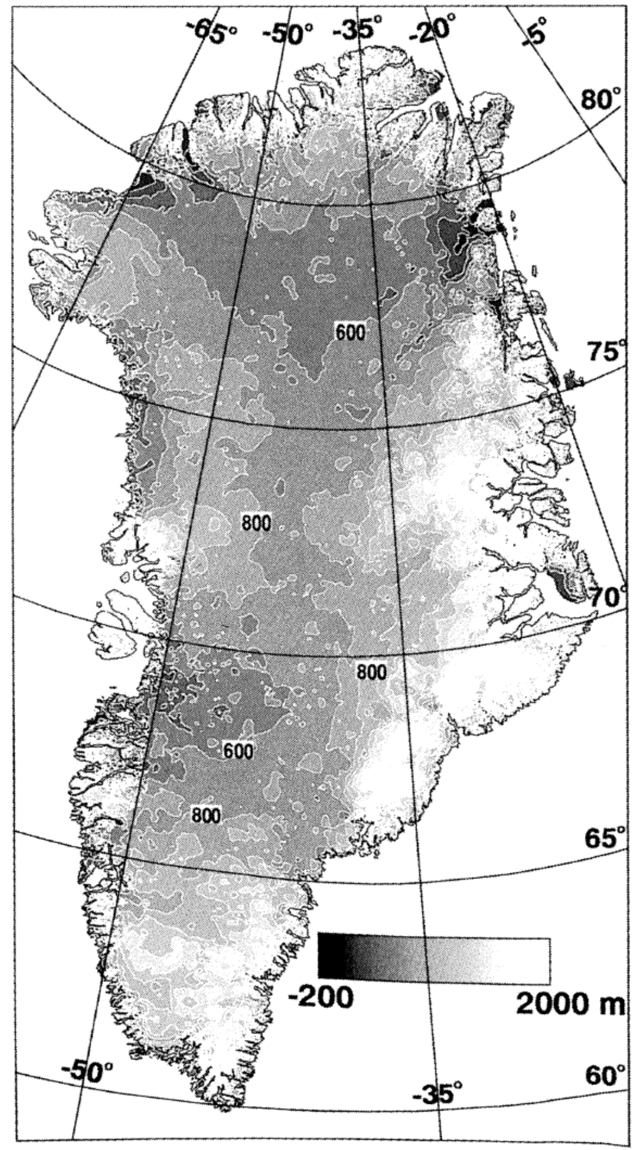
http://gsc.nrcan.gc.ca/landscapes/



Greenland Topography 15 ka after Ice Melts

Why is the bedrock now above sea level in the interior?

Bamber and others, *JGR Atmospheres* 106(D24), 33,773, 2001.

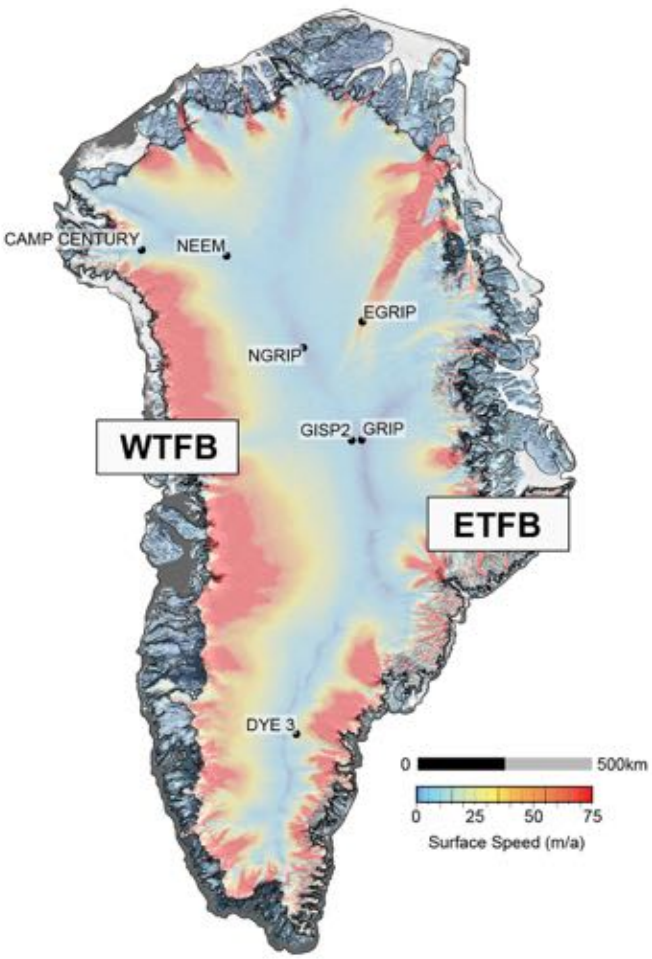


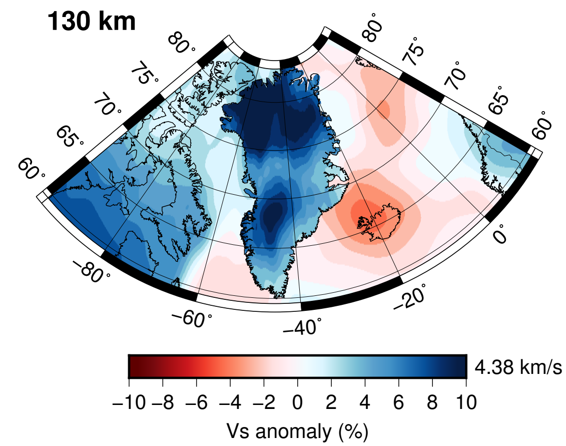
Greenland:

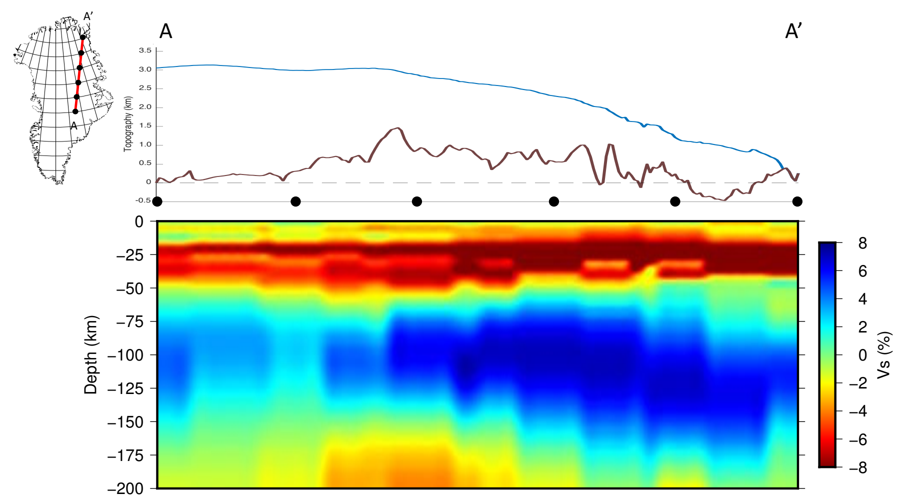
- Tectonically stable for a long time
- Old, thick continental crust, weighed down by the modern ice sheet

Is this an accurate depiction of Greenland?

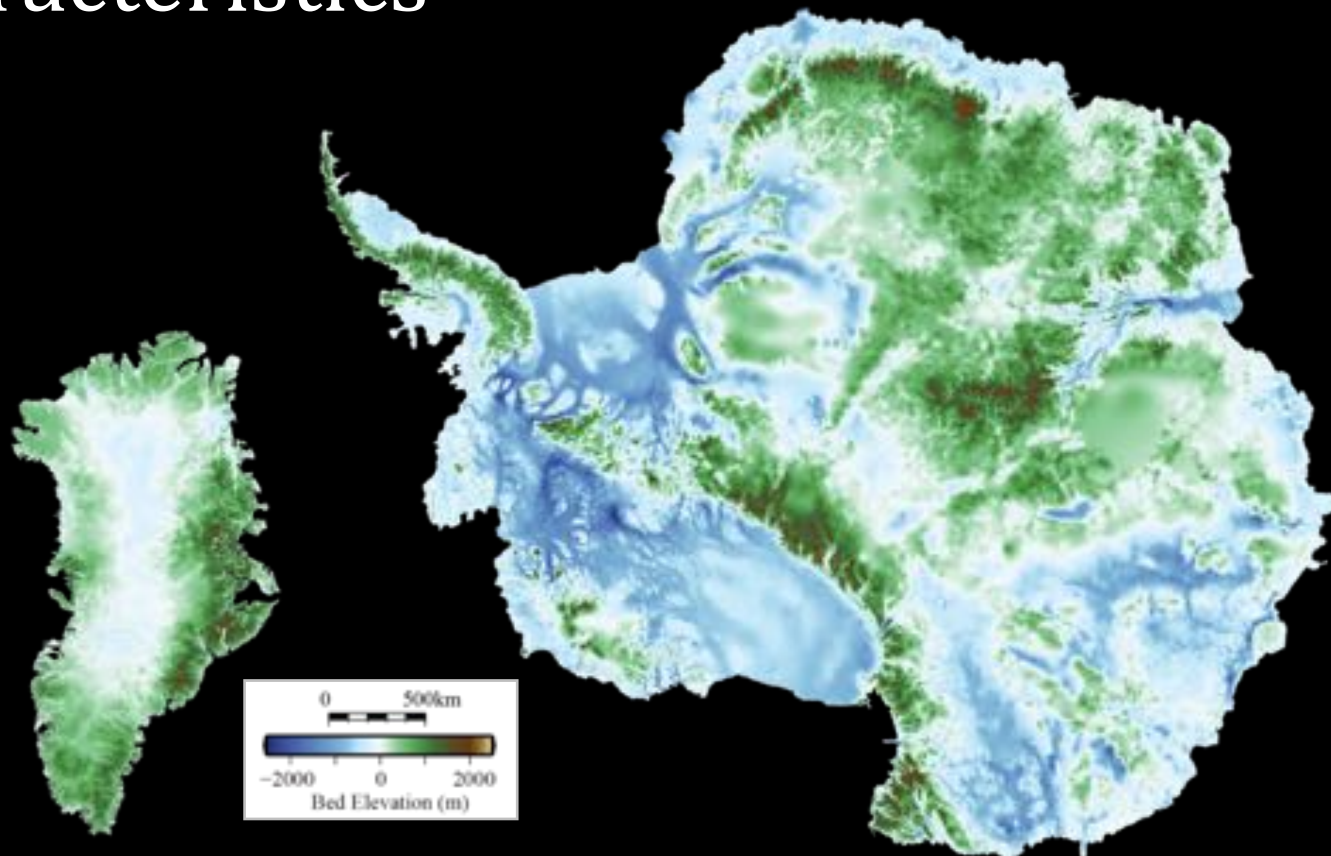
Higher geothermal flux in central Greenland?



