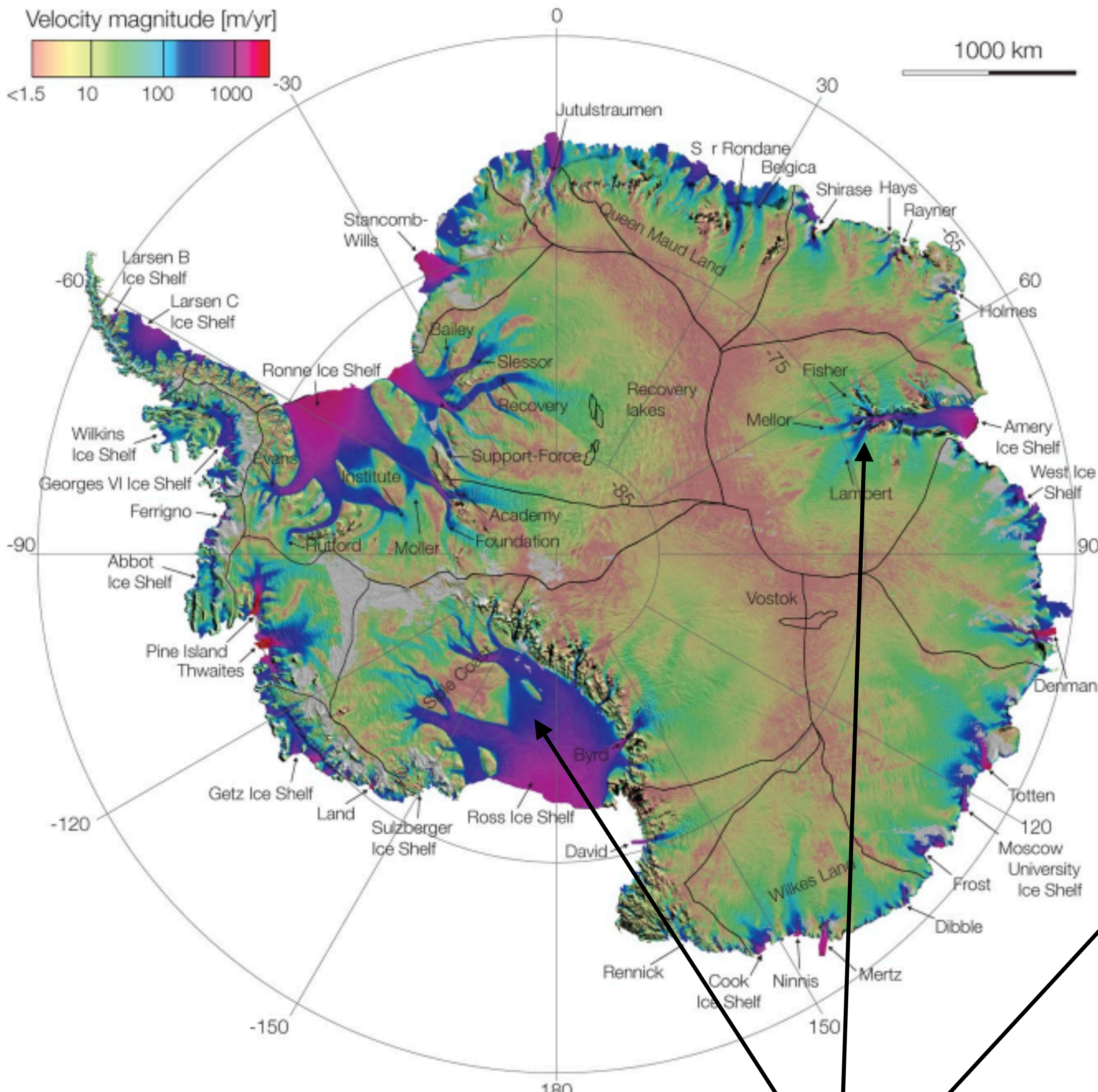
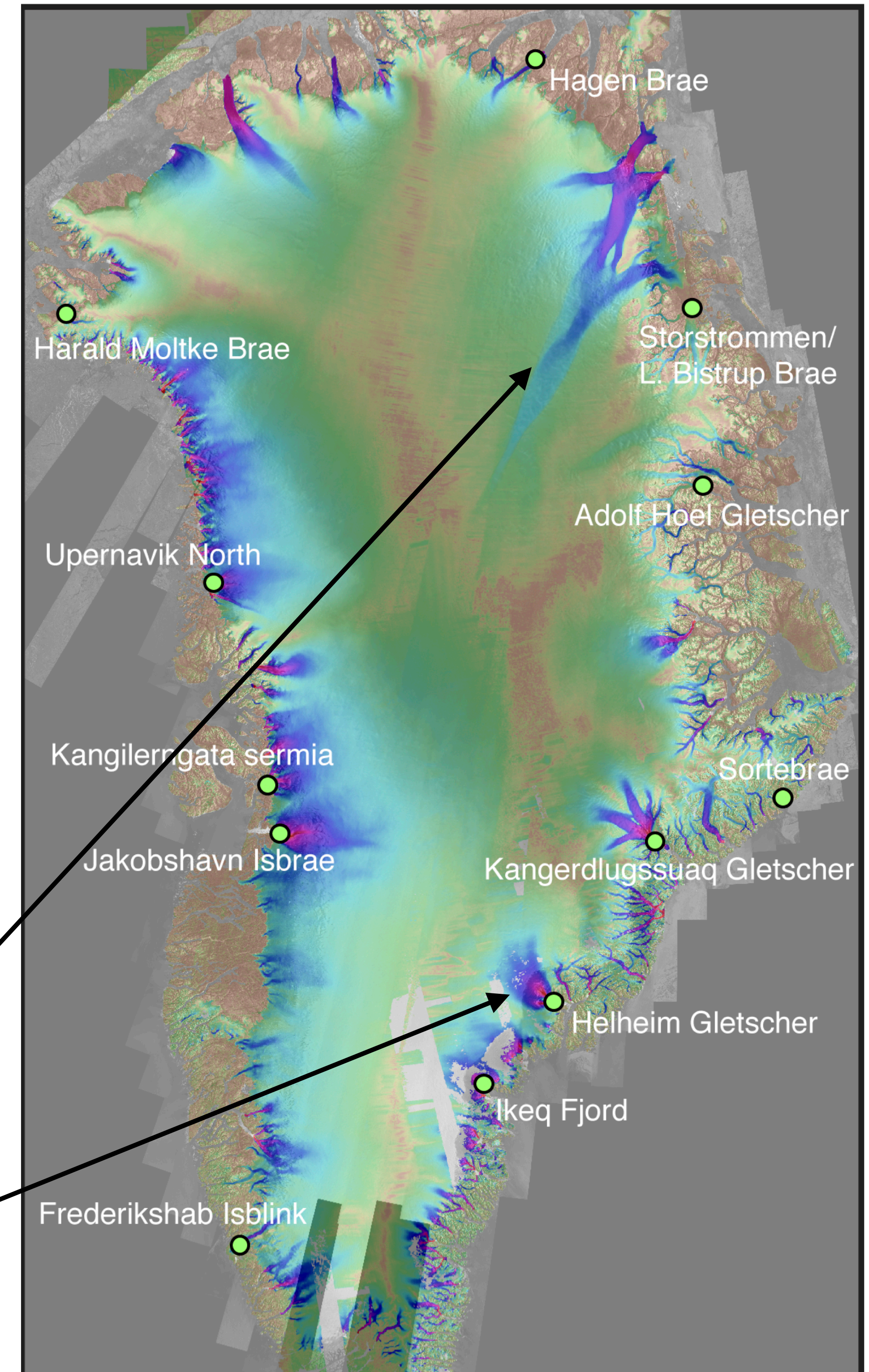
Ice Streams

Ice Sheet Velocities

Antarctic Ice Sheet

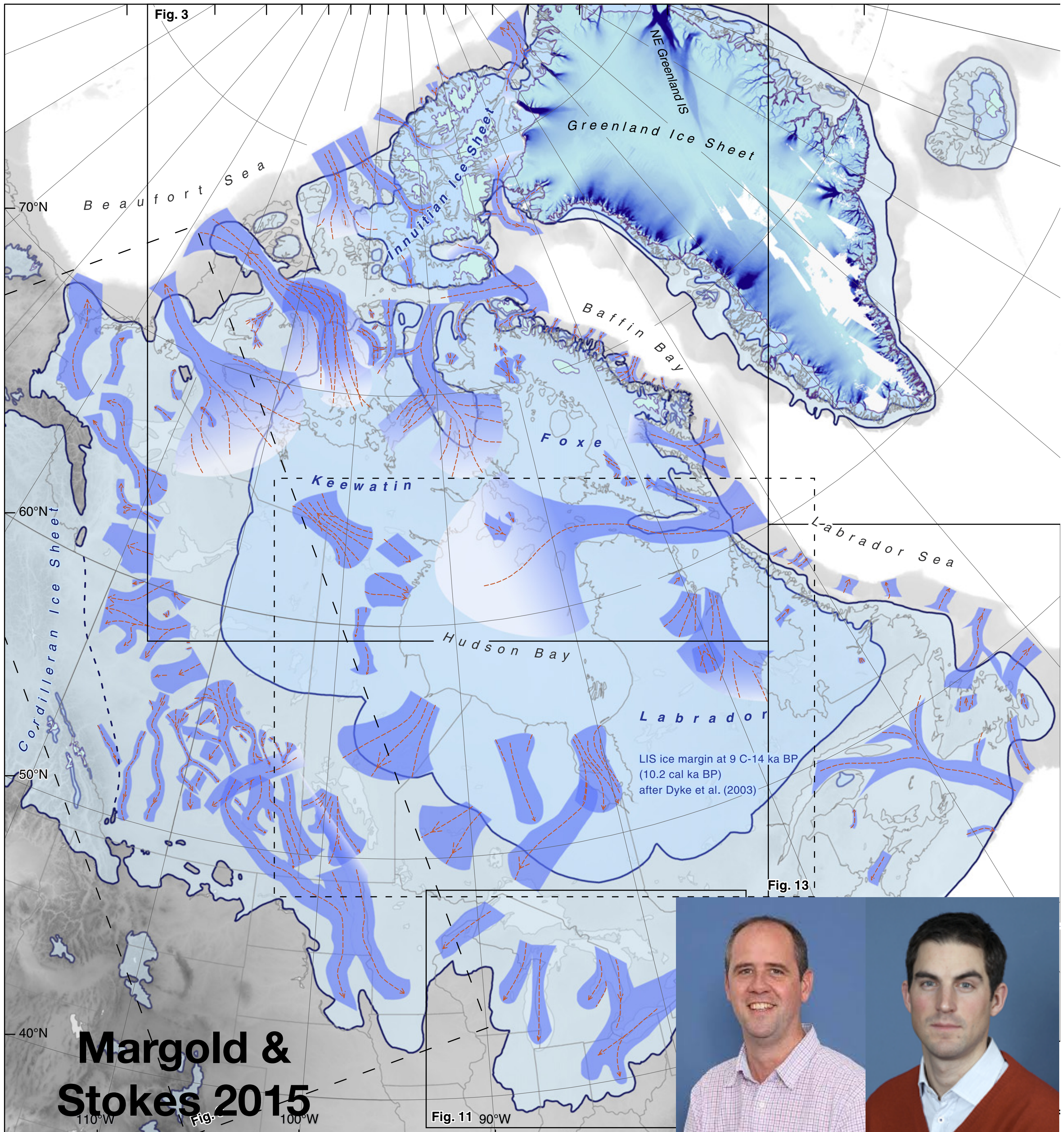


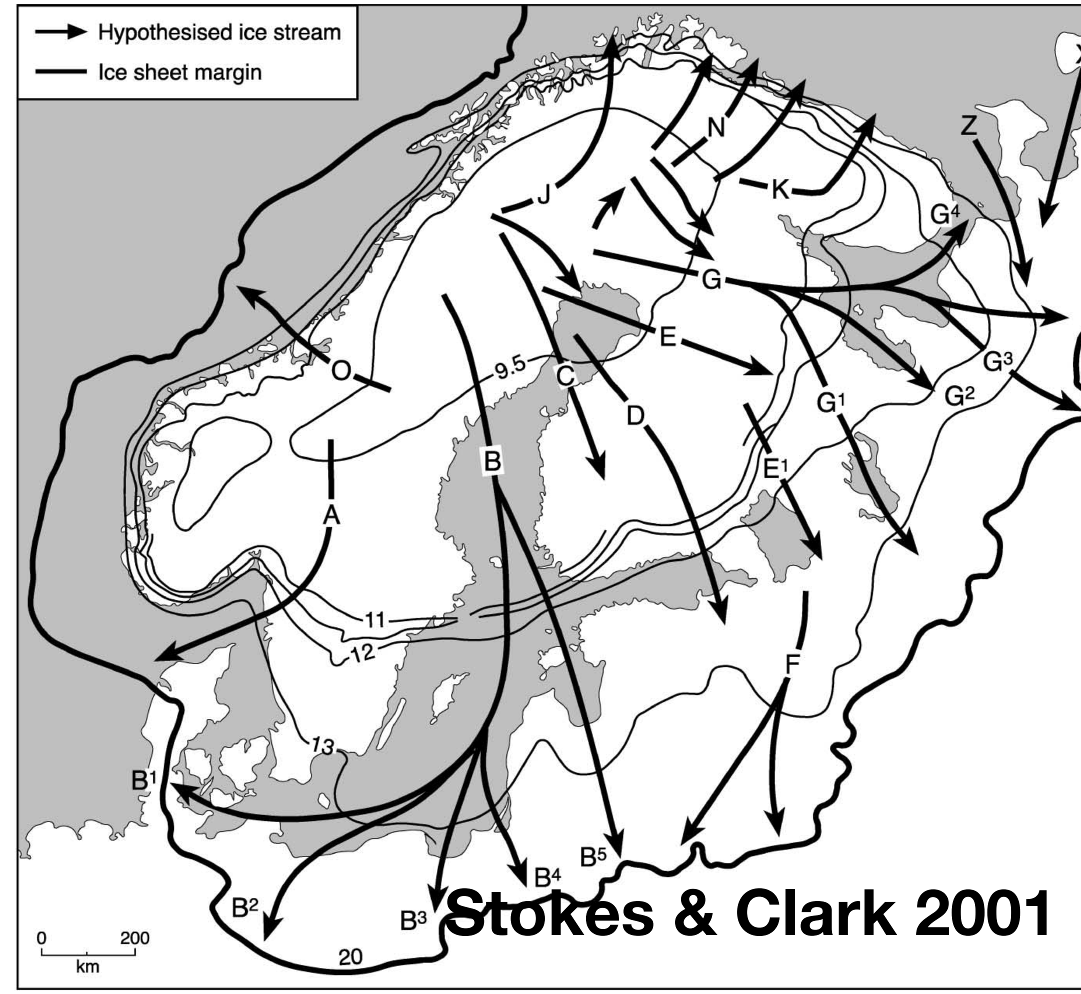
Greenland Ice Sheet



Most ice flow occurs through these. What are they? Why are they?