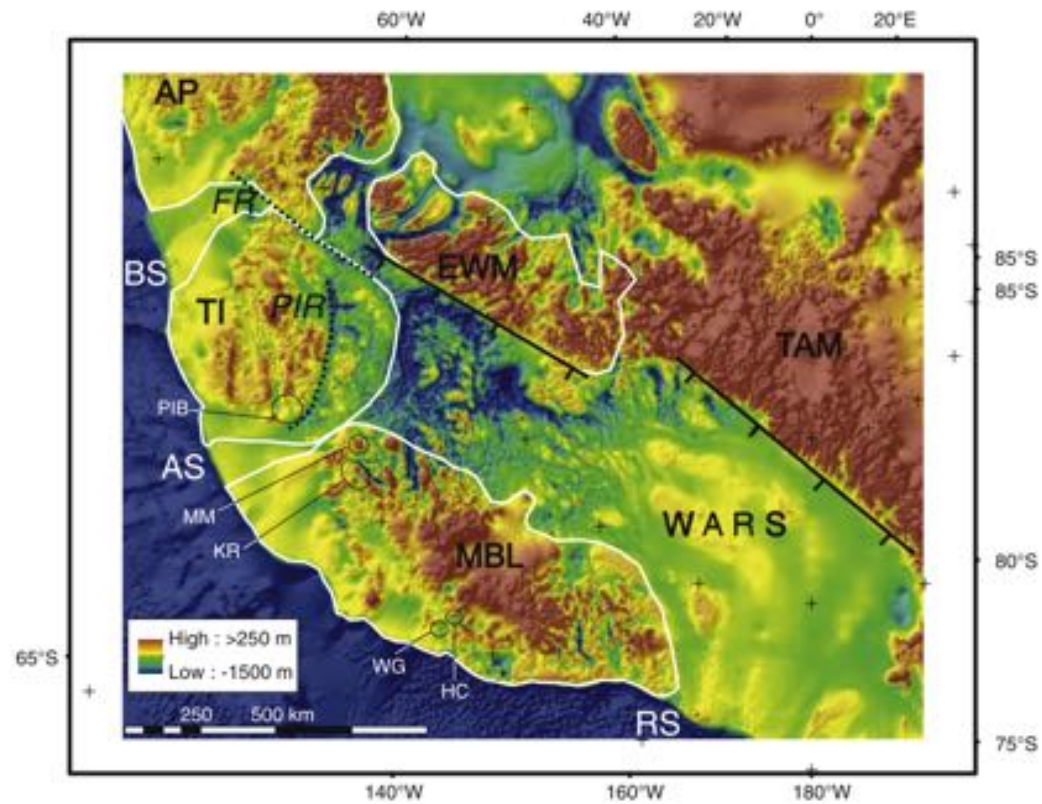




Modern Characteristics

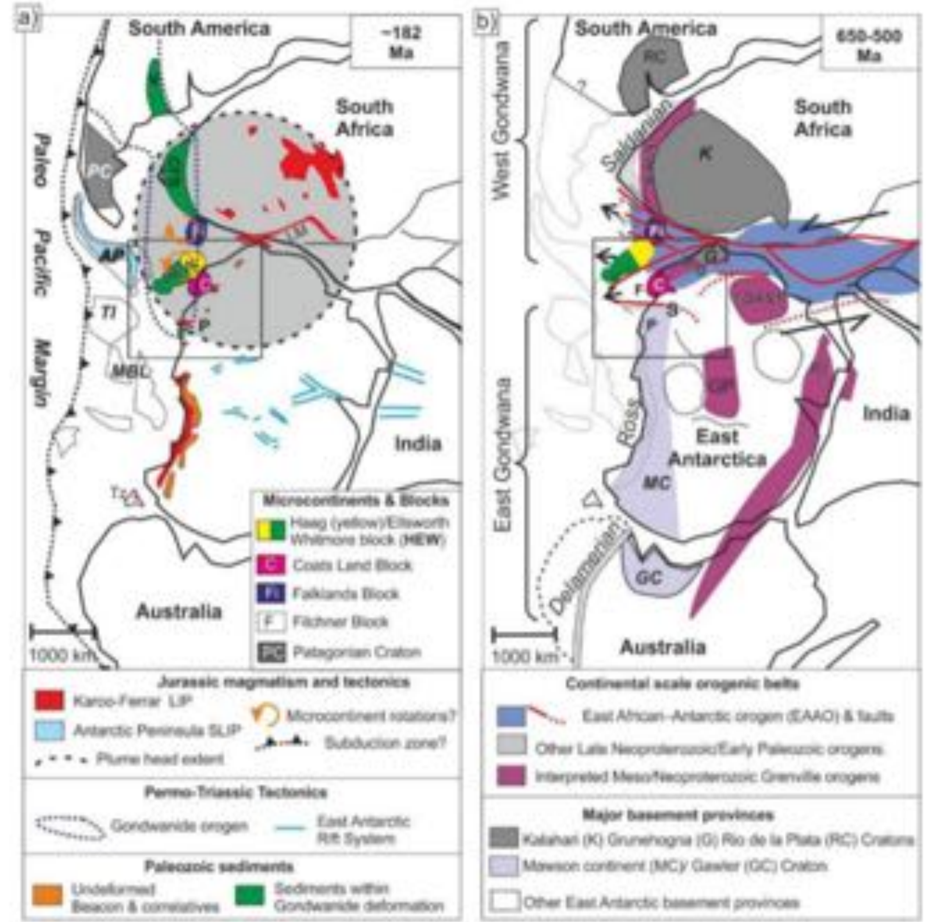


- Antarctica is composed of many distinct geologic terranes, many of which are quite old.



Spiegel et al. (2016)

- Antarctica is composed of many distinct geologic terranes, many of which are quite old.
- The West Antarctic Ice Sheet is mostly younger, thinner crust, formed from recent rifting



Jordan et al. (2017)

Greenland:

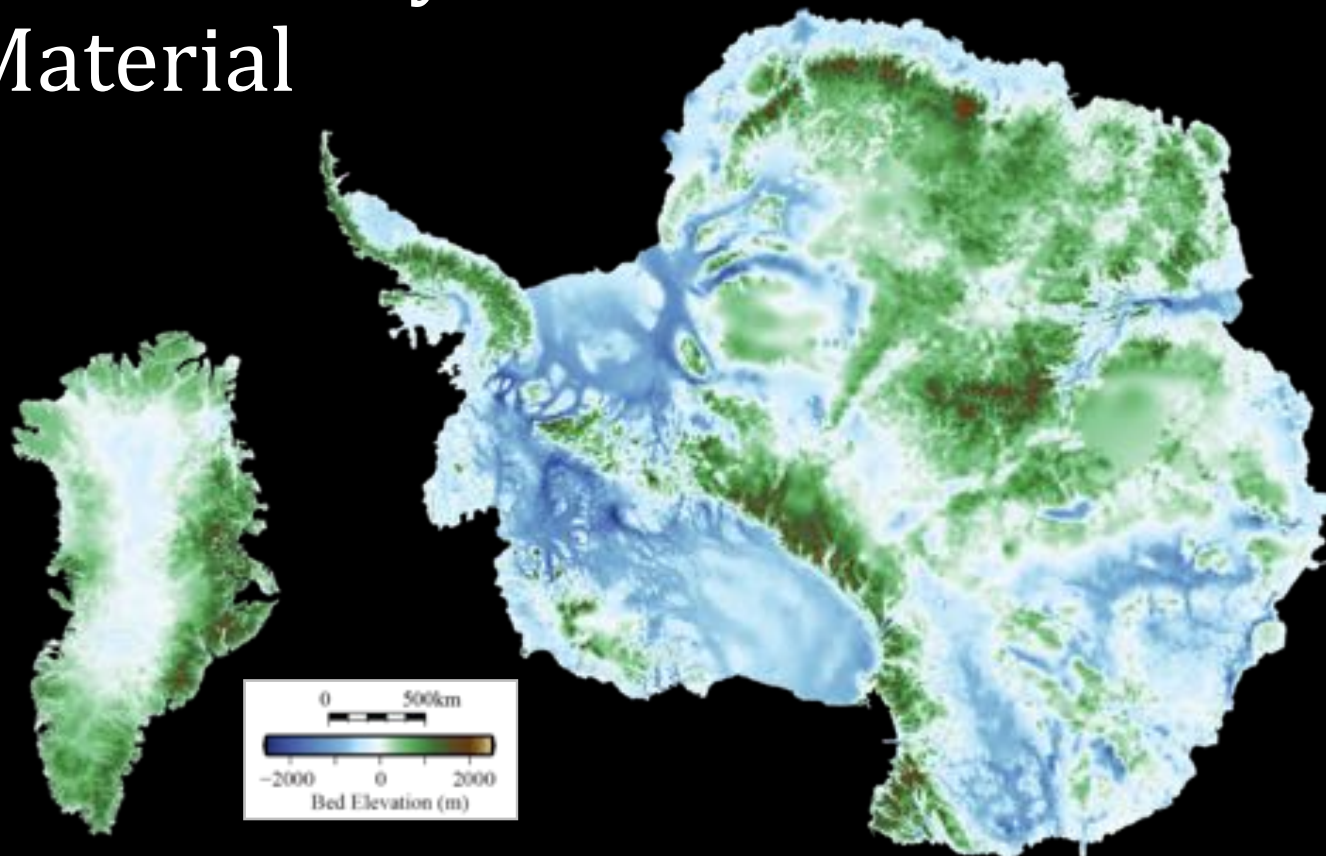
- Tectonically stable for a long time
- Old, thick continental crust, weighed down by the modern ice sheet

Antarctica:

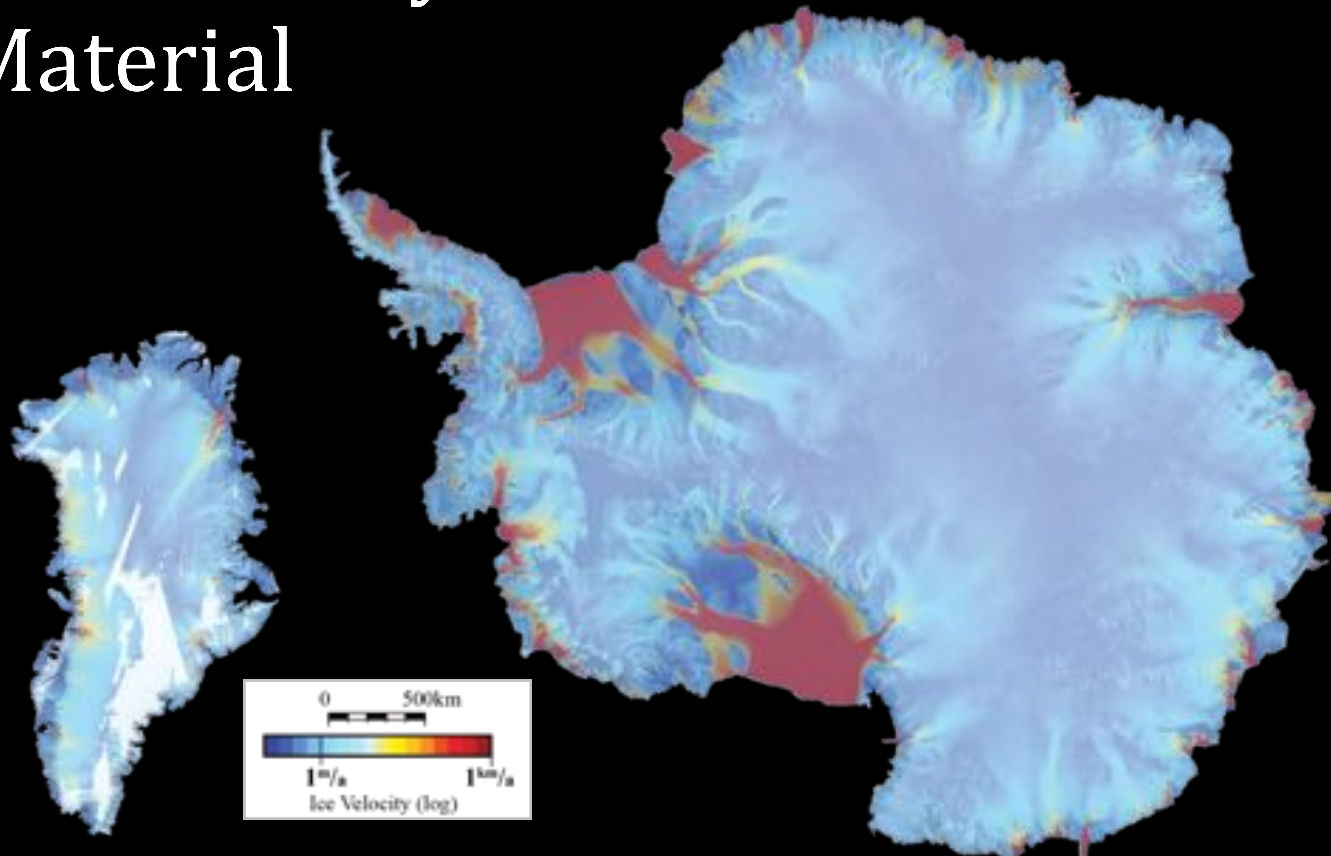
- East Antarctica is old, thick, cratonic crust
- West Antarctica is young, thin, rift generated crust