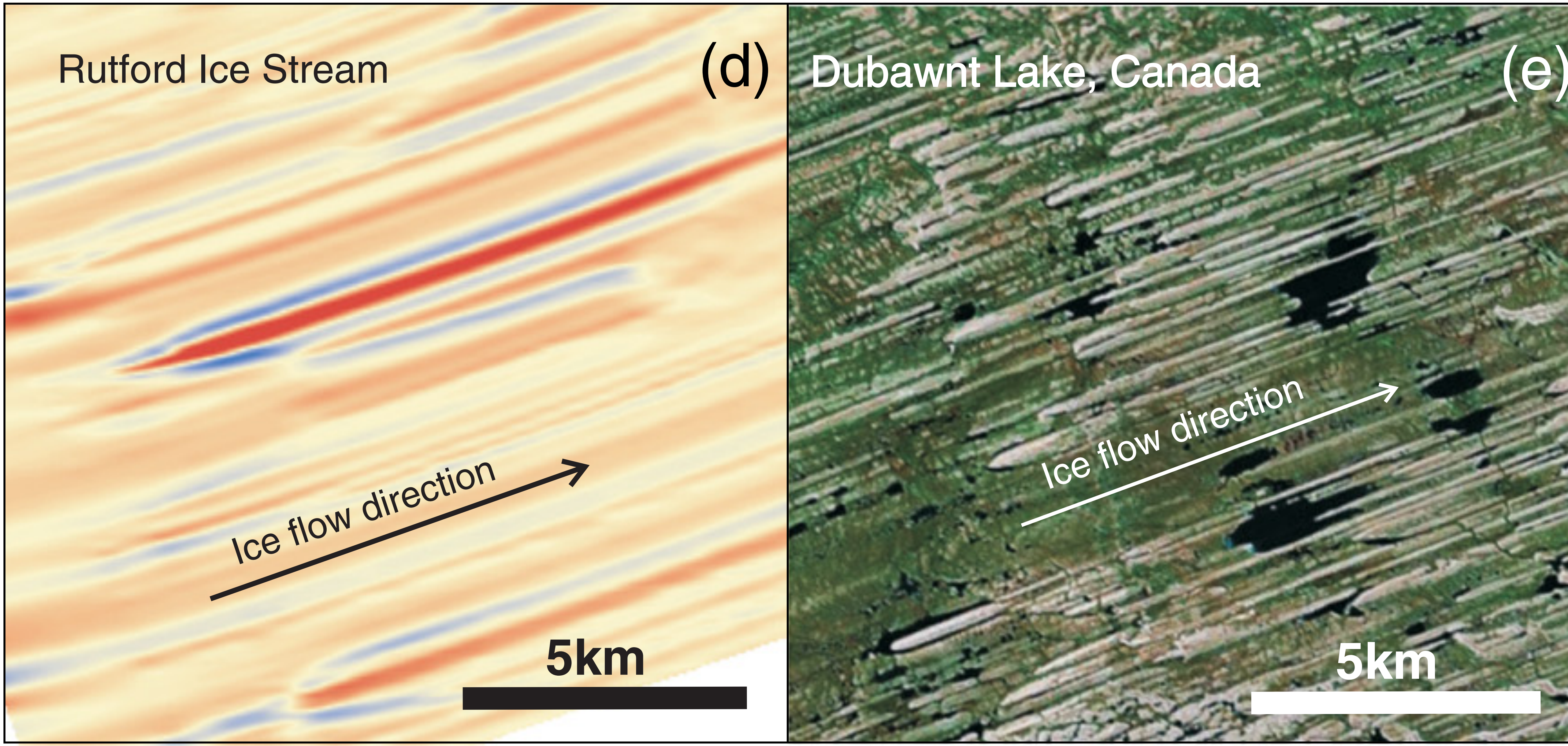
Geological evidence for ice streaming in past ice sheets





There is also strong evidence that ice streams were pervasive in past ice sheets and were important to their overall mass transport as well

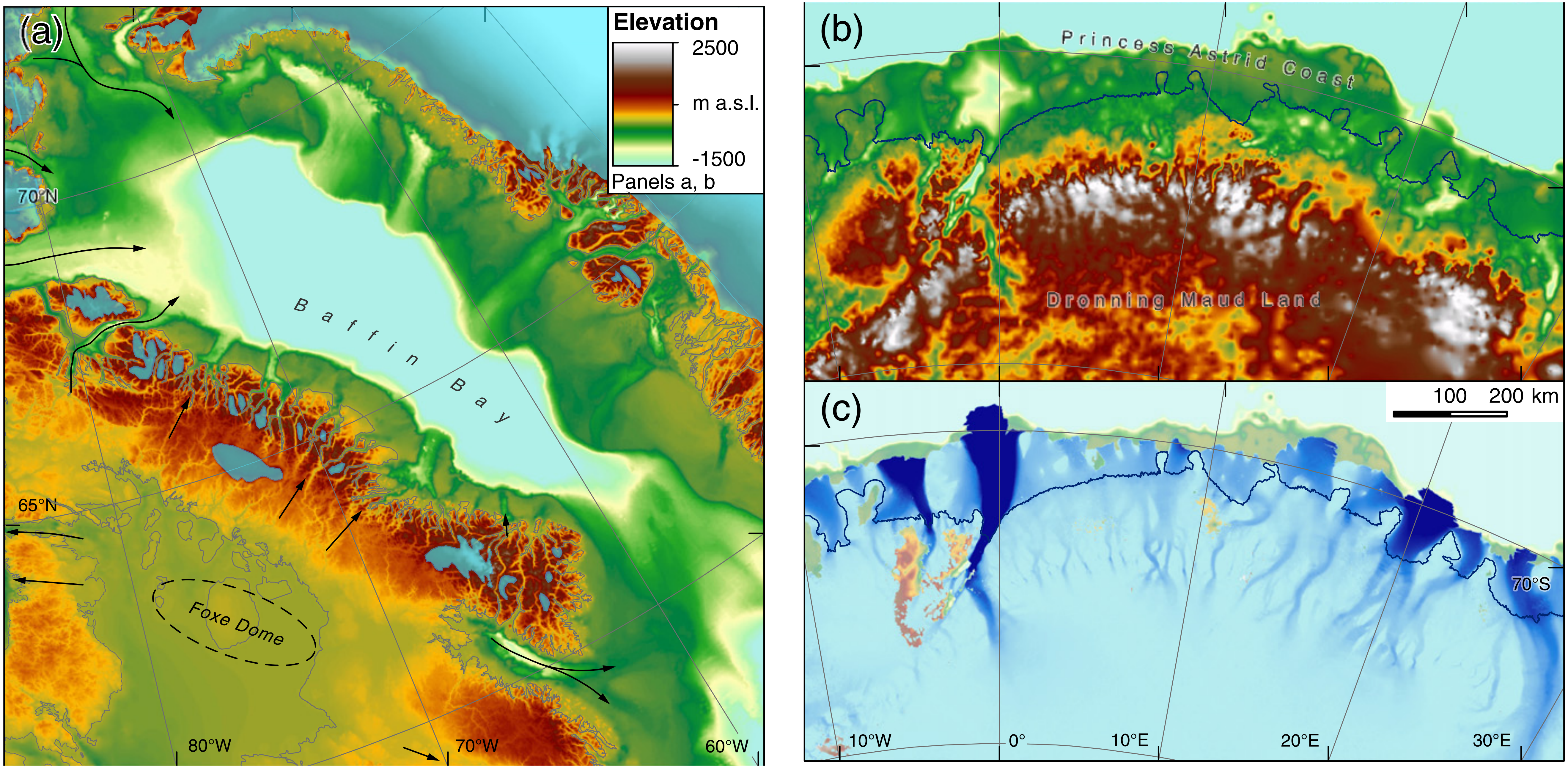
Geological evidence for ice streaming in past ice sheets



Margold and Stokes 2015

Megascale Glacial Lineations (MSGL) indicate fast flow and direction of flow from past (and current) ice streams

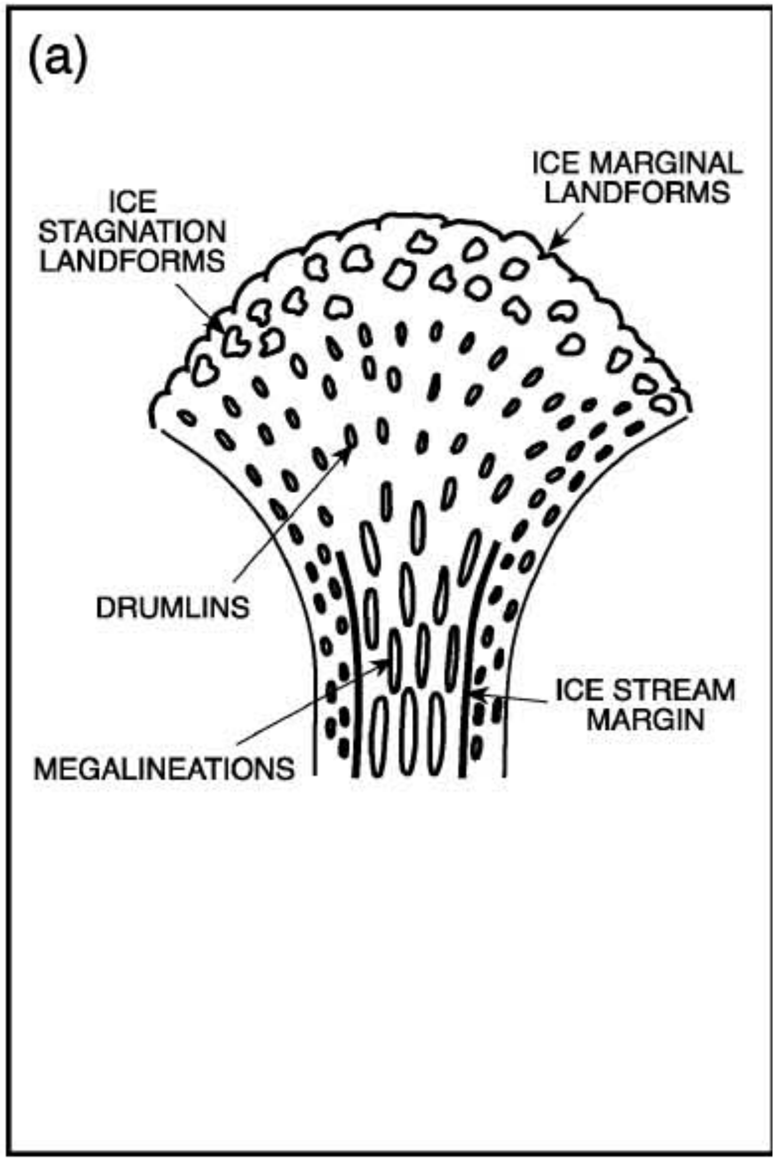
Geological evidence for ice streaming in past ice sheets

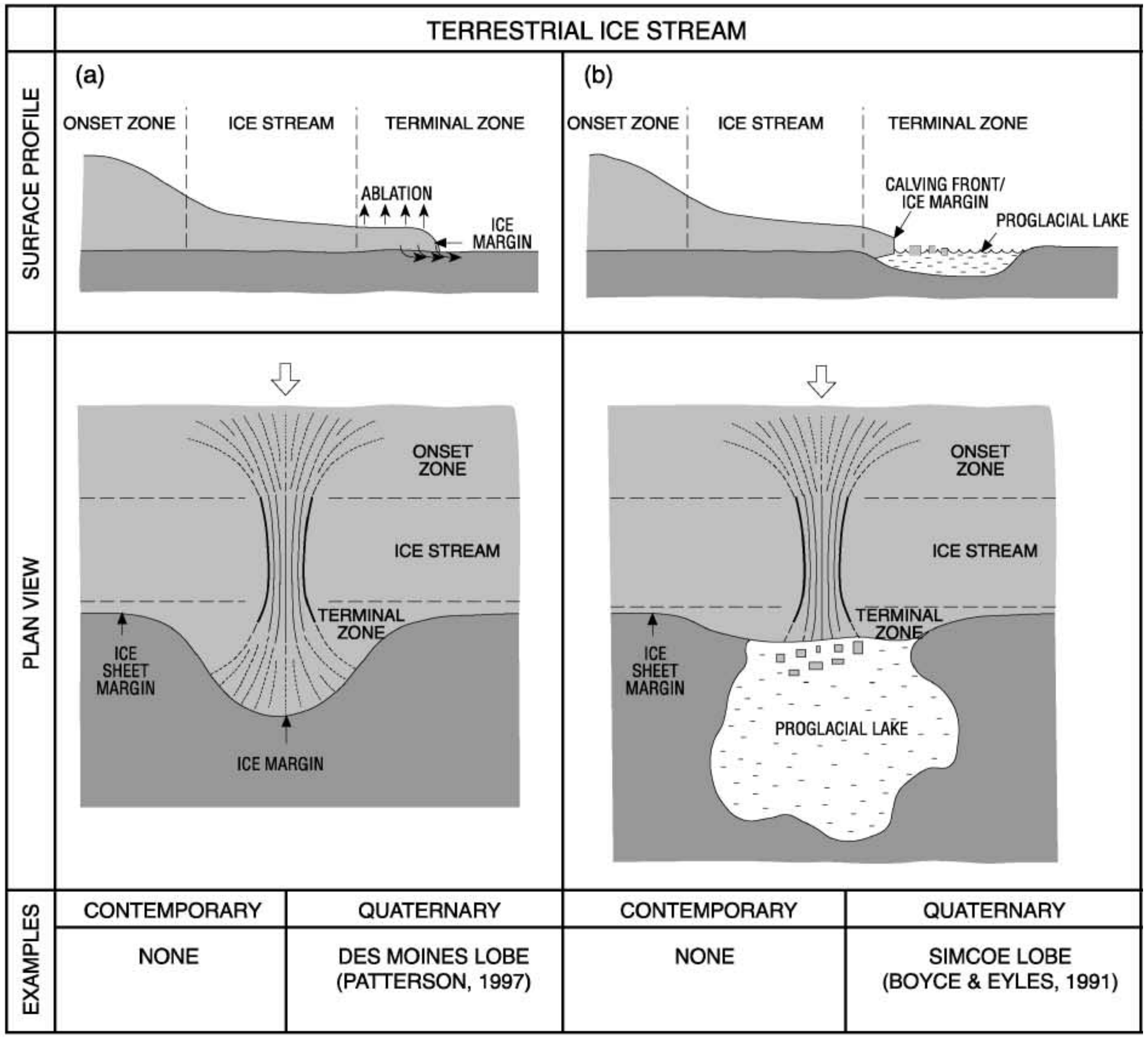


Margold and Stokes 2015

Bathymetric troughs also indicate places where past ice streams have eroded into the bed