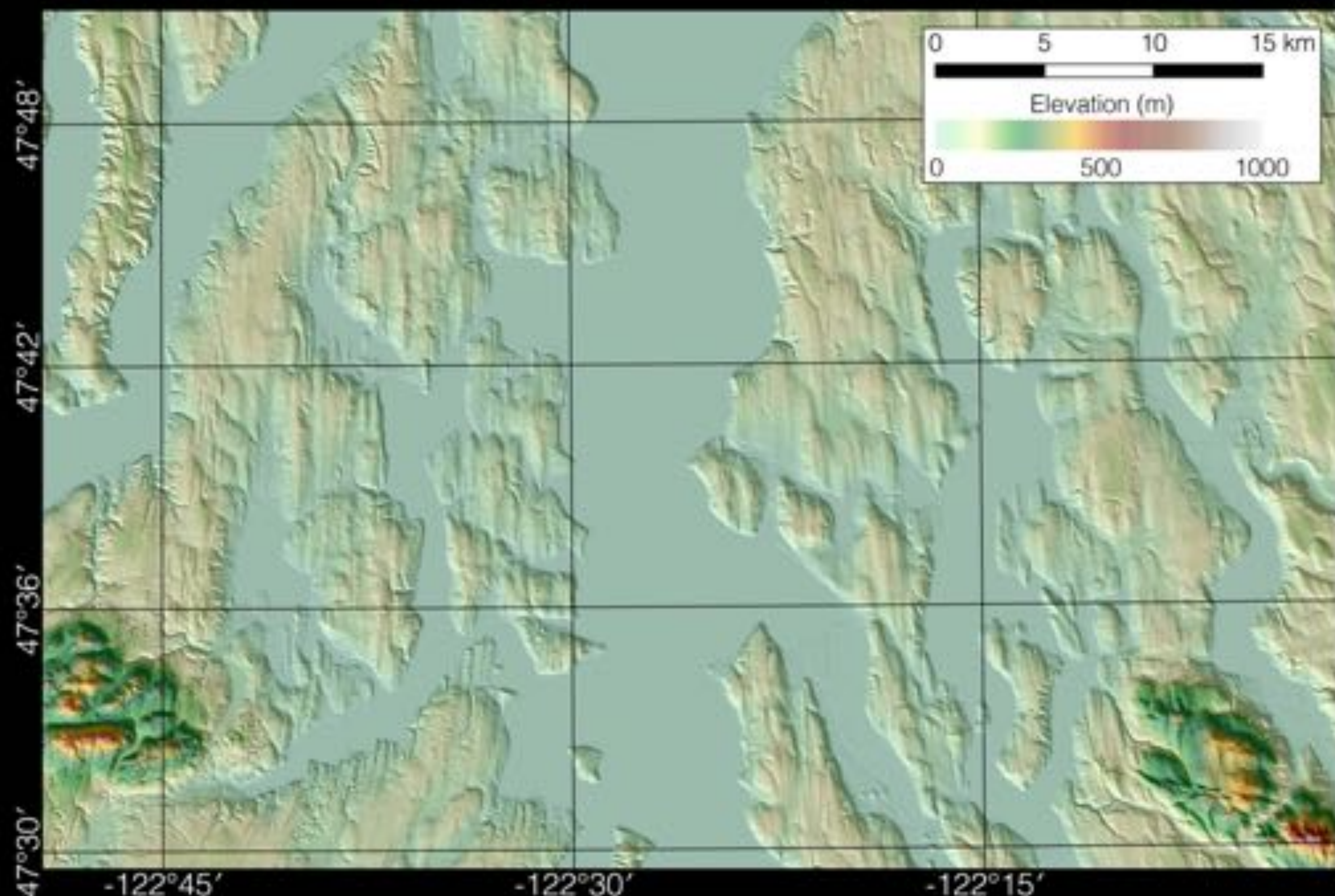
What consequences do the substrate have on Ice Flow?

Ice Flow is Controlled by Geometry + Material

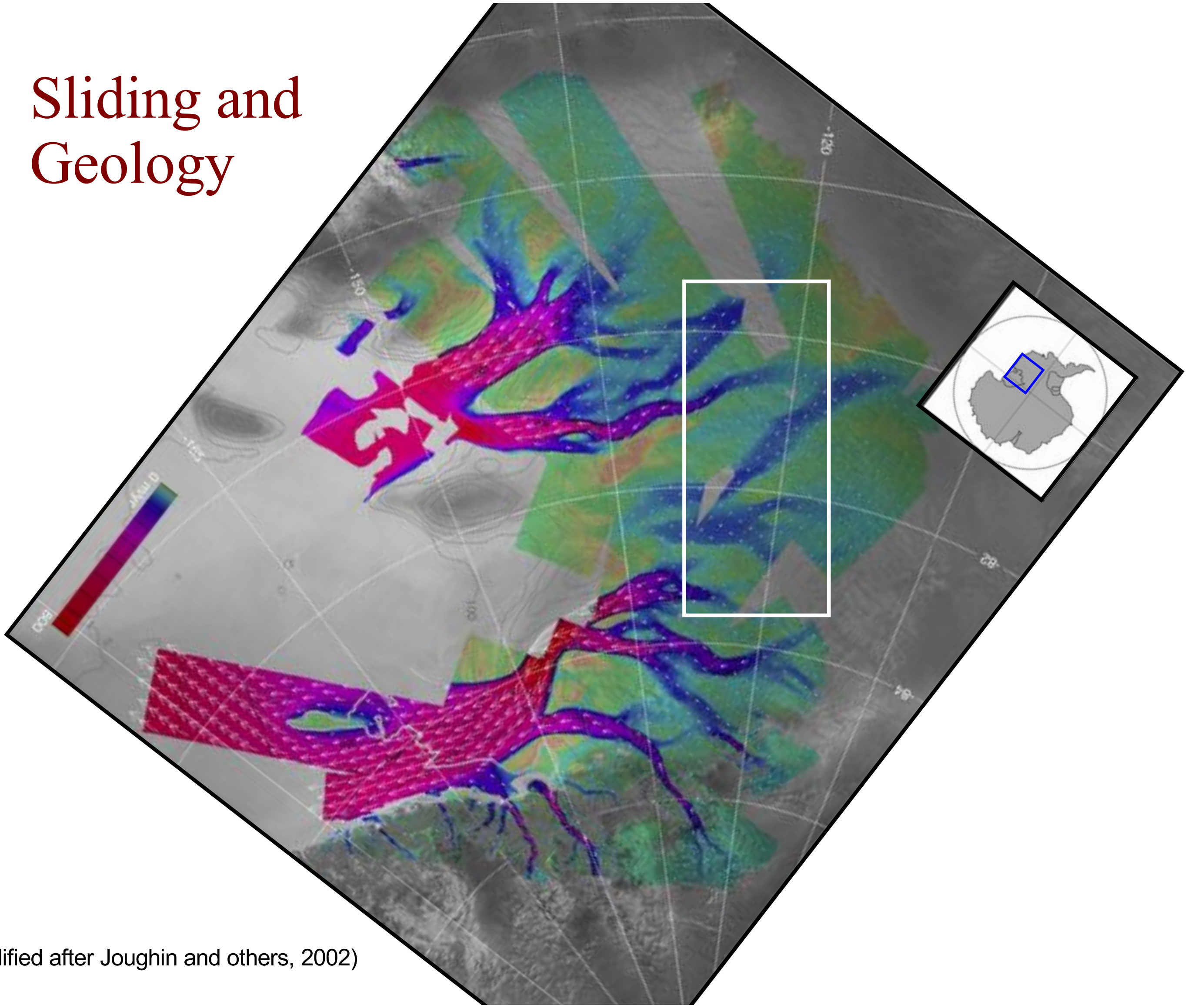


Ice Flow is Controlled by Geometry + Material




0 5 10 15 km
Elevation (m)
0 500 1000
47°48′
47°42′
47°36′
47°30′
-122°45′
-122°30′
-122°15′

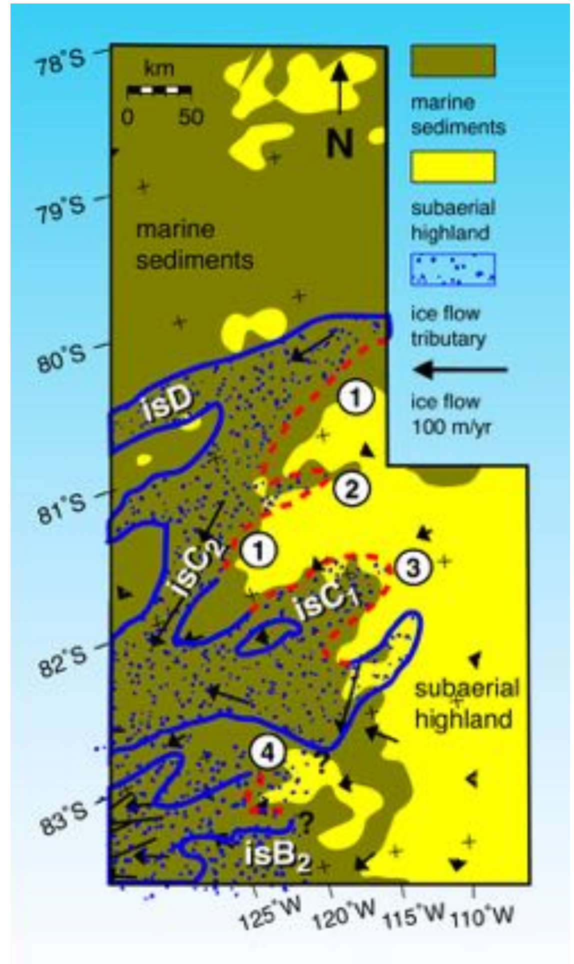
Sliding and Geology



(modified after Joughin and others, 2002)

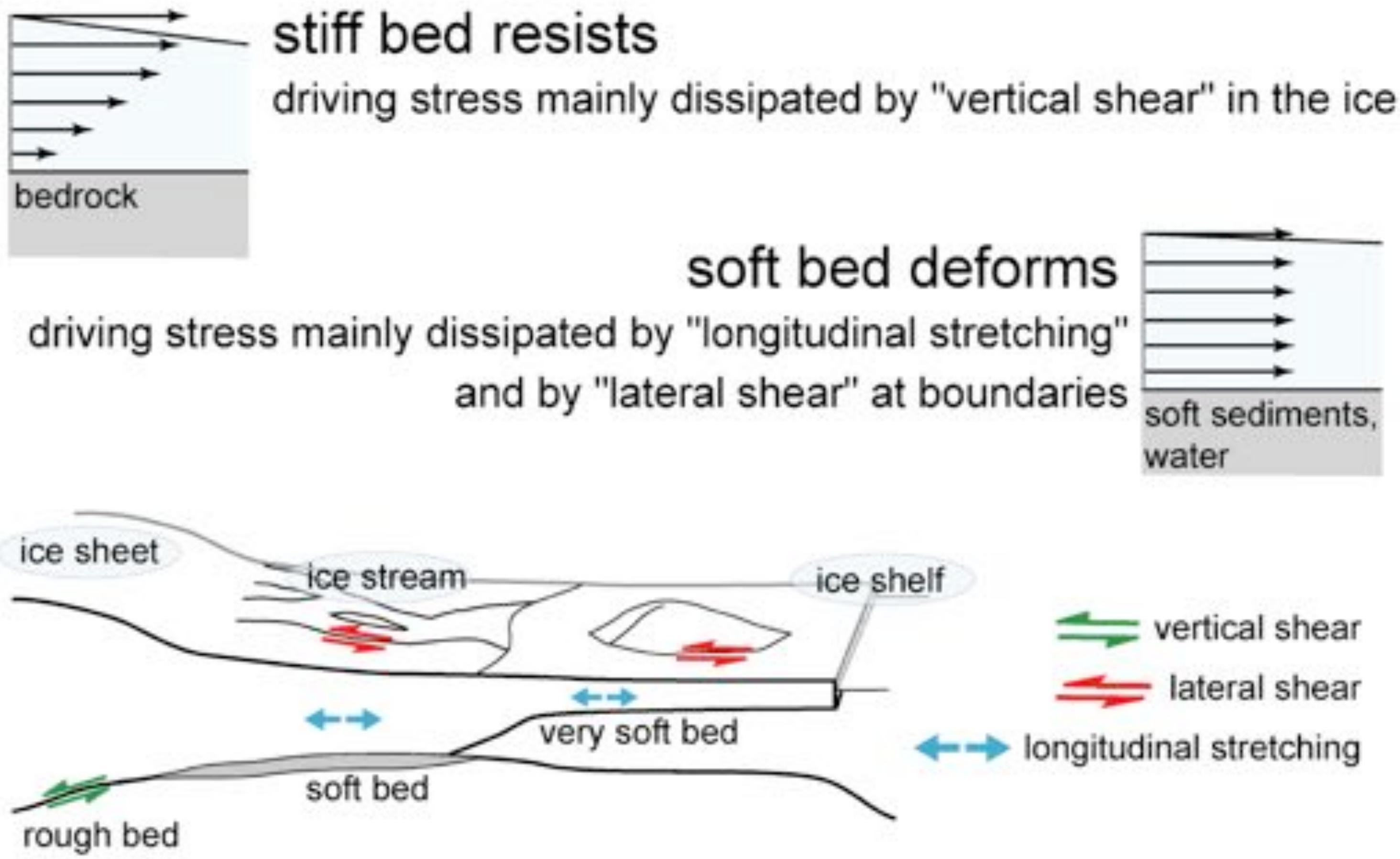
- Soft, sea-floor sediments promote faster flow
- Hard, crystalline bedrock promotes slower flow

The availability of soft sediments is one factor that dictates the location and speed of ice streams



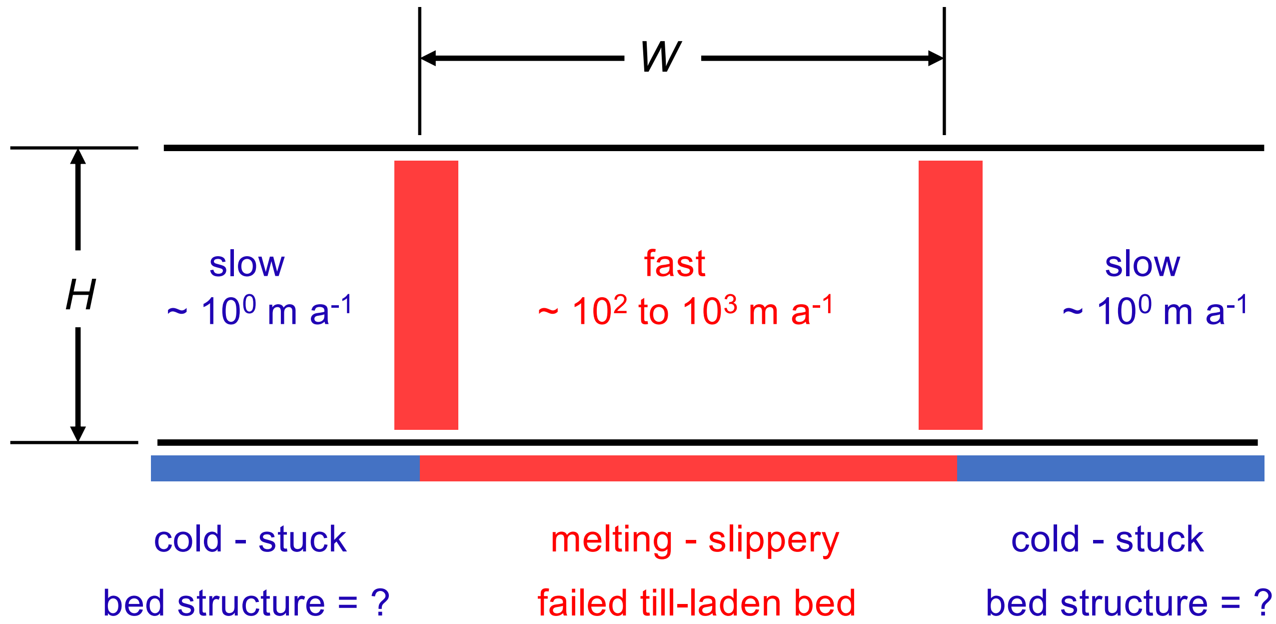
Studinger and others (2000, WAIS Workshop)

ice sheet flow



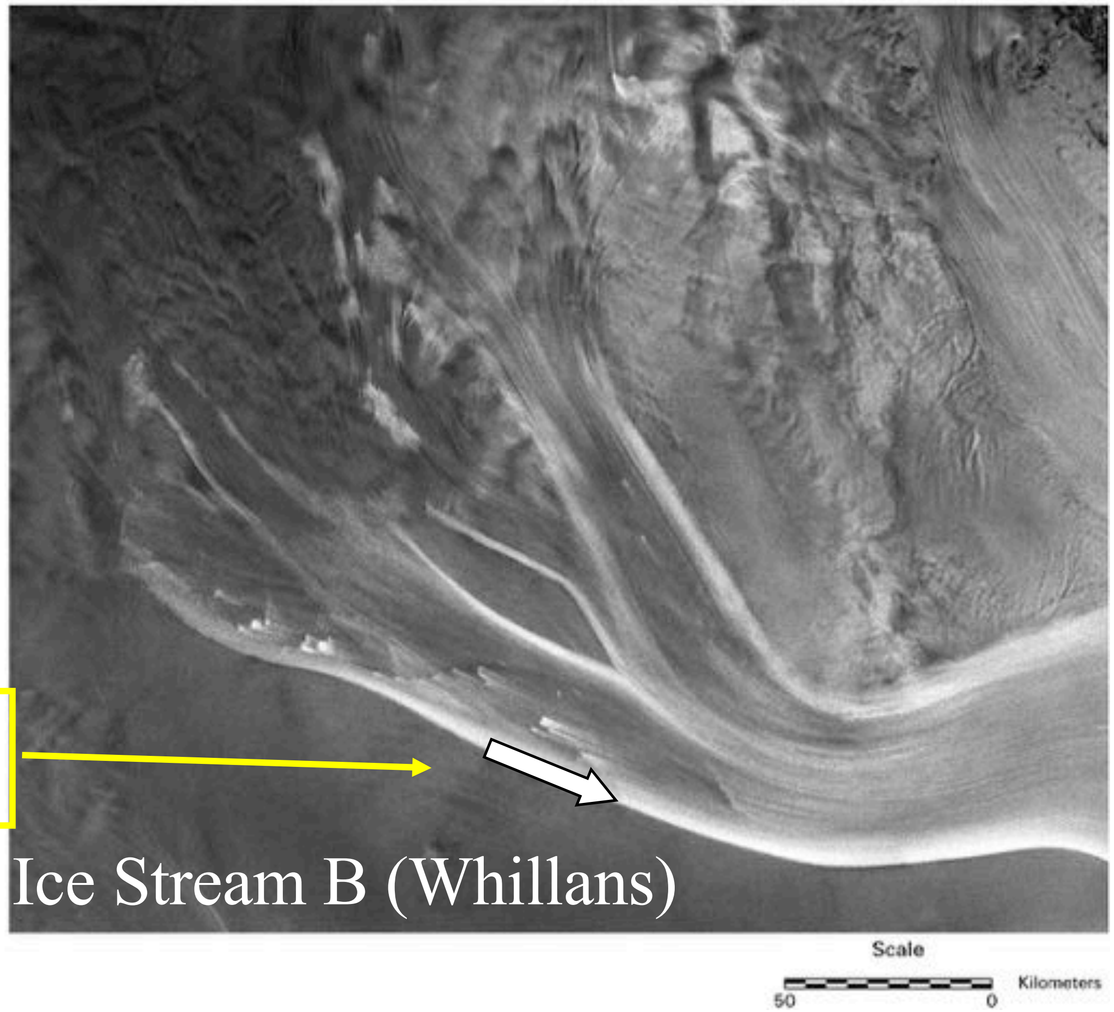
(courtesy of C. Hulbe, Portland State Univ.)

Schematic Ice Stream Cross Section



ice thickness $H \sim 10^0$ km
half width $W \sim 10^1$ km

Note abrupt
shear margins

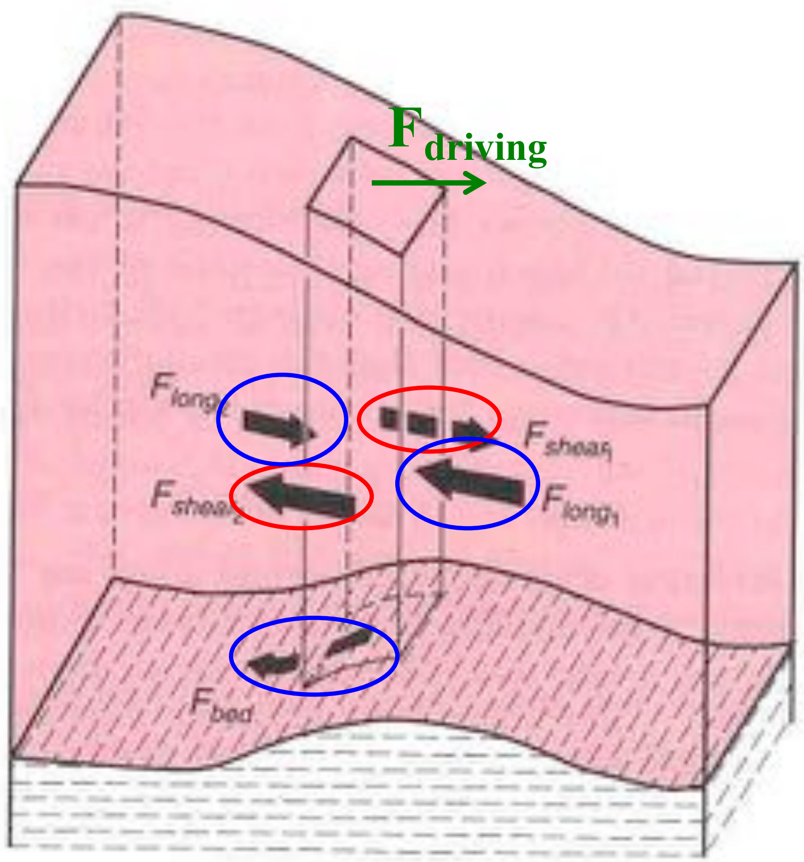


(source: http://nsidc.org/data/ramp/gallery/icestreamb_mapw.html)

Margin of Ice Stream D (Bindschadler)

Photo by Nadine Nereson

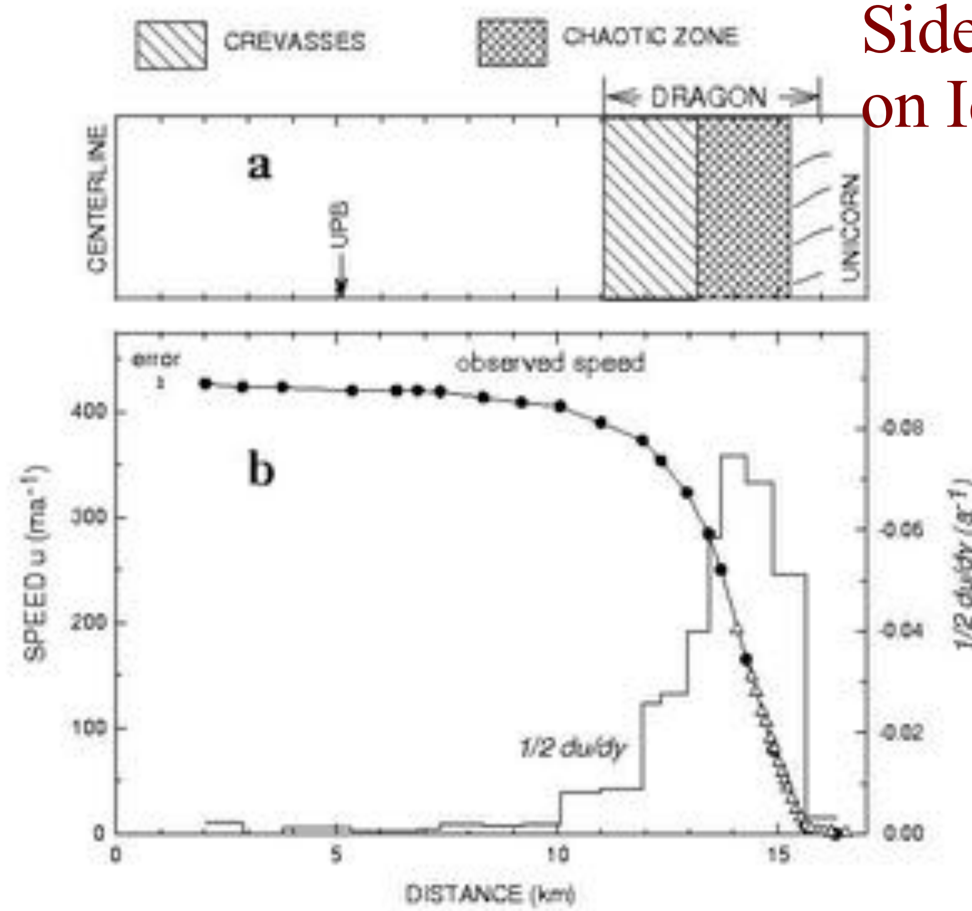
Forces Resisting Driving Stress: Ice Stream