Geological evidence for ice streaming in past ice sheets

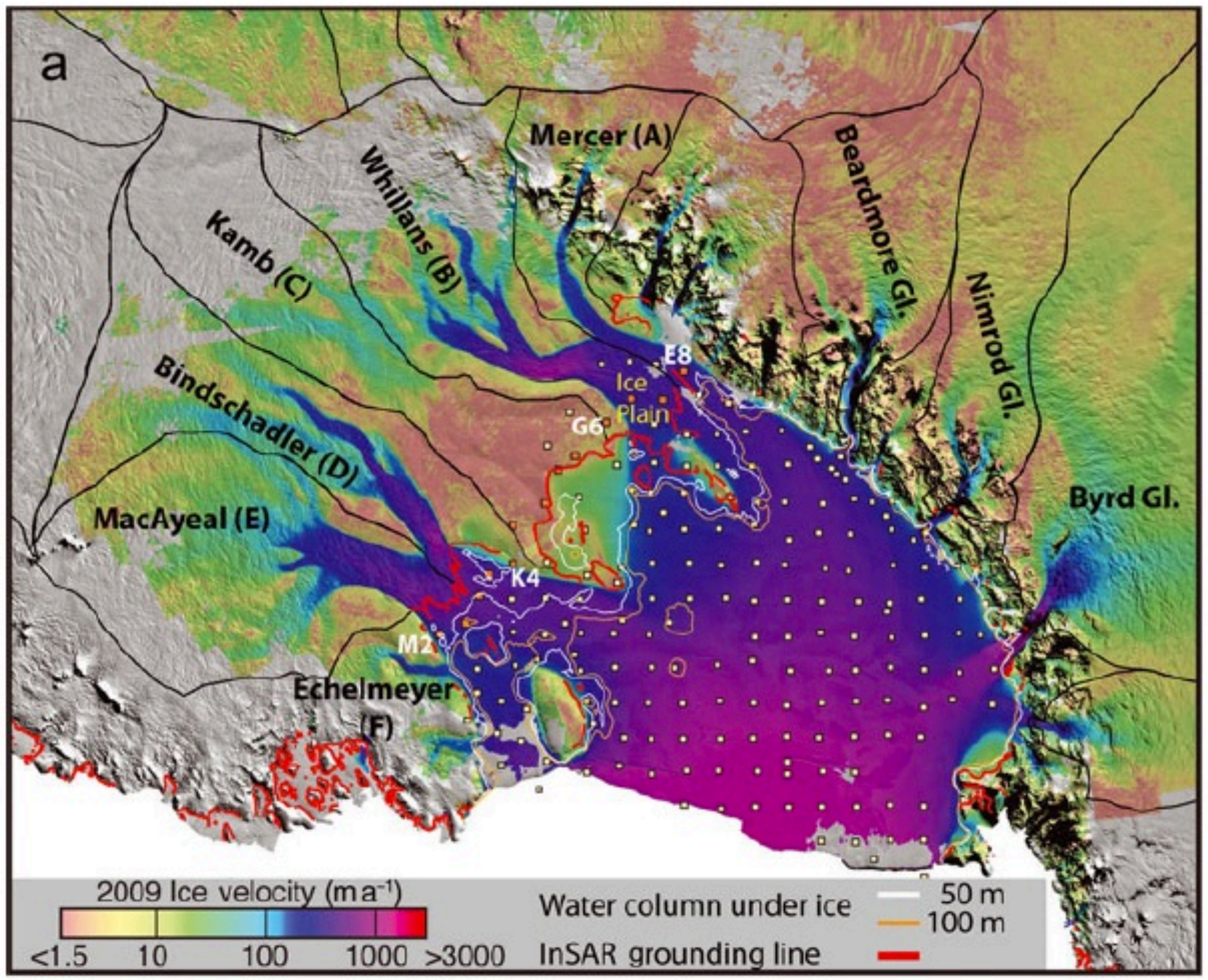




Stokes & Clark 2001

Moraines, drumlins, and other sedimentary deposits may indicate furthest extent of ice stream flow (since ice streams often terminate at different places than rest of margin)

Terminology



"Ice stream" is used interchangeably with "outlet glacier" - refers to any place in an ice sheet where high ice velocities (>100 m/yr) are embedded within slower ice velocities (<100 m/yr)

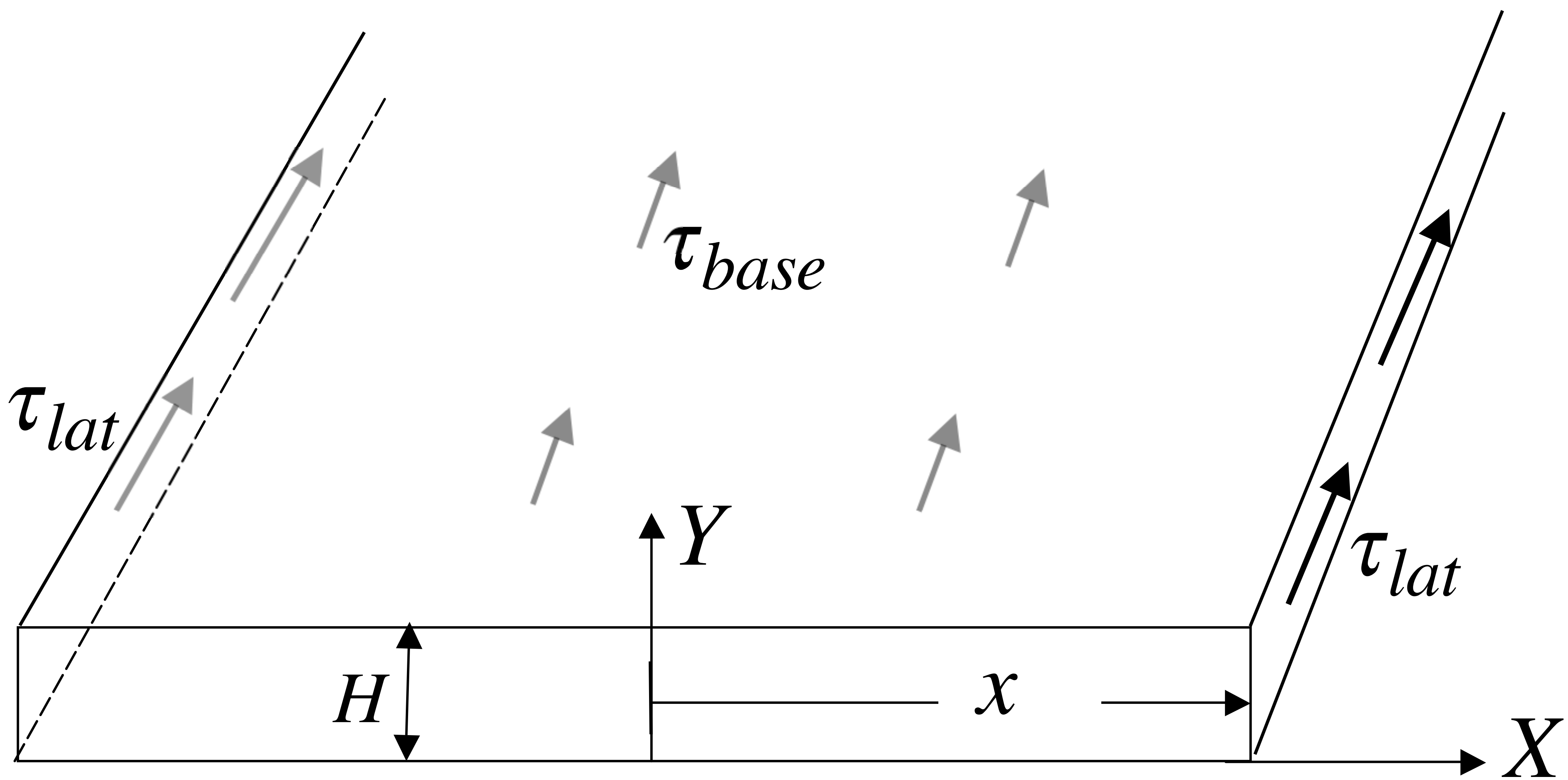
Ice streams are like the jet stream in the atmosphere or boundary currents in the ocean - they are "jets" of fast flow embedded within slow flow - typically indicates that something special is happening

So…why do ice streams exist?

Group discussion (3 min): what processes can cause localized regions of fast ice flow?

(Think back to previous classes about what sets ice flow velocity - there is not a single right answer)

The force balance of an ice stream



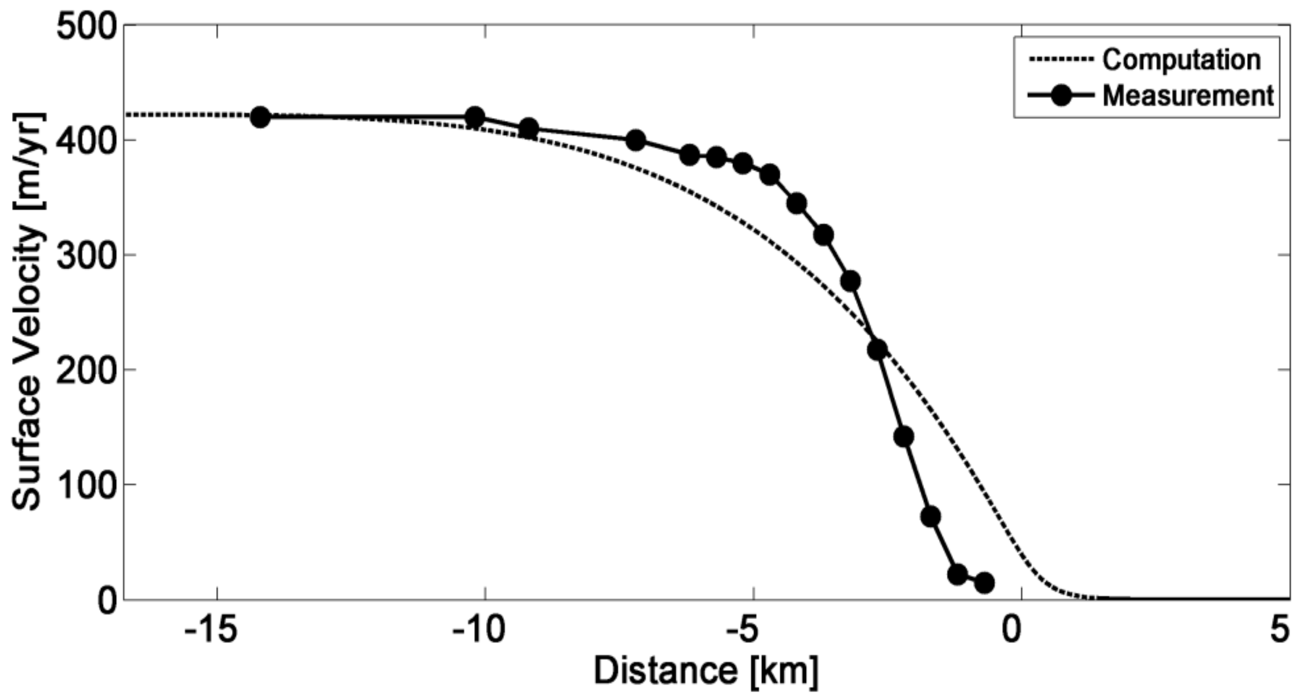
Driving stress is balanced by friction at the bed and lateral friction on the ice stream sides from rock or slow ice

High ice stream velocities can be understood from a simple force balance

- To the board!

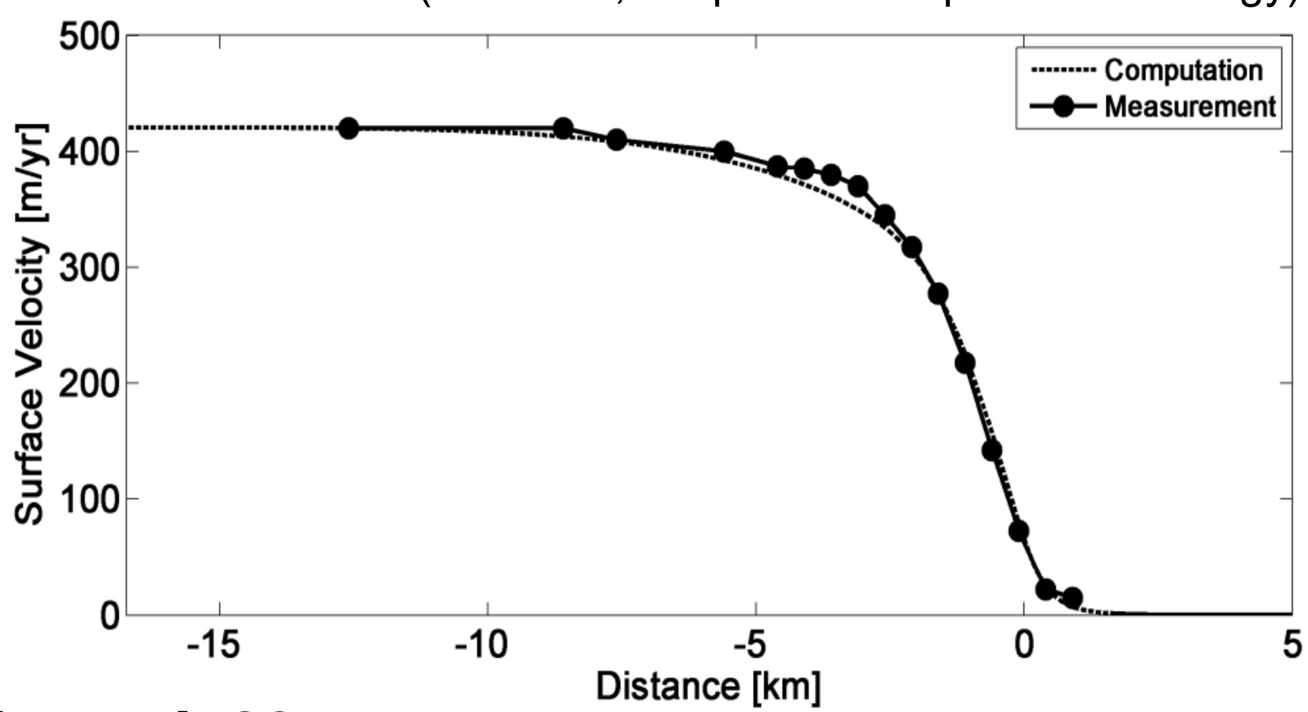
Structure of shear margins

B2. Surface velocities (nonlinear, temperature-independent rheology)



Shear-dependent viscosity

B3. Surface velocities (nonlinear, temperature-dependent rheology)

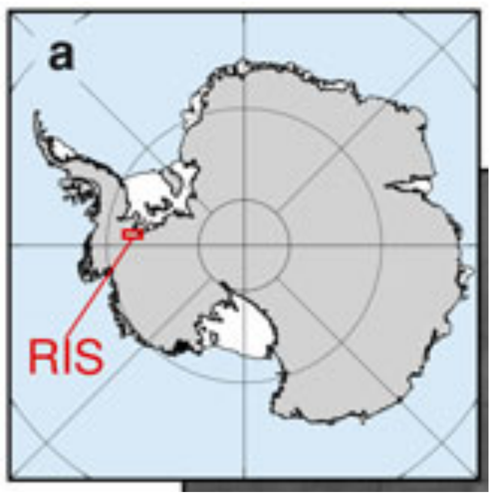


Shear- and temperature-dependent viscosity (shear heating in the margin)