Large

Small

Side Drag is Huge on Ice Streams



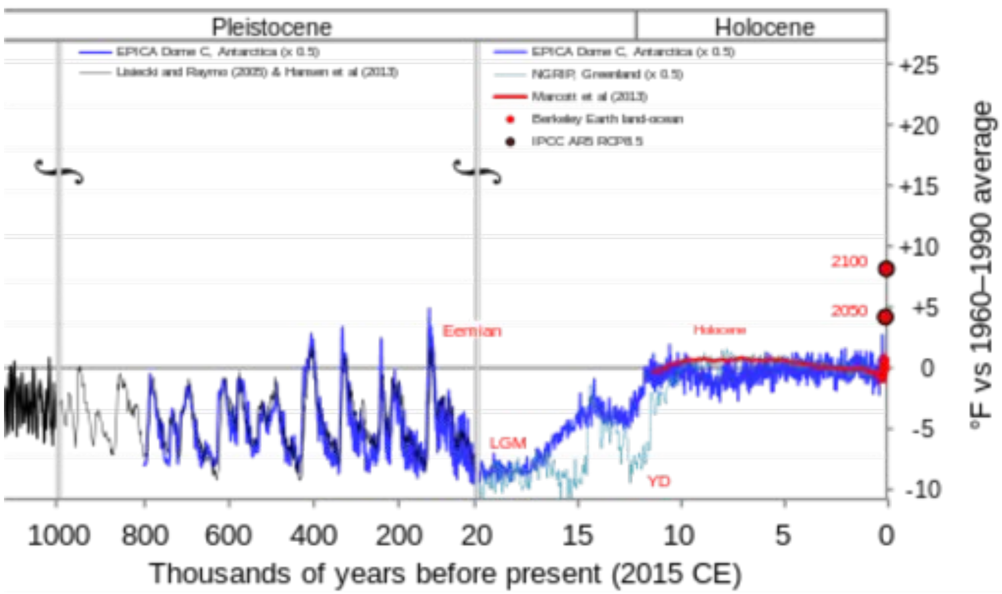
From Echelmeyer et al. (1994, JGlac.)

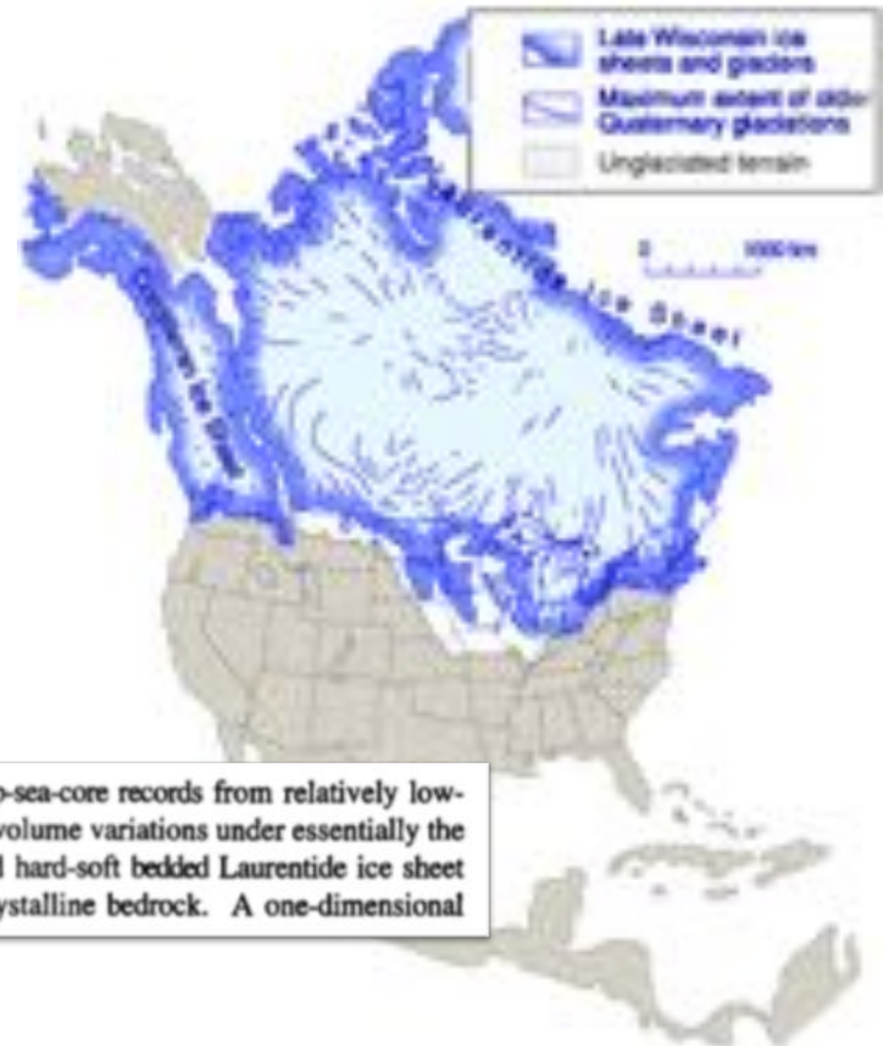
Ice Stream B (Whillans)

Side drag > 50% of τ_d

(Here τ is not a characteristic time)

$\tau_d = \rho g h \sin(\theta)$ would be the basal shear stress, in absence of side drag and longitudinal forces.





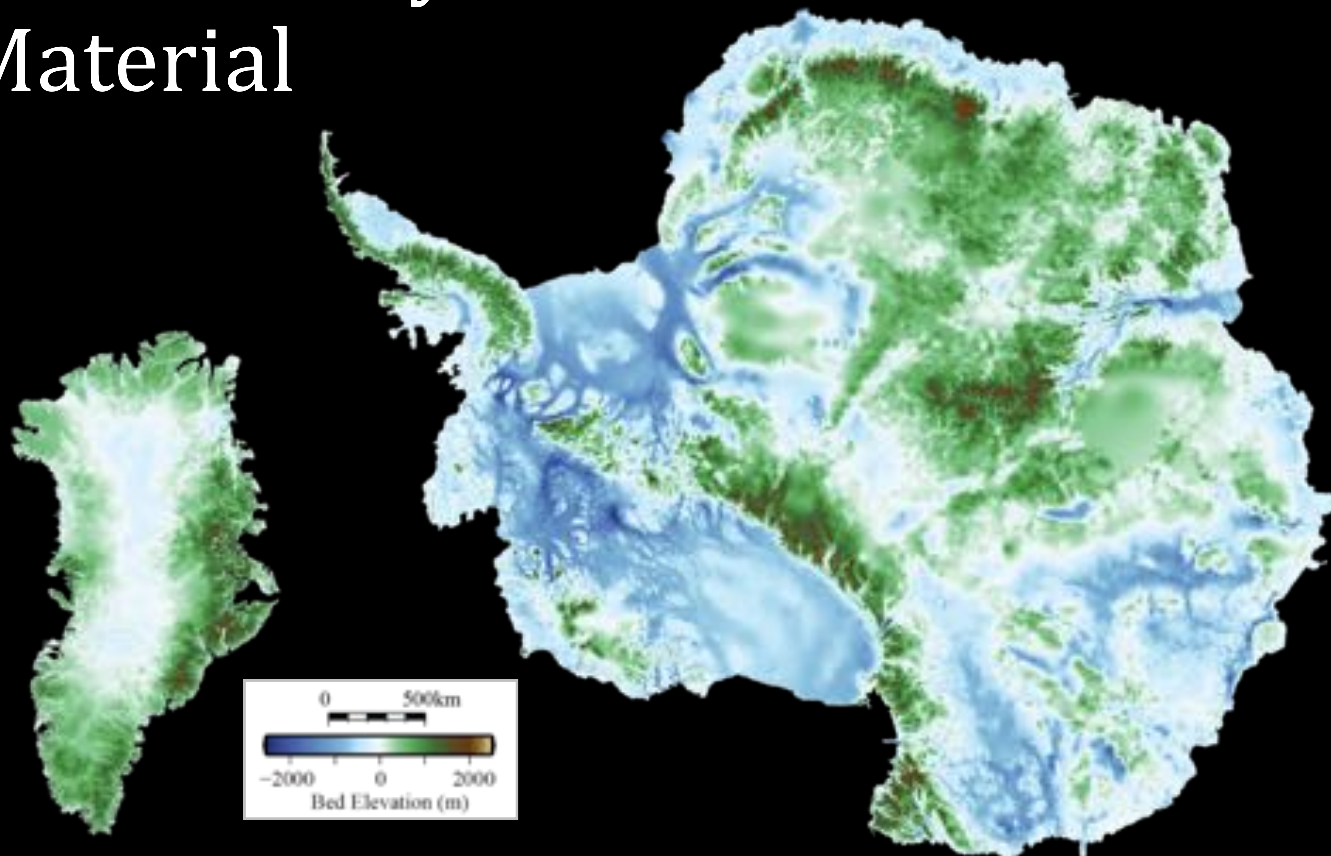
Abstract. The transition in the middle Pleistocene (~0.9 Ma) seen in $\delta^{18}O$ deep-sea-core records from relatively low-amplitude, high-frequency (41 kyr) to high-amplitude, low-frequency (100 kyr) ice volume variations under essentially the same orbital forcing can be attributed to a change from an all soft-bedded to a mixed hard-soft bedded Laurentide ice sheet through glacial erosion of a thick regolith and resulting exposure of unweathered crystalline bedrock. A one-dimensional

Clark and Pollard, 1998

- Antarctica and Greenland are Tectonically and Geologically Distinct

What are the consequences for Ice Sheet stability?

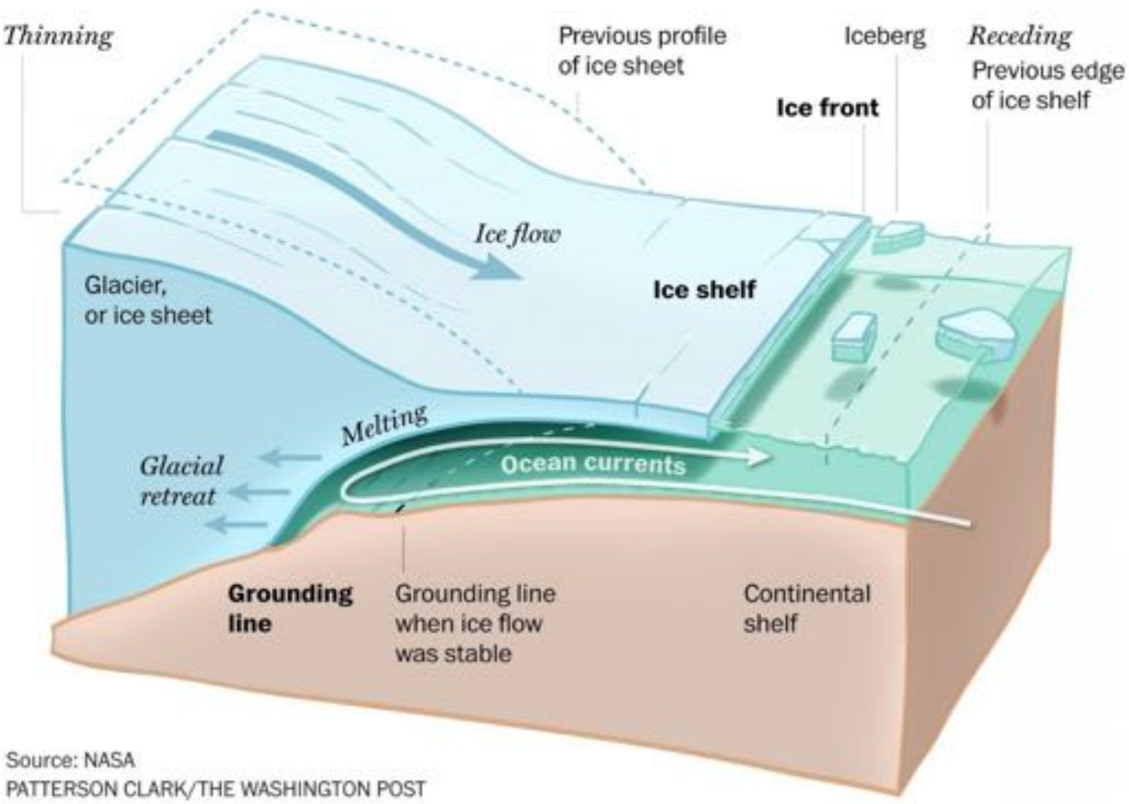
Ice Flow is Controlled by Geometry + Material



The Marine Ice-Sheet Instability

The problem with a retrograde bed

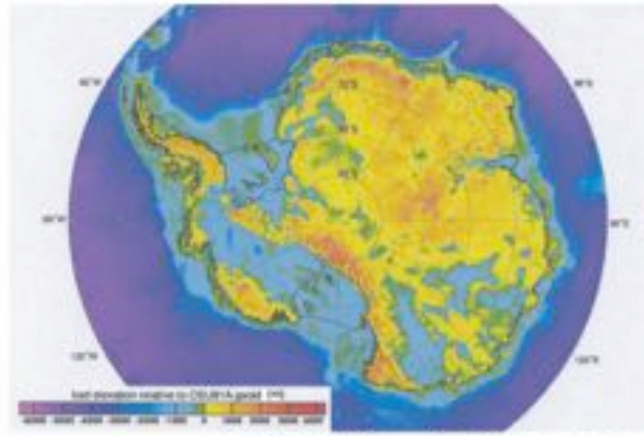
The bedrock under the front of some Antarctic glaciers slopes down and away from the sea bed, making the glaciers especially vulnerable to collapse. Warm, circumpolar deep water flows in under the glacier's ice shelf, melting the glacier's base, causing it to race into the sea at a faster pace, which leads to thinning and recession of the ice sheet.



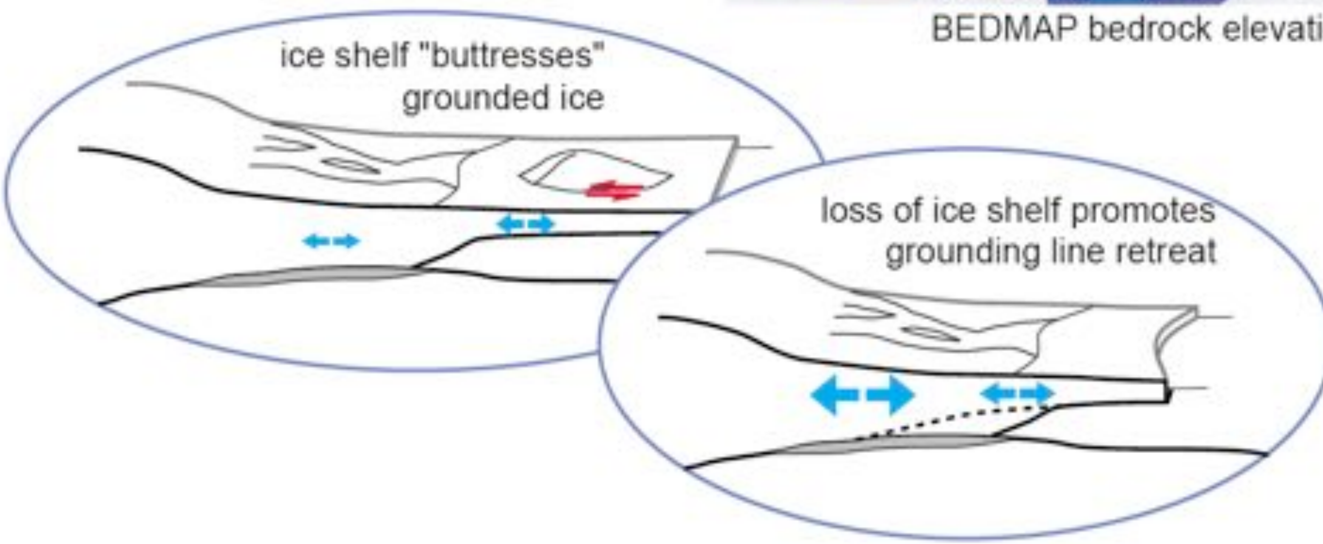
Source: NASA
PATTERSON CLARK/THE WASHINGTON POST

marine ice sheet instability hypothesis

1. resistive stresses in the ice shelf resist driving stress at the grounding line
2. removal of ice shelf increases lateral spreading at the grounding line, causing the ice to go afloat
3. floating ice spreads more quickly than grounded ice
4. grounding line retreats into inland-deepening basin



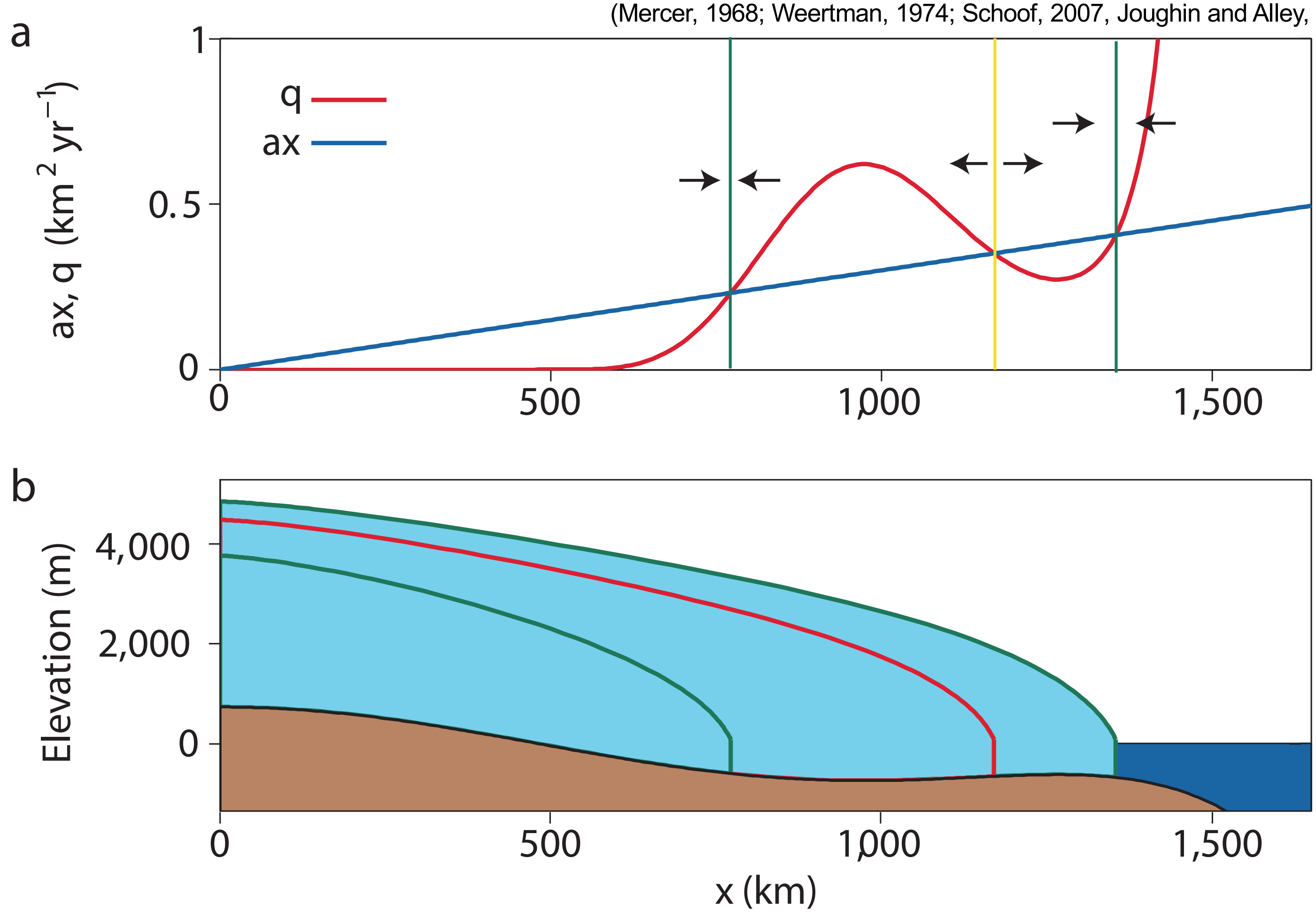
BEDMAP bedrock elevation



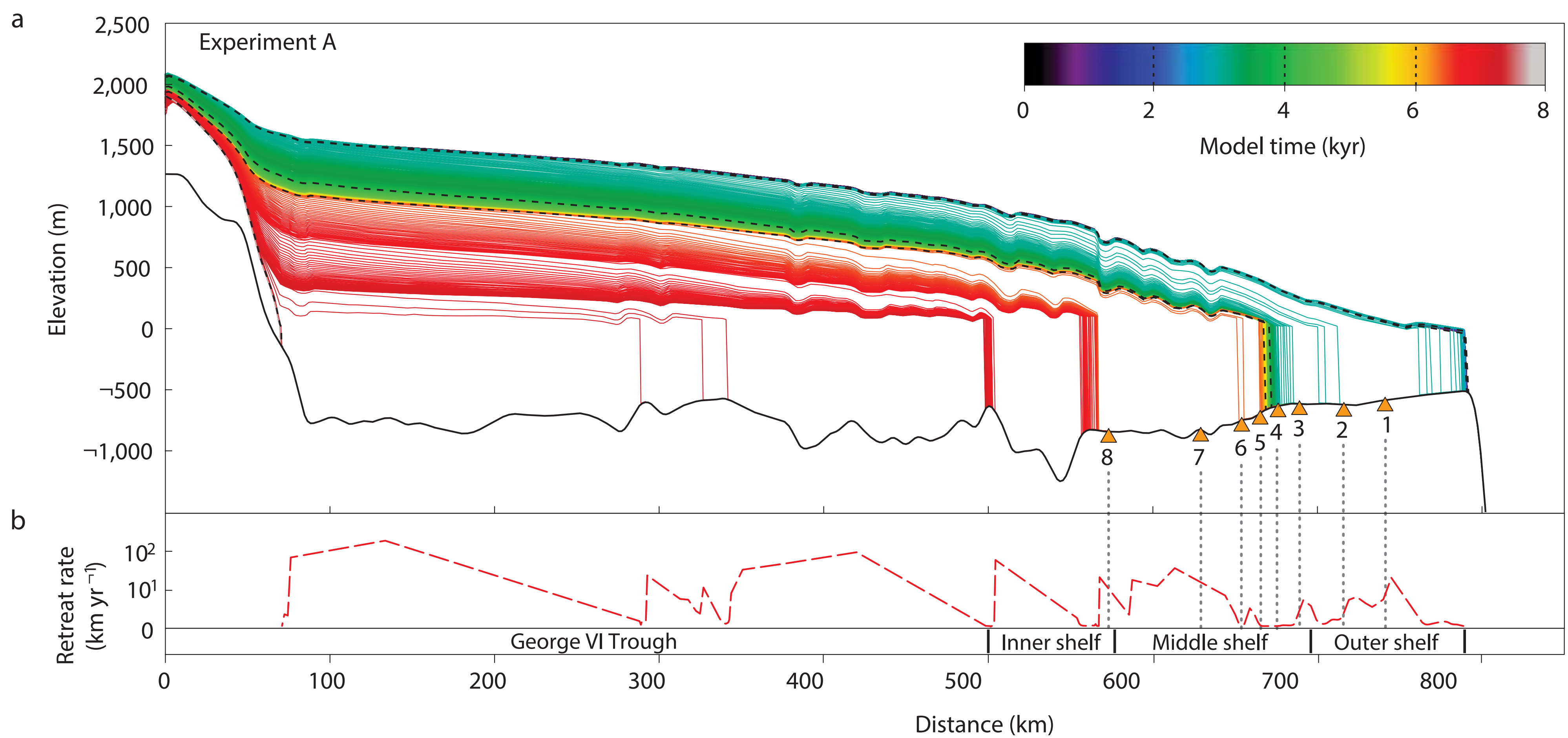
(courtesy of C. Hulbe, Portland State Univ.)