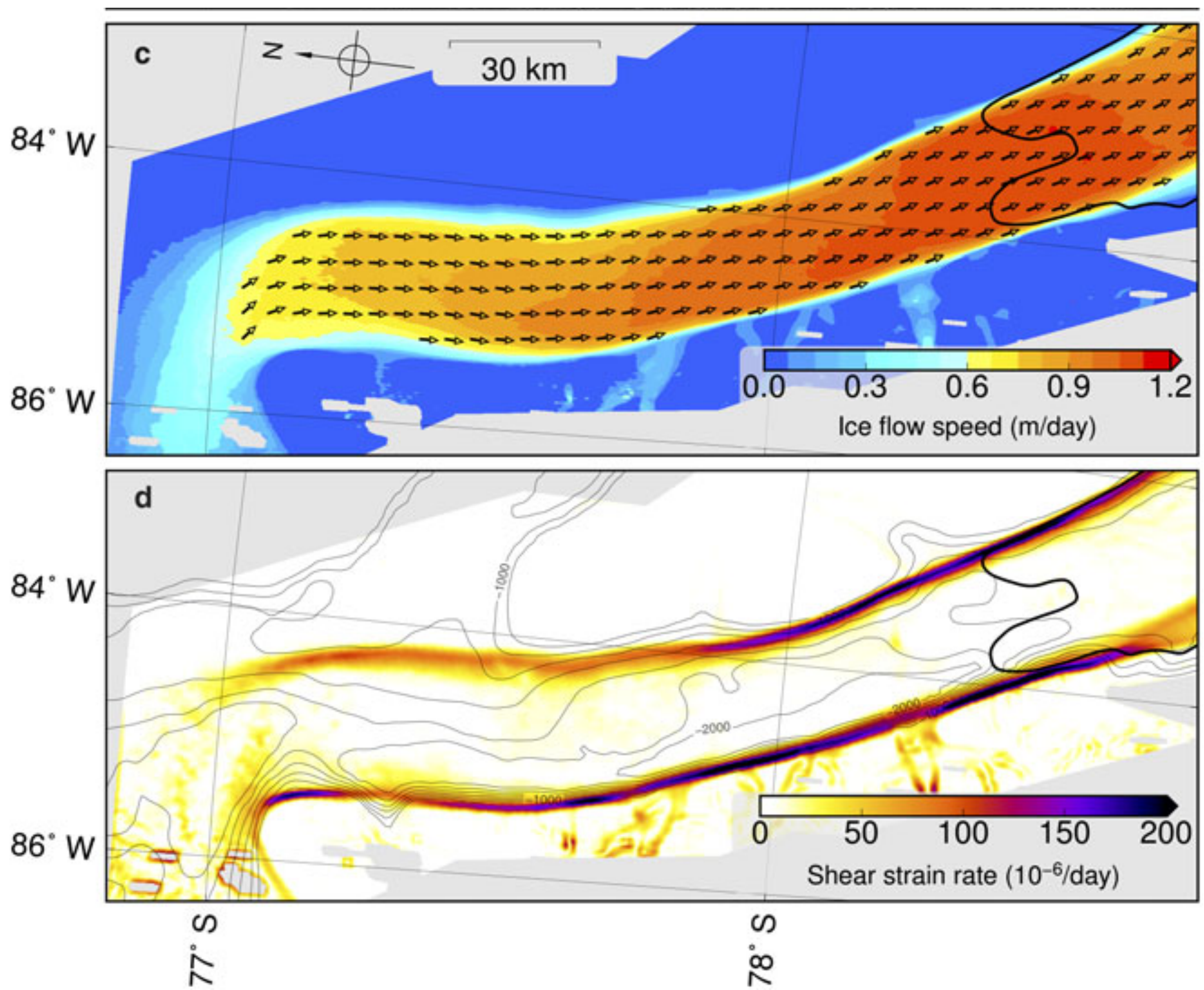
Suckale et al. 2014

Shear margins

Shear margins are the transition zones in between fast ice flow in the ice stream to slow ice flow outside the ice stream - very high shear stresses in shear margins



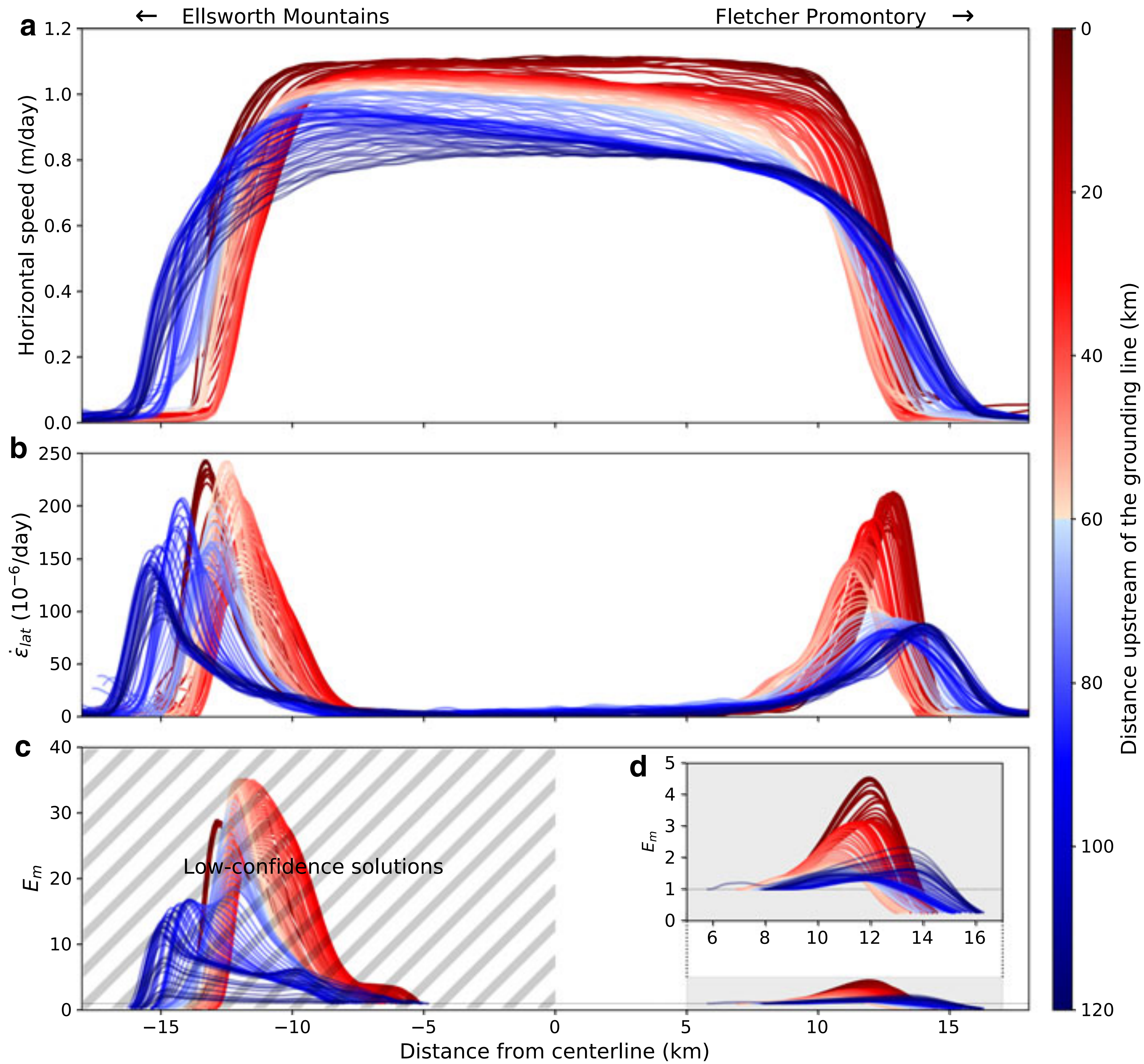
Minchew et al. 2018



Shear margins

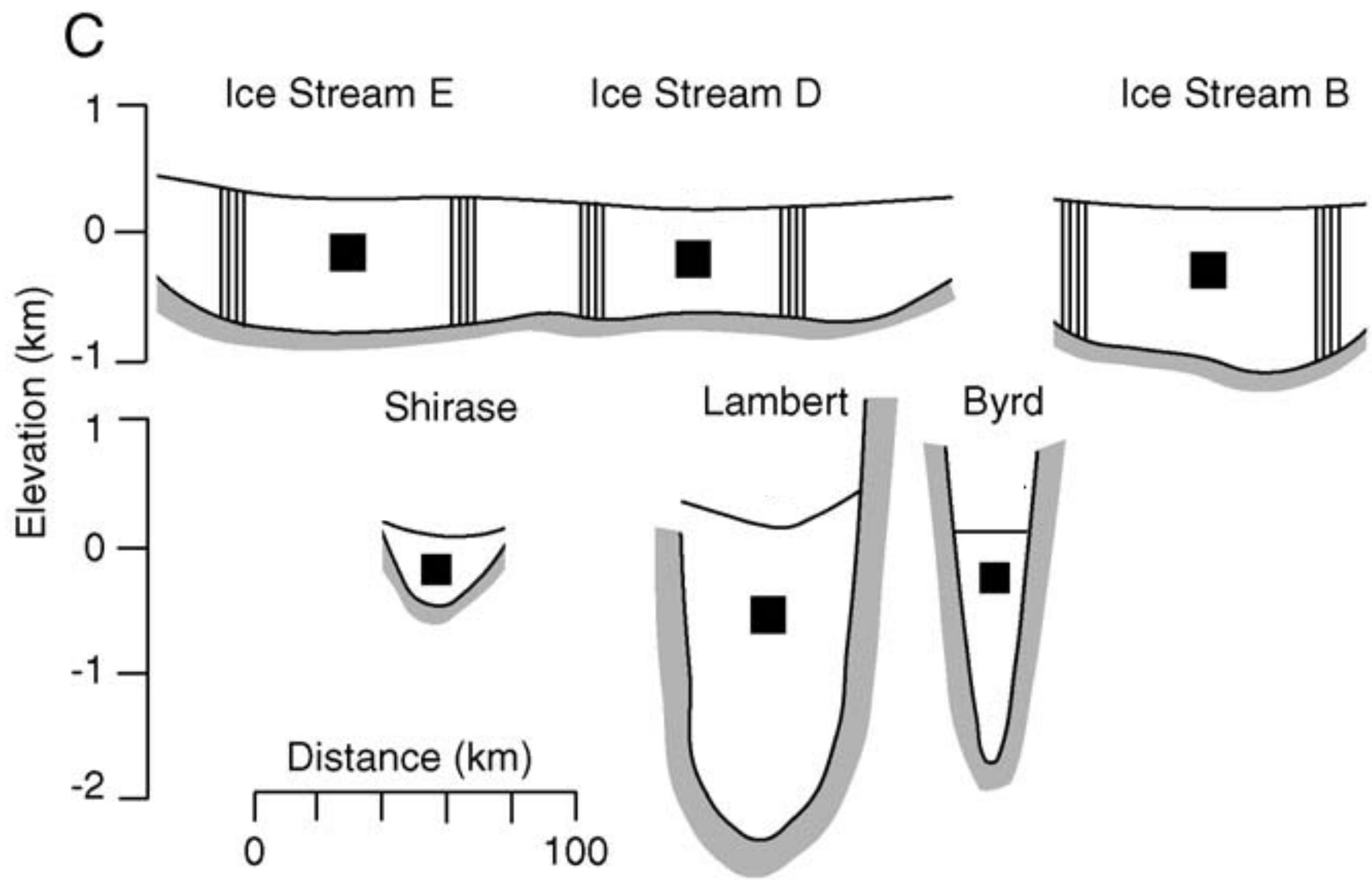
Shear margins are the transition zones in between fast ice flow in the ice stream to slow ice flow outside the ice stream - very high shear stresses in shear margins - very low shear stresses in ice stream interior

Minchew et al. 2018



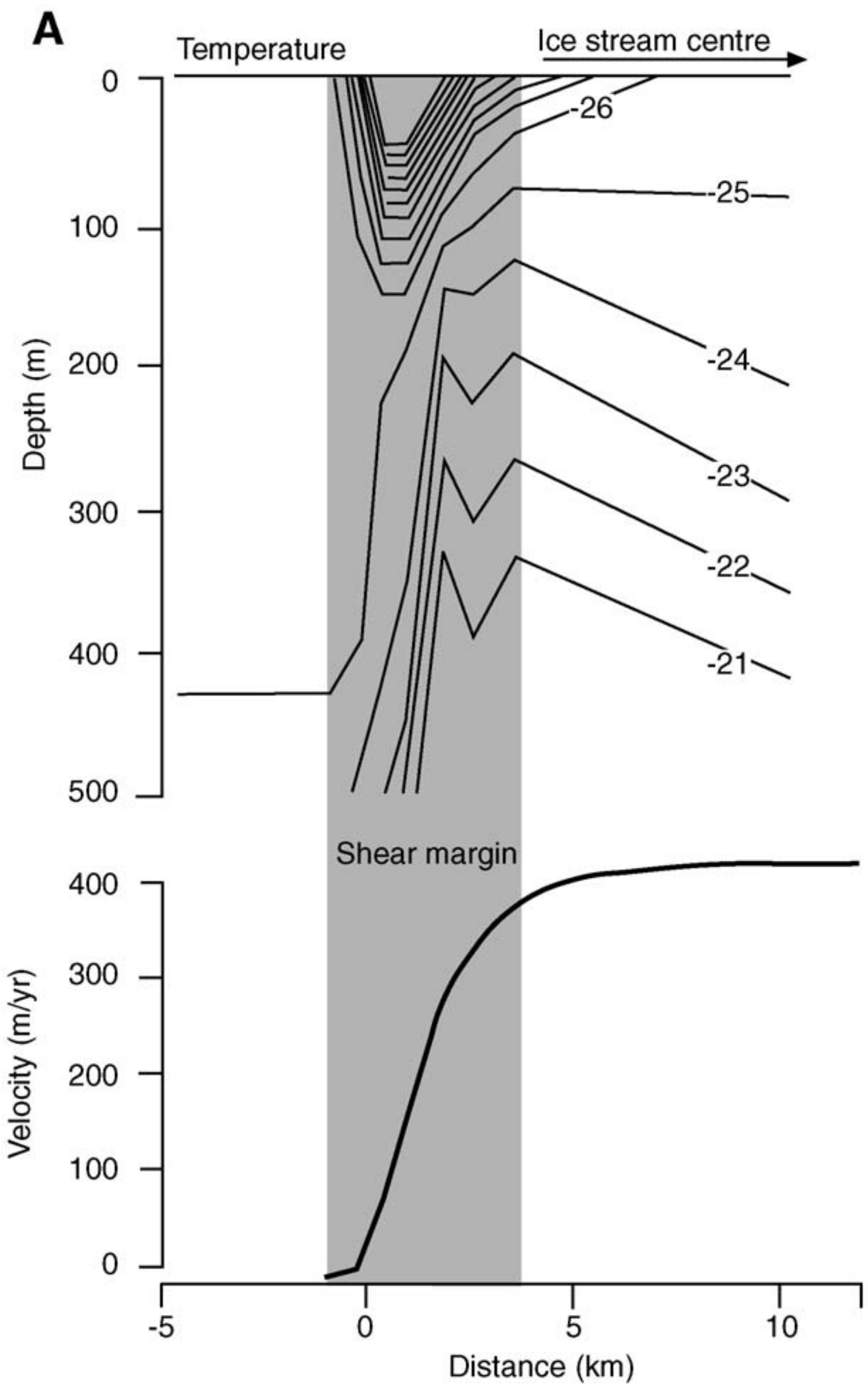
Shear margins

Ice-ice or ice-rock



Bennett 2003

Shear margins

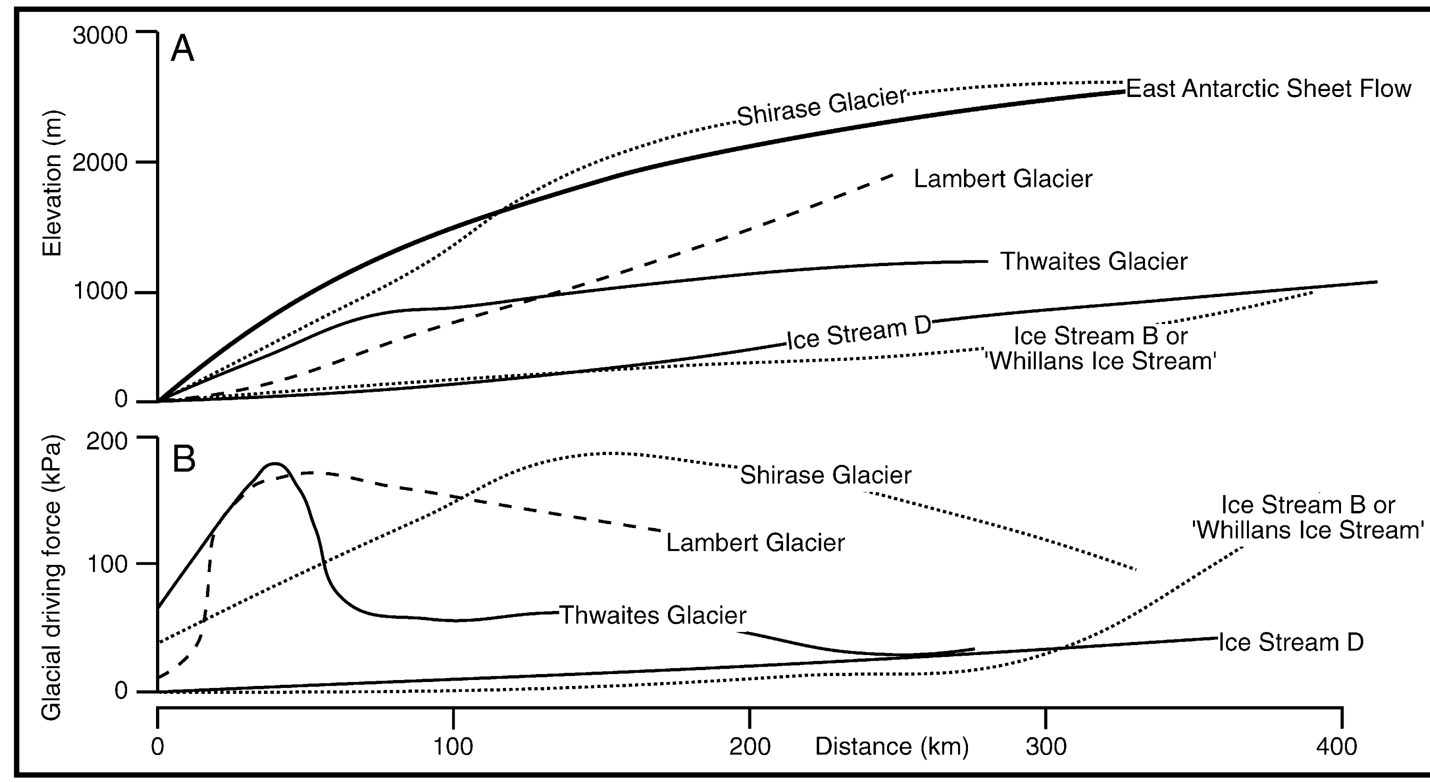


Shear margins also tend to be quite warm because shear causes heat production within ice (due to the rapid conversion of ice crystal bond dislocations to heat)

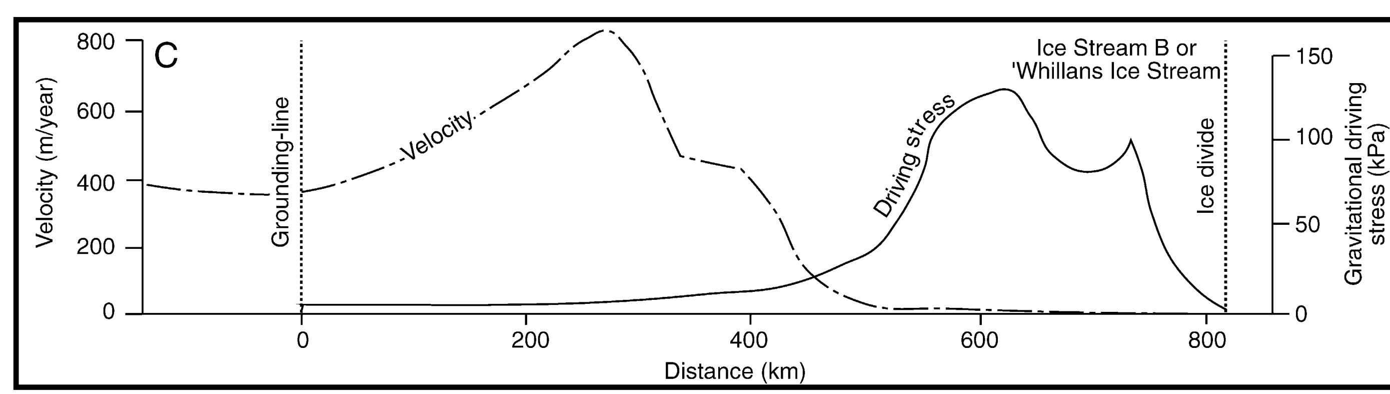
Bennett 2003

Two types of ice streams

- **Topographic ice streams**: Gravitational driving stress is high (perhaps due to strongly sloping bed topography) - more common in Greenland and East Antarctica



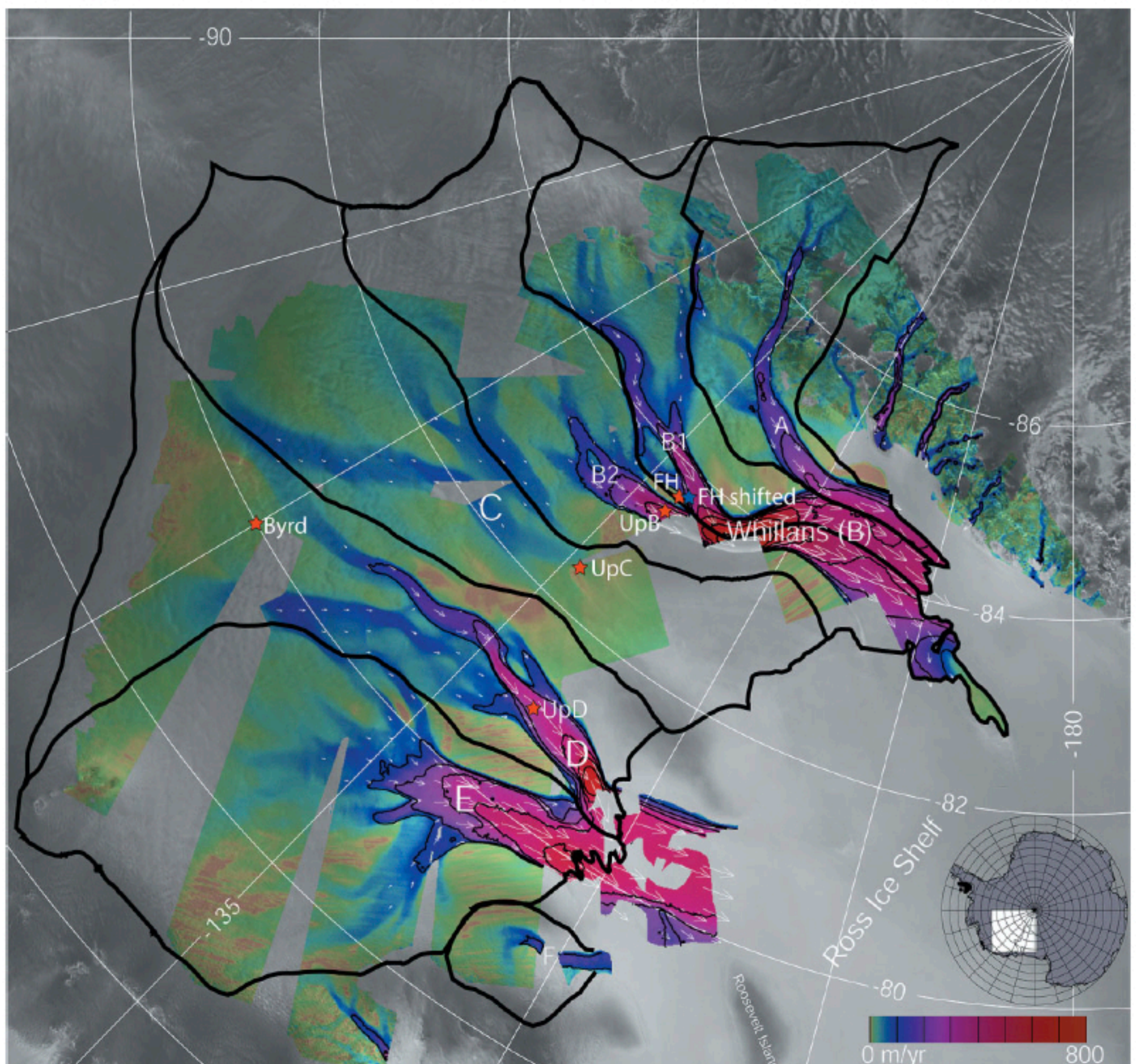
- **Pure ice streams:** the bed is very weak, driving stress is weak too - more common in West Antarctica



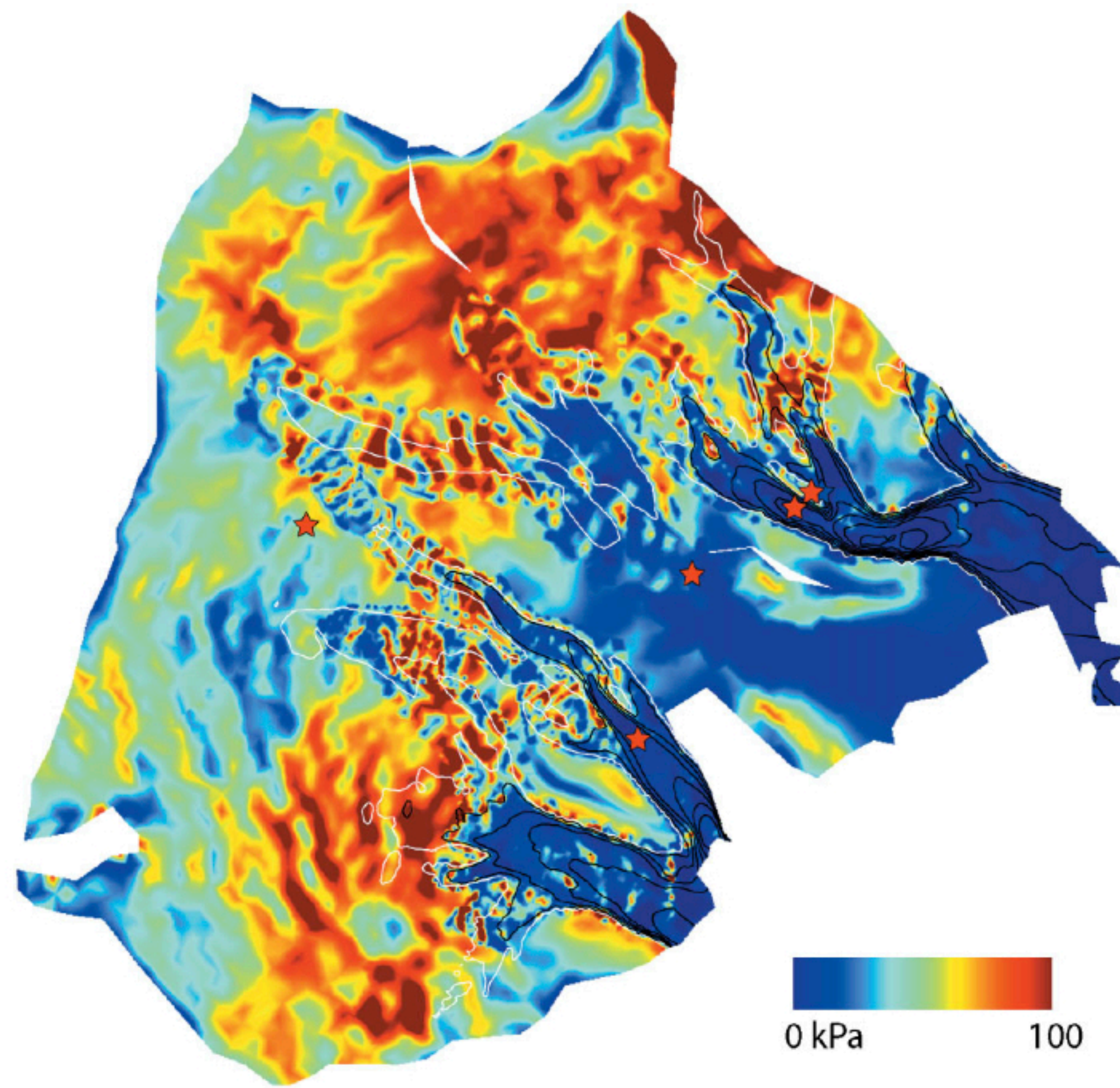
Bennett 2003

So how does the bed get so weak in pure ice streams?