The Marine Ice-Sheet Instability: Flux Explanation

(Mercer, 1968; Weertman, 1974; Schoof, 2007, Joughin and Alley, 2011)



This makes marine ice sheets prone to episodic retreat

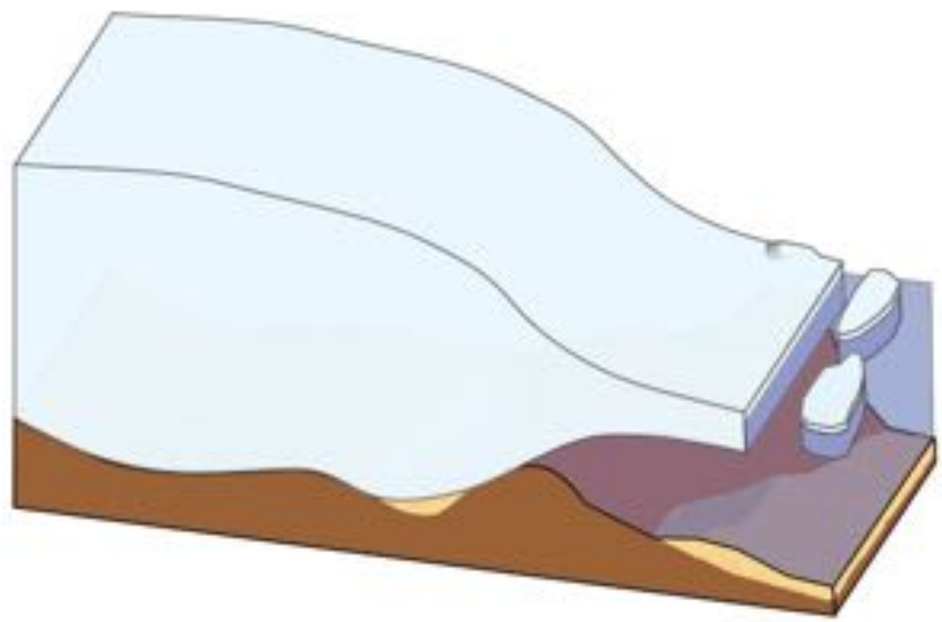


- Antarctica and Greenland are Tectonically and Geologically Distinct
- The subglacial topography under West Antarctica (reverse bed slope, below sea-level) makes it prone to catastrophic retreat.

What might trigger it?

Ice Shelf Backstress

- Ice Shelves restrain flow from grounded ice by:
  - friction at ice rises
  - side drag on fjord walls



Ice Shelf Backstress

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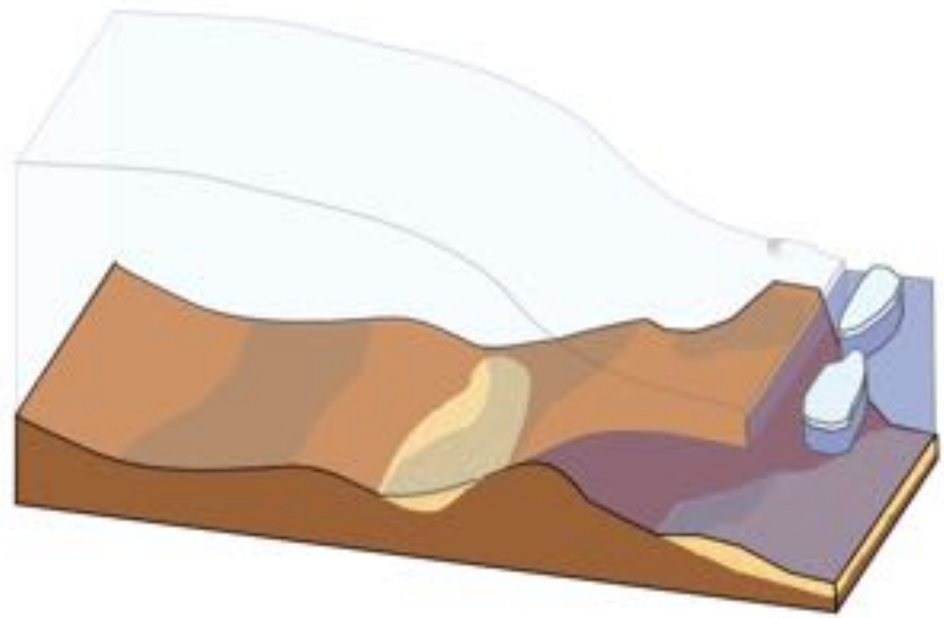
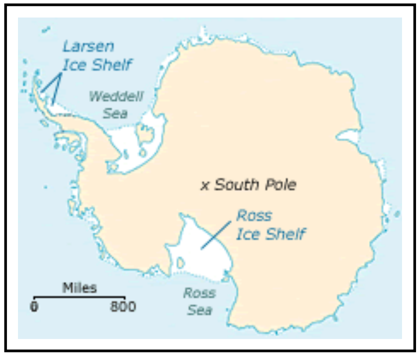
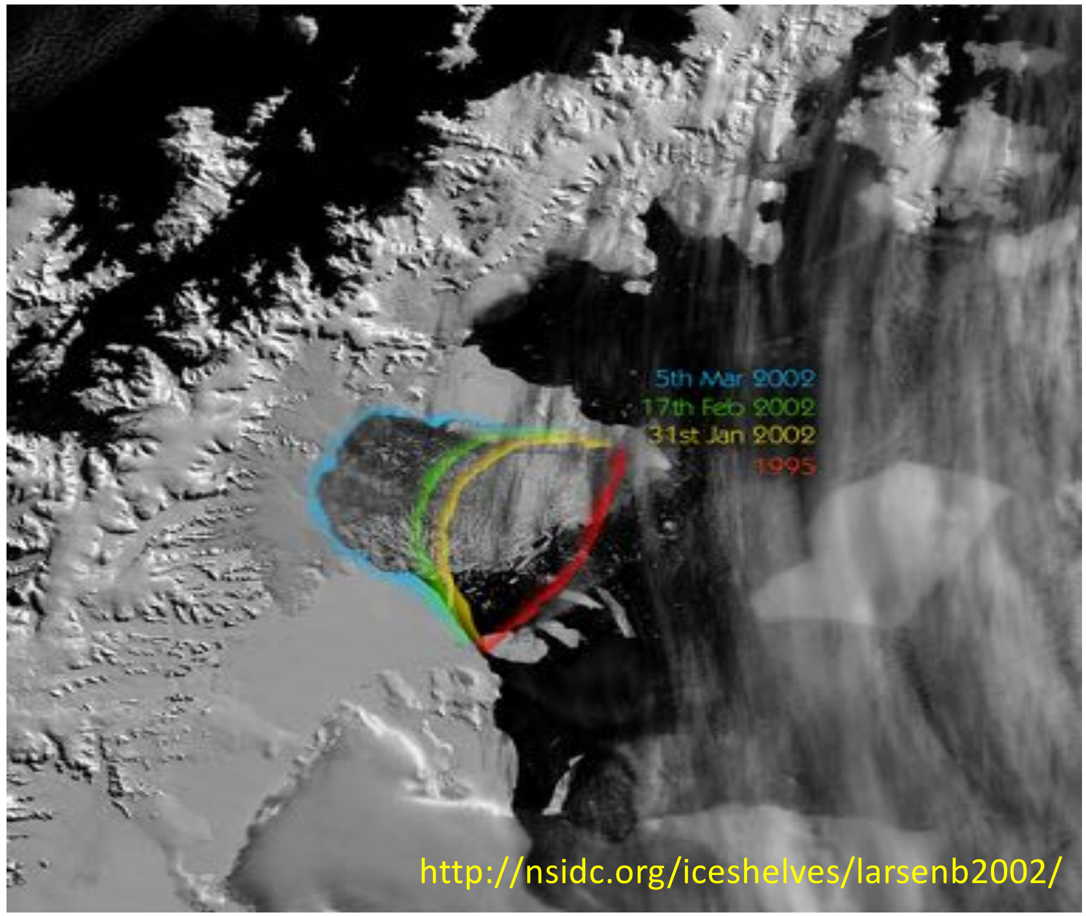


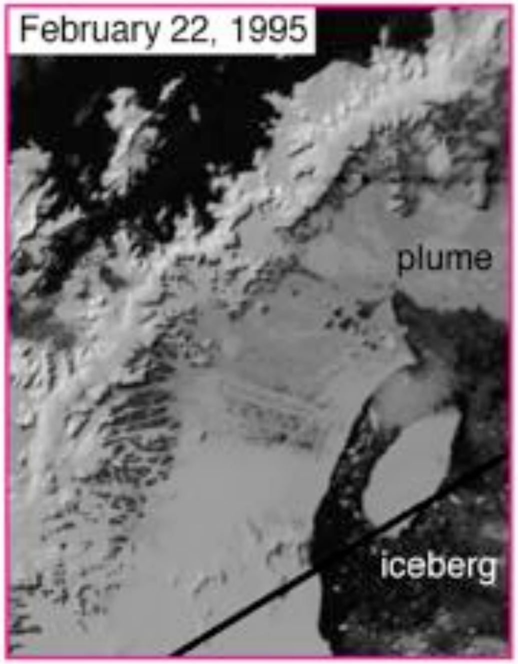


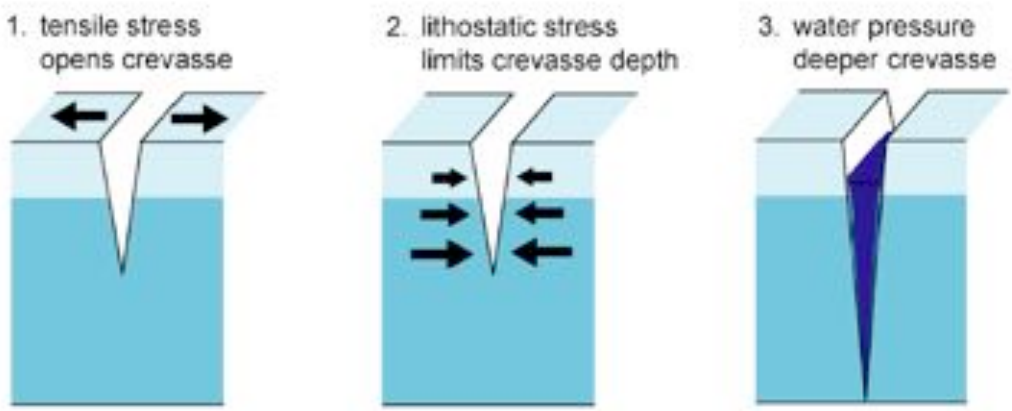
Breakup of Larsen B Ice Shelf
March 2002