Siple Coast, W. Antarctica Velocities



Siple Coast, W. Antarctica Bed Friction



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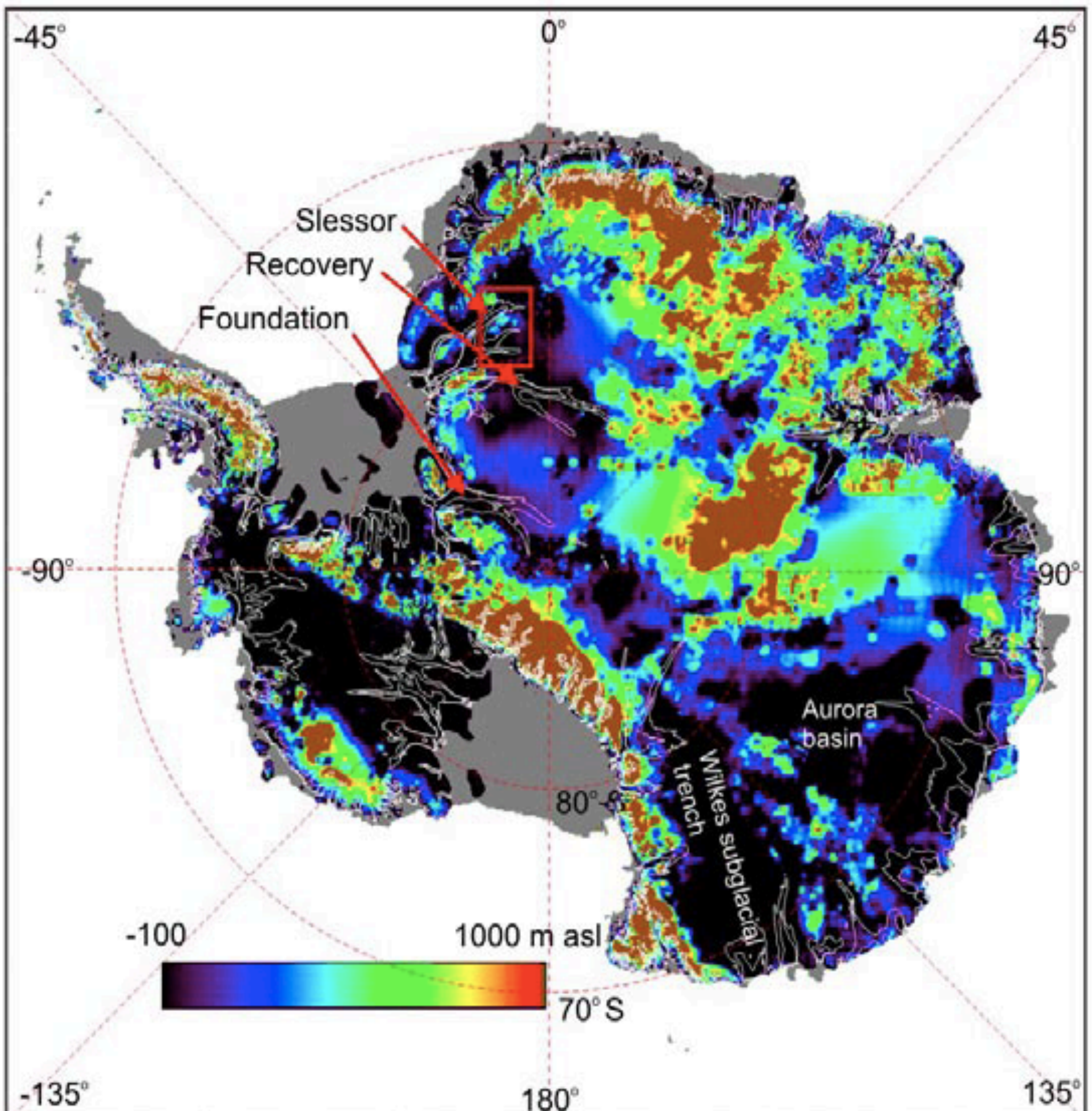
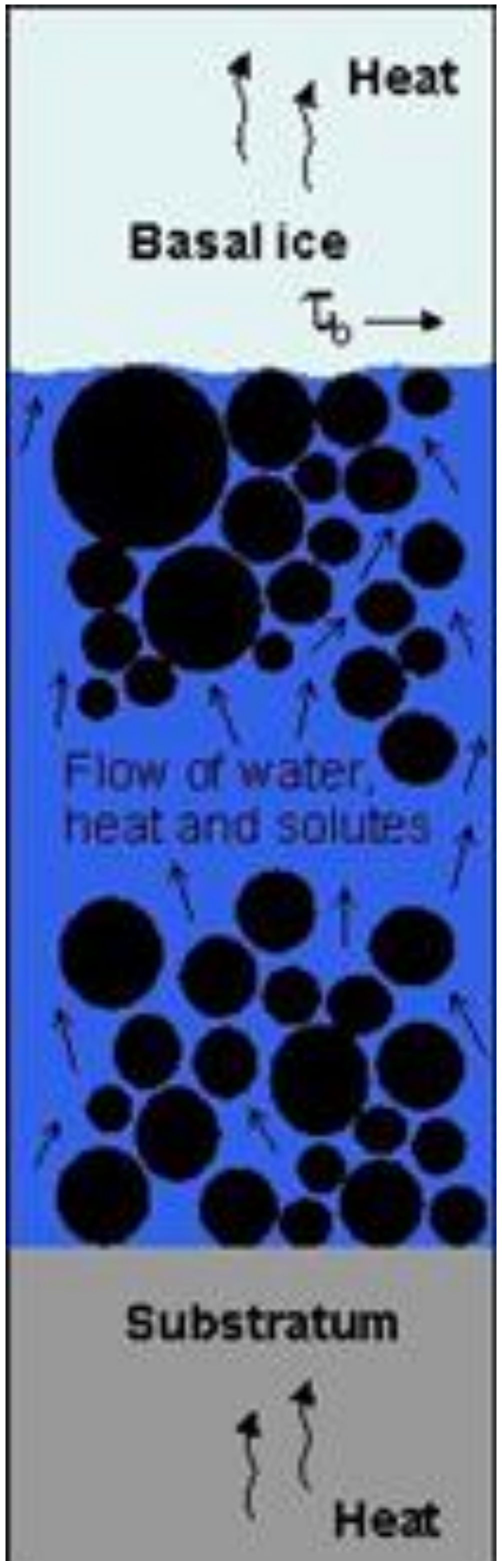
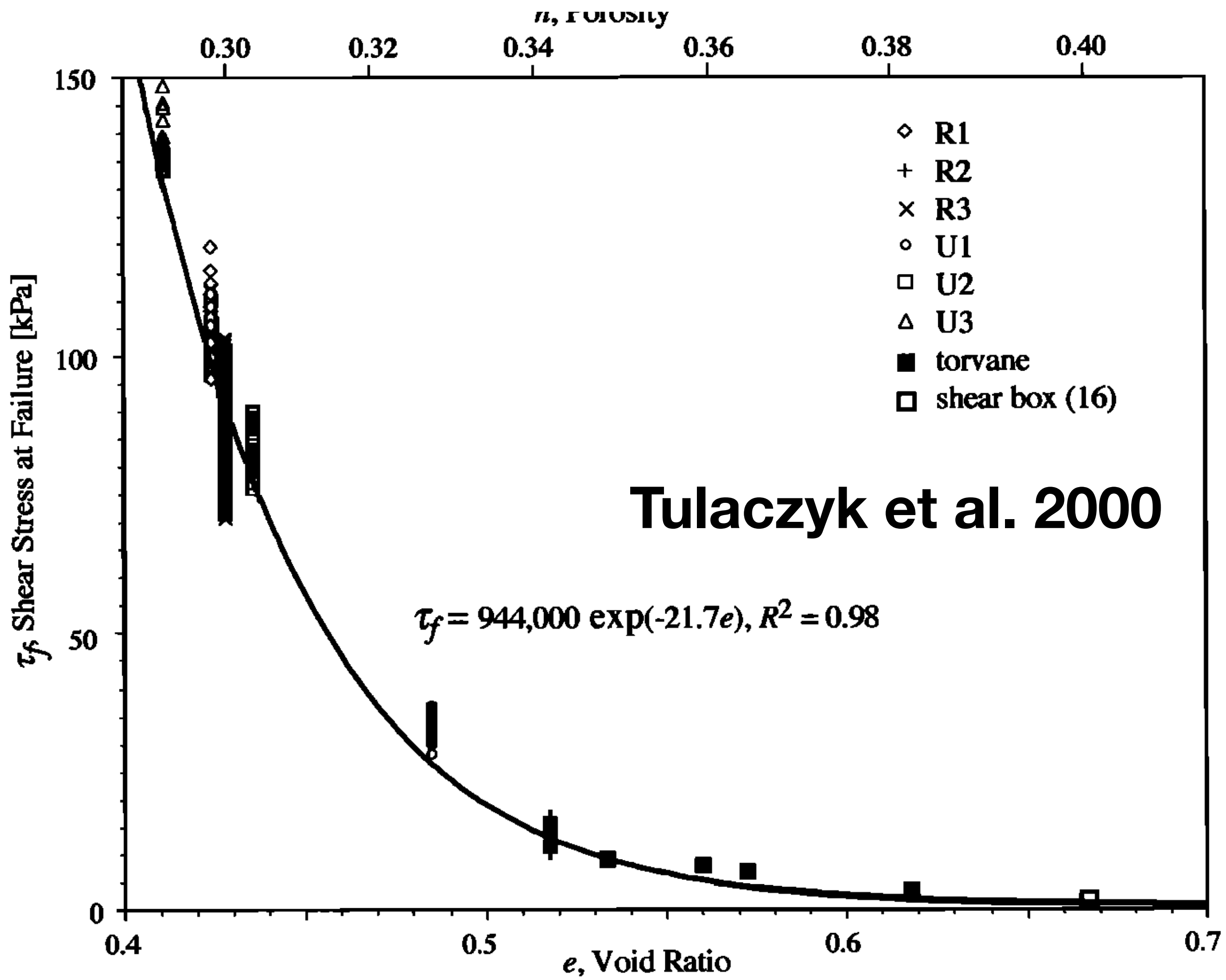


Parts of Antarctic Ice Sheet that are below sea level (black on plot to the left) have been covered by ocean in the past when the ice sheet was much smaller and so there are lots of marine sediments

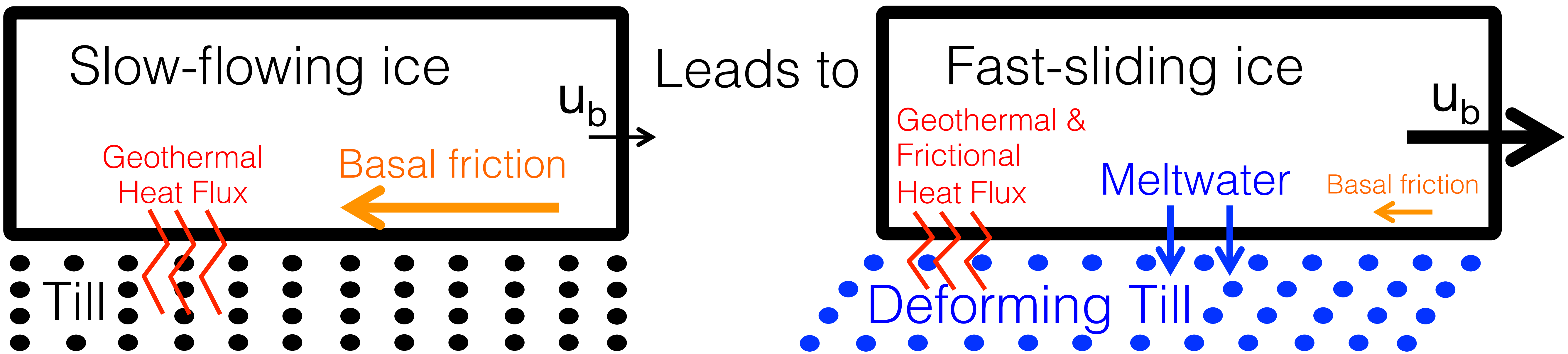
Till yield strength and water content





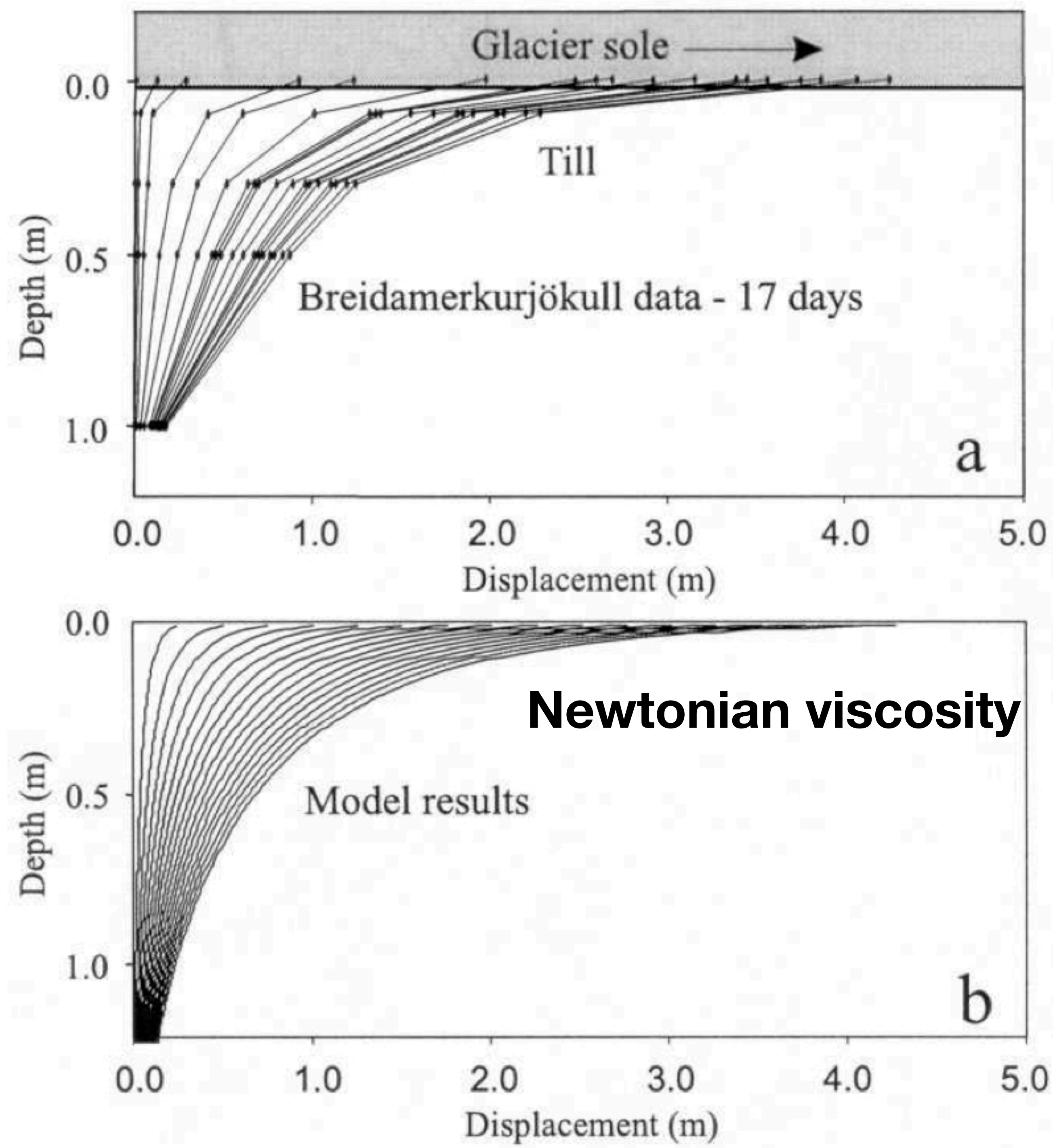
In water-rich tills, the addition of more water beyond the consolidation threshold of till causes a reduction in contact between grains within the till, lowering the basal shear stress require for plastic yielding of the till

So how does the bed get so weak in pure ice streams?



What happens where the bed is soft and can deform?

Measurements from stakes underneath a glacier in Iceland (Boulton 1979)



What happens where the bed is soft and can deform?

Measurements from a ring shear apparatus with till extracted from glaciers

What happens where the bed is soft and can deform?

Till is plastic (not deformation below a certain yield stress) - that yield stress depends on effective pressure

Mohr-Coulomb failure criterion

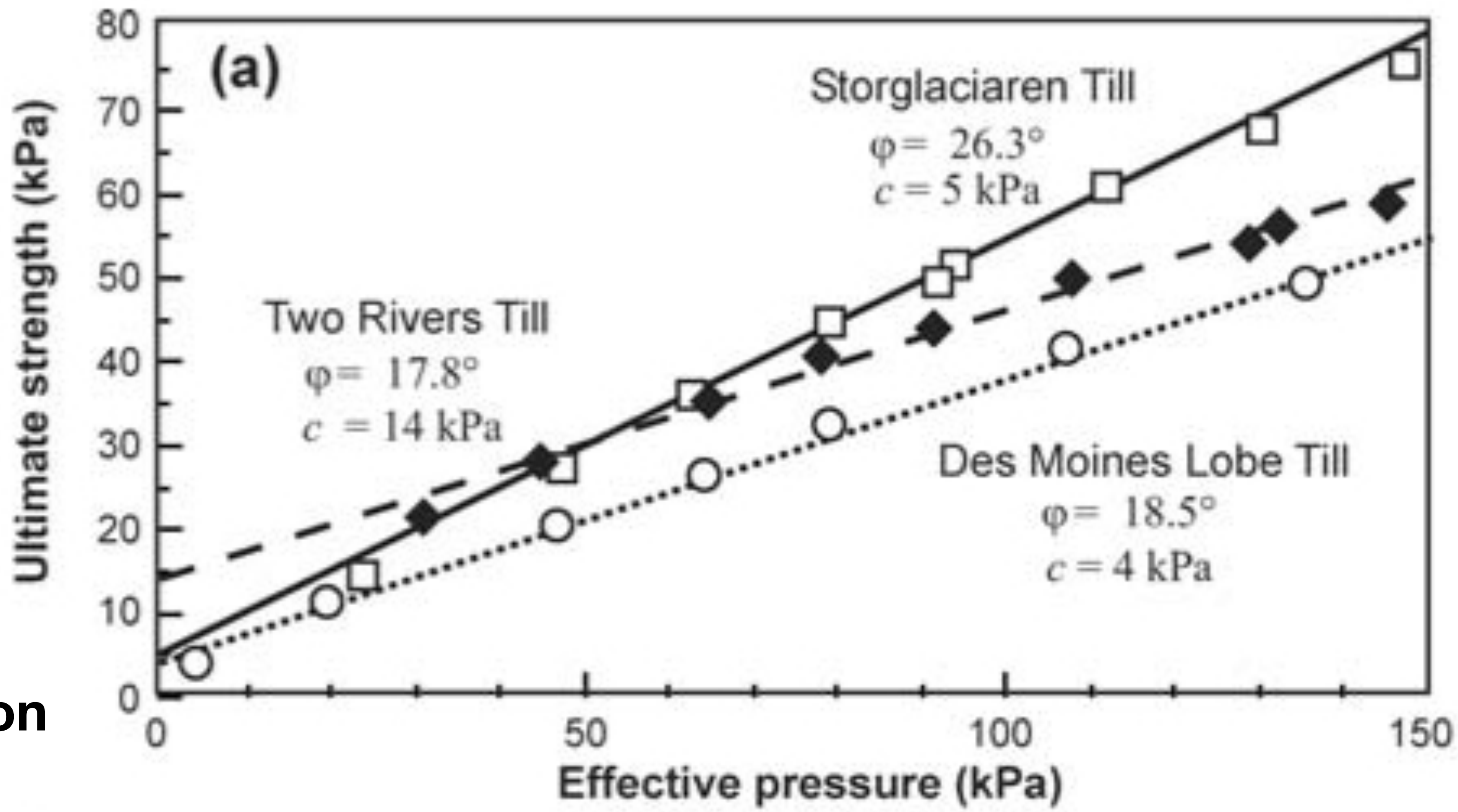
$$\tau = N \tan(\phi) + c$$

Applied effective normal stress

Till friction angle

Till cohesion

Measurements from a ring shear apparatus with till extracted from glaciers



Effective pressure increases with depth in till - lowest yield stress nearest to the ice-till interface - still explains Iceland measurements!

Cohesion

Cohesion - the attraction of grains to each other - depends on the grain properties and what's in between the grain

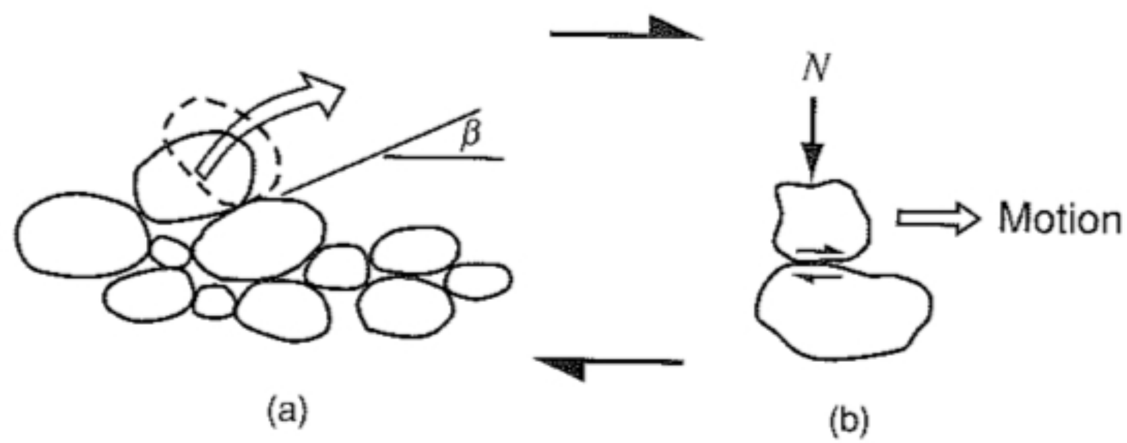
Sand grains are not very cohesive. They will only stick to one another if there is some water in the sand, but <u>not too much</u>

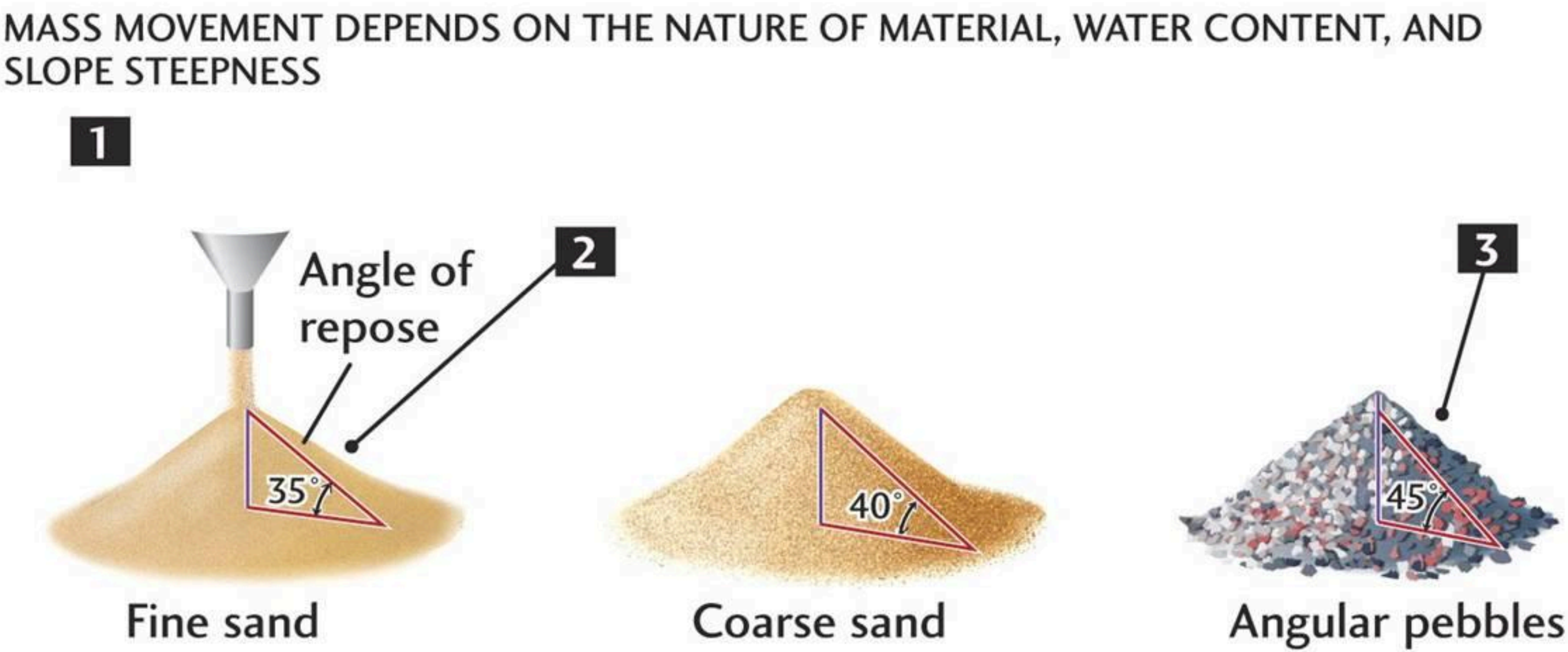
Cohesion

Cohesion - the attraction of grains to each other - depends on the grain properties and what's in between the grain

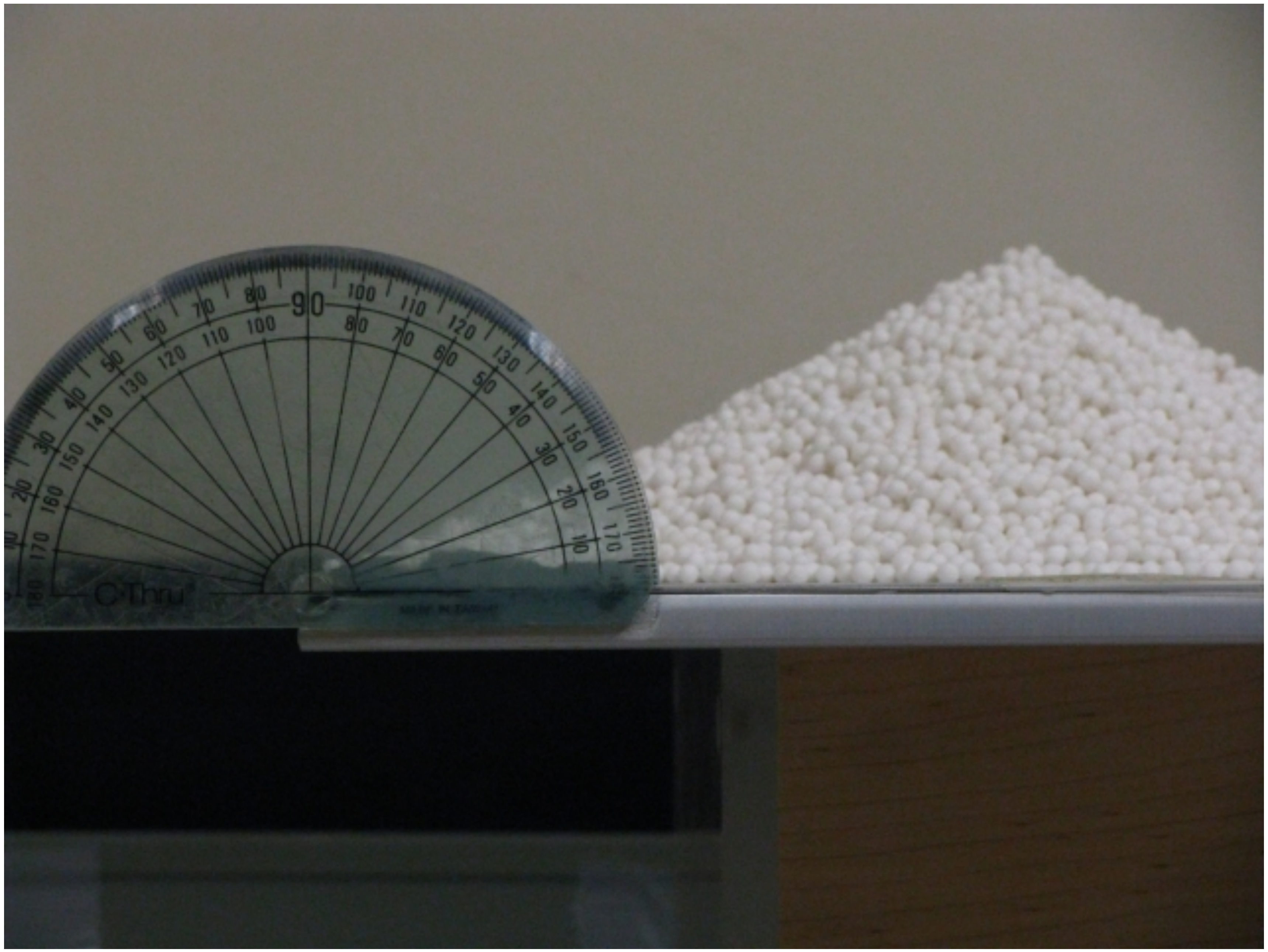
Clay grains are very small, and hence cohesive. Water makes them even more cohesive