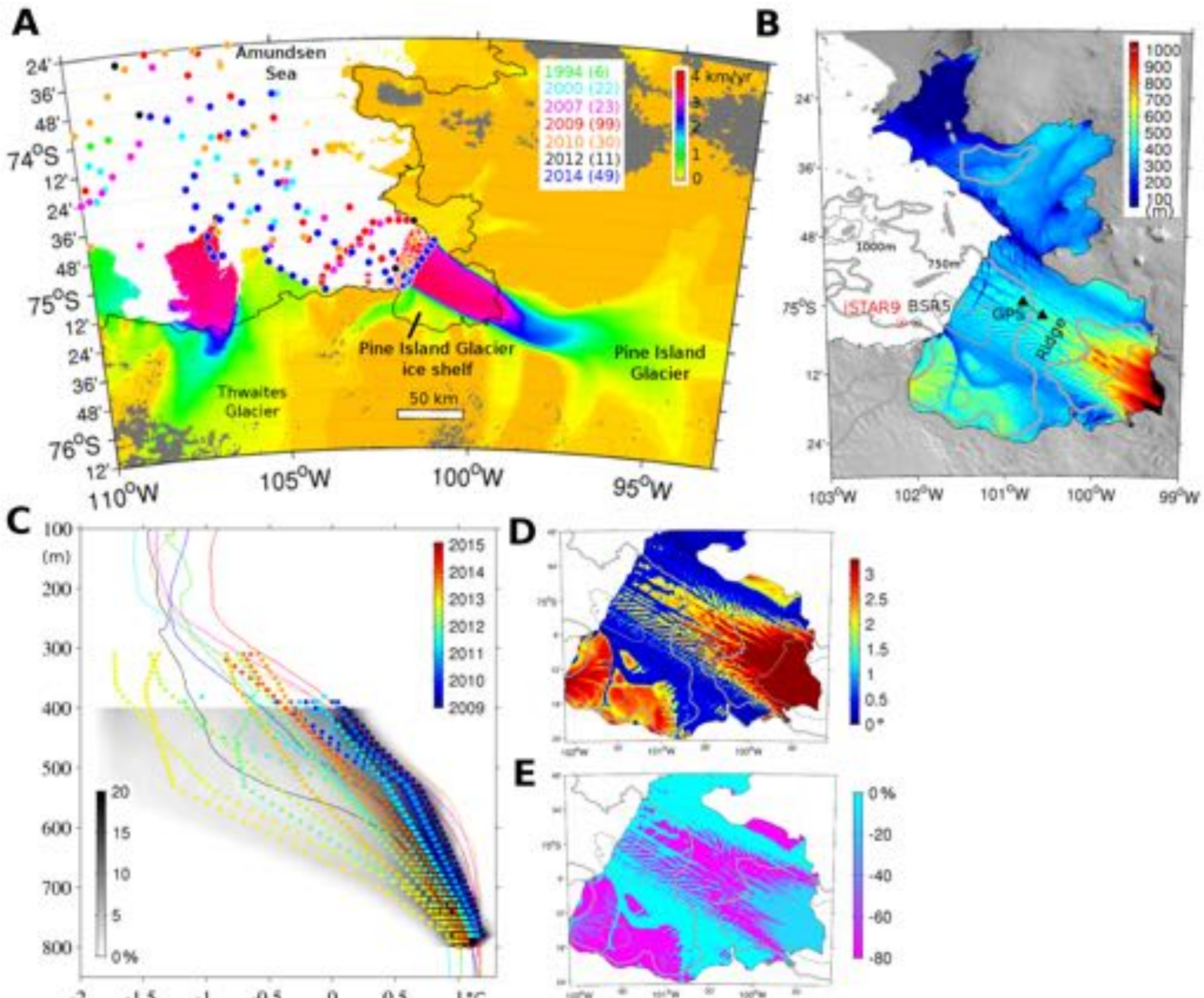
(courtesy of C. Hulbe, Portland State Univ.)

ice shelf disintegration events



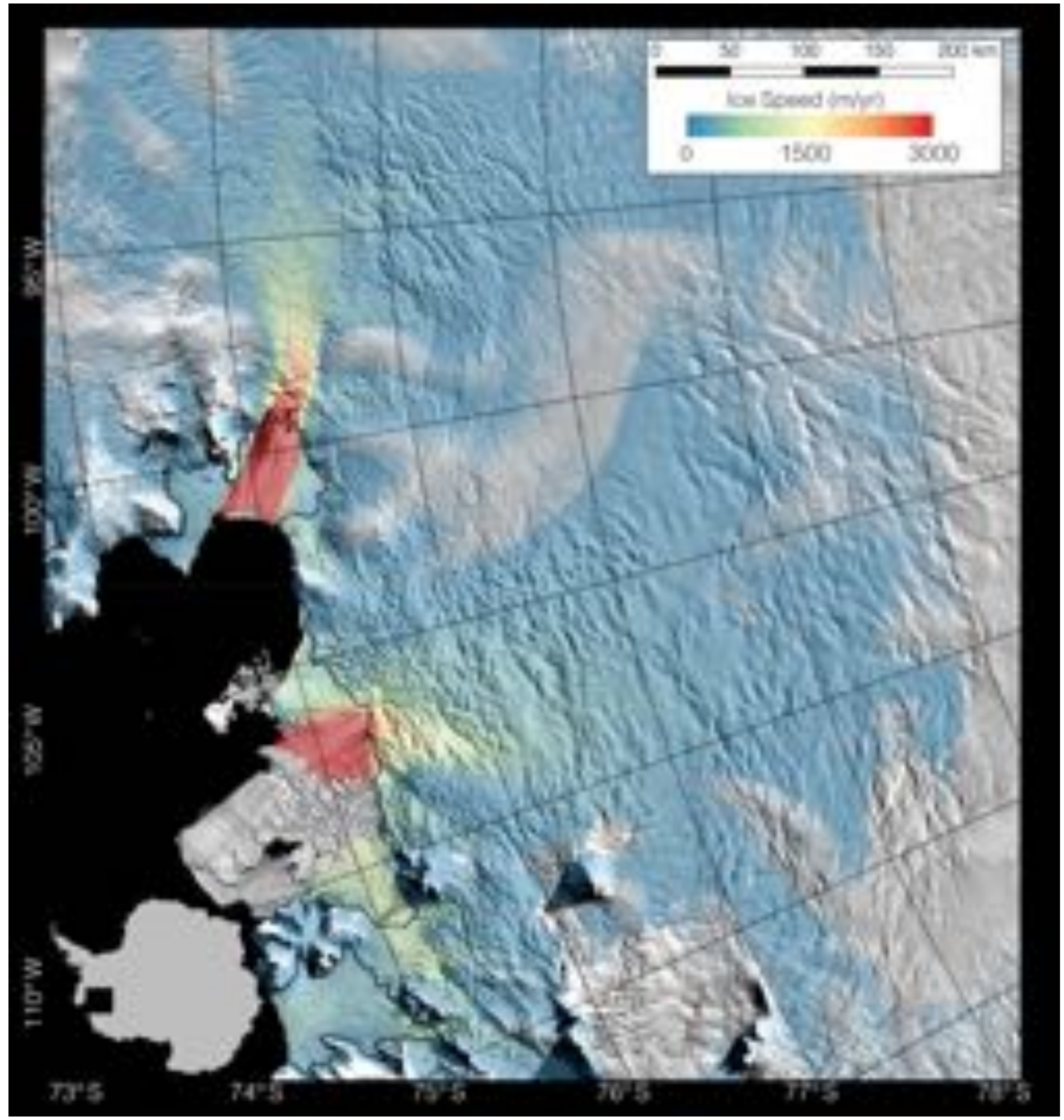


Ocean Conditions under the Pine Island Glacier



(Christianson et al., 2016)

Thwaites and Pine Island Glacier



Is a marine ice-sheet collapse underway?
Work at UW suggests….

Dynamic (in)stability of Thwaites Glacier, West Antarctica

B. R. Parizek,[1] K. Christianson,[2,3] S. Anandakrishnan,[2] R. B. Alley,[2] R. T. Walker,[2,4] R. A. Edwards,[5] D. S. Wolfe,[6] G. T. Bertini,[7] S. K. Rinehart,[8] R. A. Bindschadler,[9] and S. M. J. Nowicki[9]

Received 4 June 2012; revised 30 January 2013; accepted 11 February 2013.

Marine Ice Sheet Collapse Potentially Under Way for the Thwaites Glacier Basin, West Antarctica

Ian Joughin, Benjamin E. Smith, Brooke Medley

Oceanic Forcing of Ice-Sheet Retreat: West Antarctica and More

Richard B. Alley,[1] Sridhar Anandakrishnan,[1] Knut Christianson,[2,3] Huw J. Horgan,[4] Atsu Muto,[1] Byron R. Parizek,[5] David Pollard,[1] and Ryan T. Walker[6,7]

Sensitivity of 21st century sea level to ocean-induced thinning of Pine Island Glacier, Antarctica

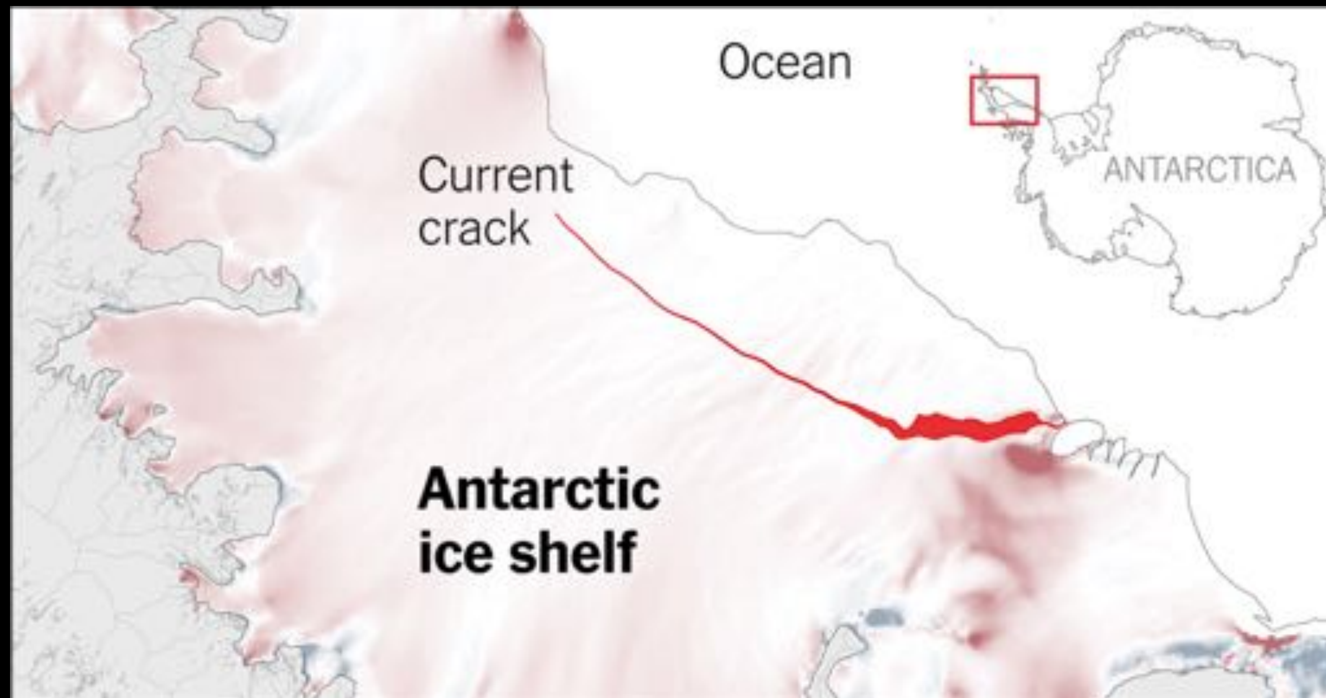
Ian Joughin,[1] Benjamin E. Smith,[1] and David M. Holland[2]

Received 22 July 2010; revised 3 September 2010; accepted 13 September 2010; published 21 October 2010.

Strong Sensitivity of Pine Island Ice-Shelf Melting to Climatic Variability

Pierre Dutrieux,[1*] Jan De Rydt,[1] Adrian Jenkins,[1] Paul R. Holland,[1] Ho Kyung Ha,[2] Sang Hoon Lee,[2] Eric J. Steig,[3] Qinghua Ding,[3] E. Povl Abrahamsen,[1] Michael Schröder[4]

How do we judge what's significant when it comes to Ice Sheet change?



- Is this unexpected?
- How will it change the ice sheet mass balance?
- How much ice is affected?