Friction angle and the angle of repose



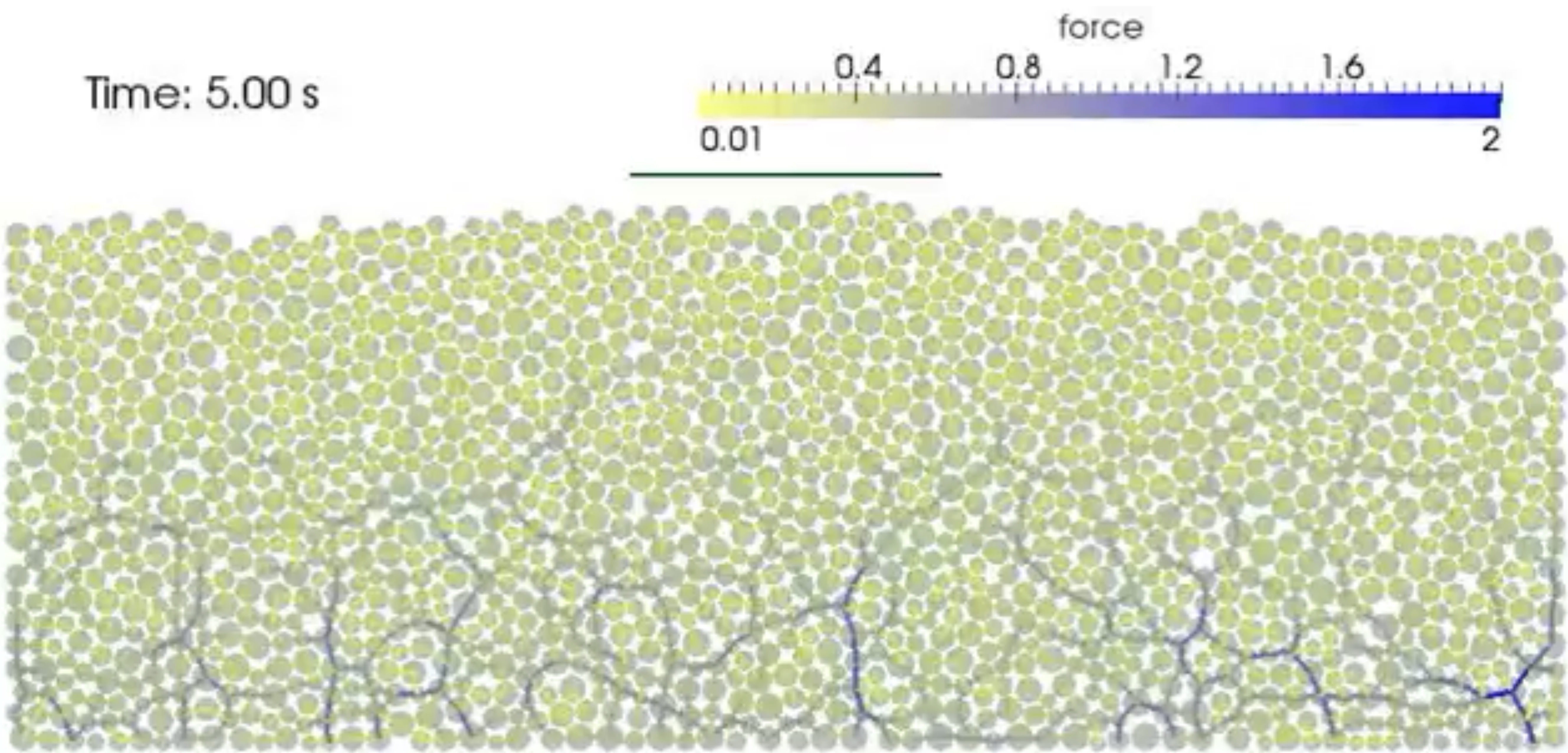


Friction angle and the angle of repose

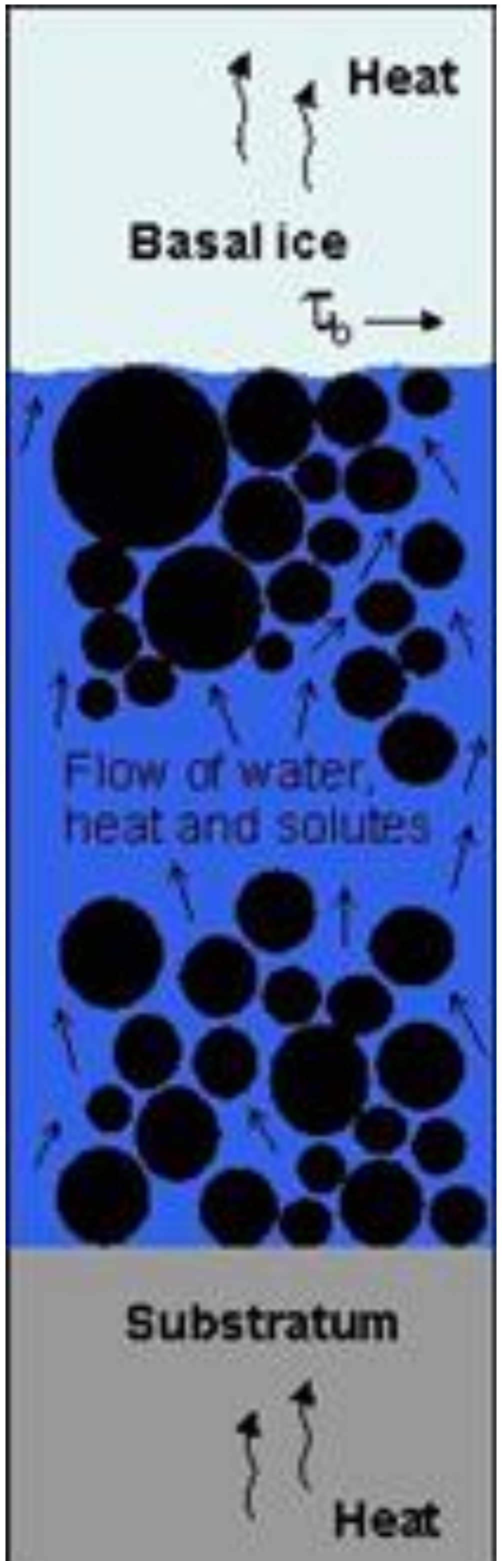


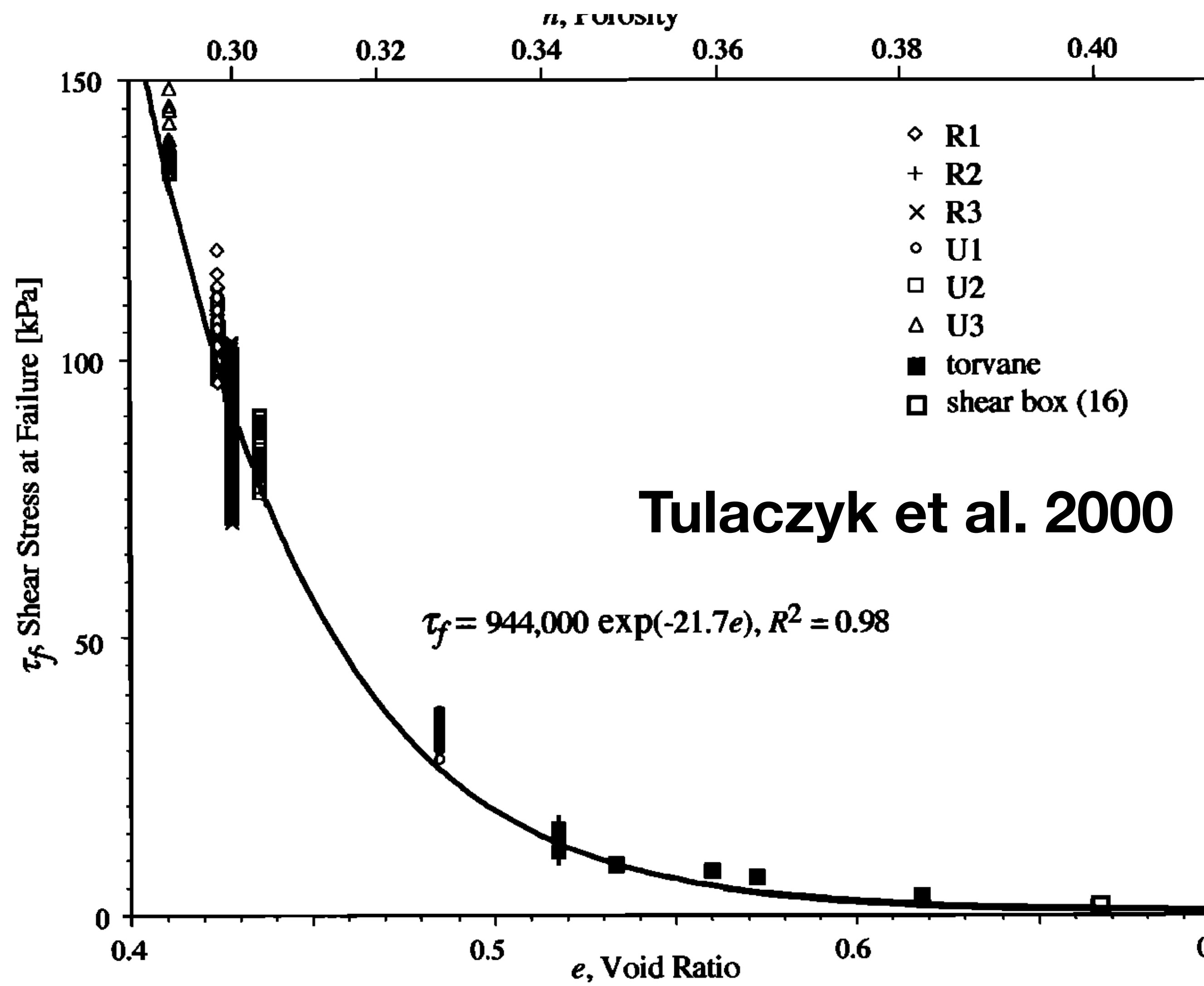
Grain contacts transmit stress from boundaries over long distances

Grain contacts transmit stress from boundaries over long distances



Saturation of till





In water-rich tills, the addition of more water beyond the consolidation threshold of till causes a reduction in contact between grains within the till, lowering the basal shear stress require for plastic yielding of the till

Saturation of till

Water in till

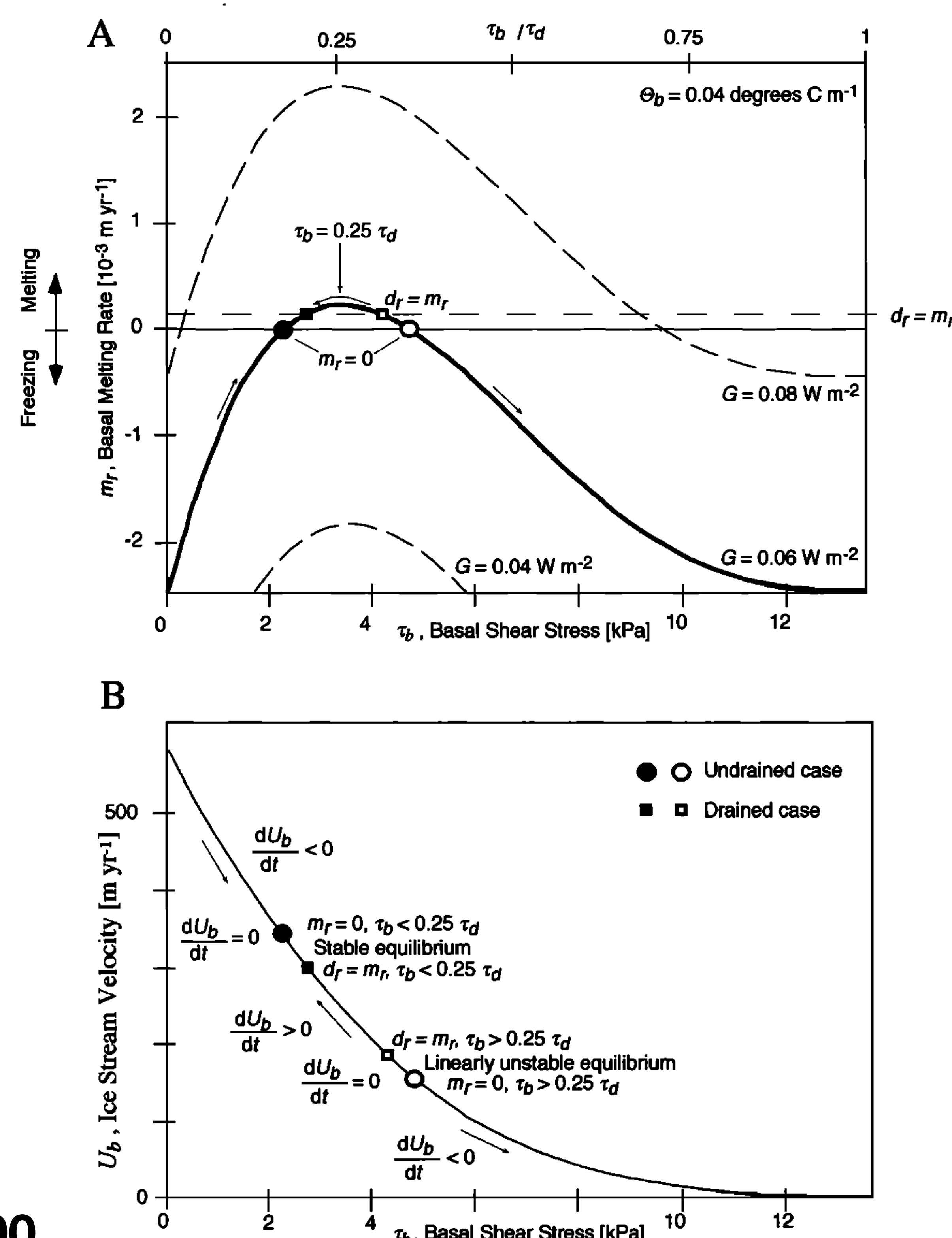
Stress lowers till
deforms more

More heat generated by friction
at interface (velocity x friction)

Water generated by friction heat

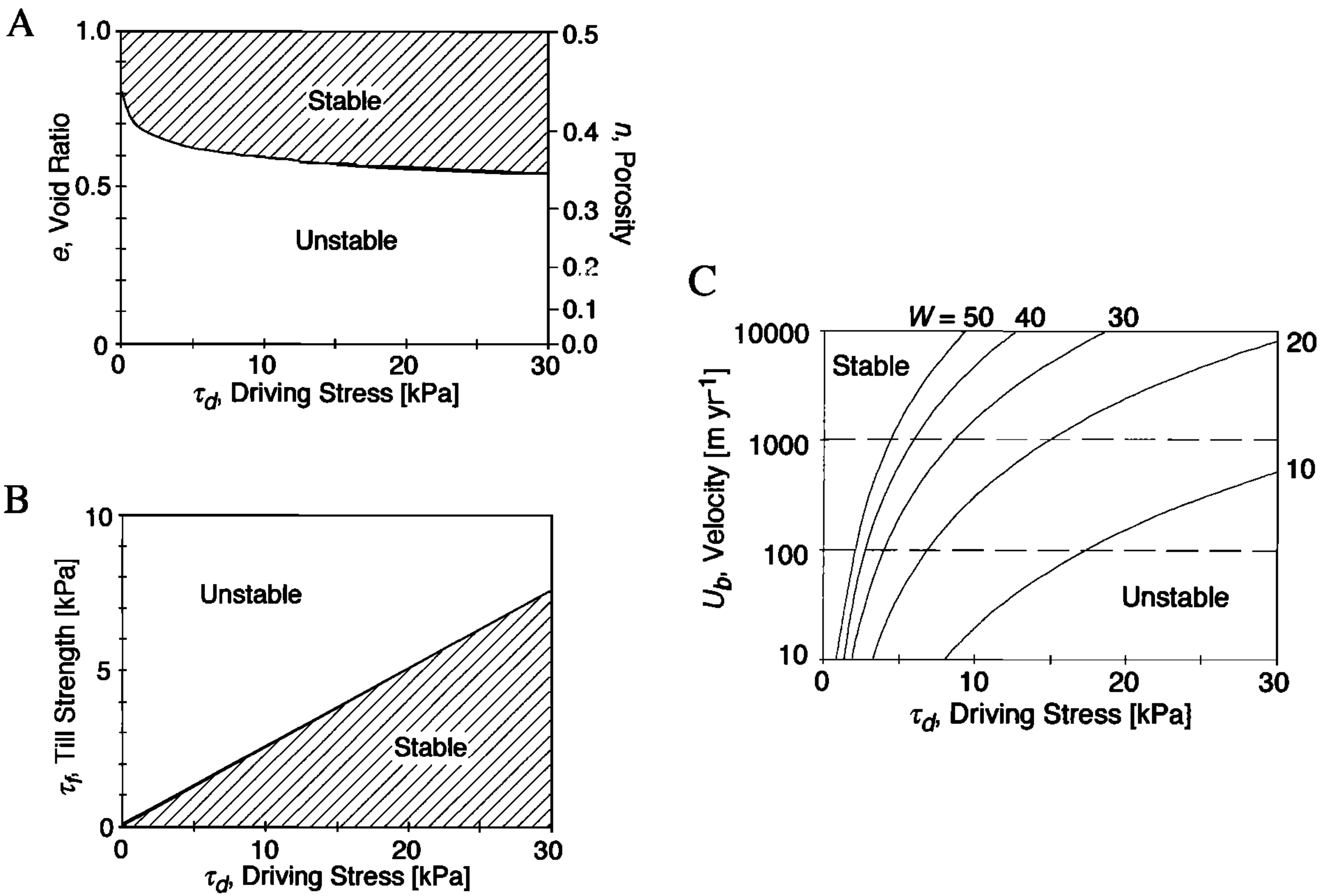
Positive feedback?

Saturation of till



Tulaczyk et al. 2000

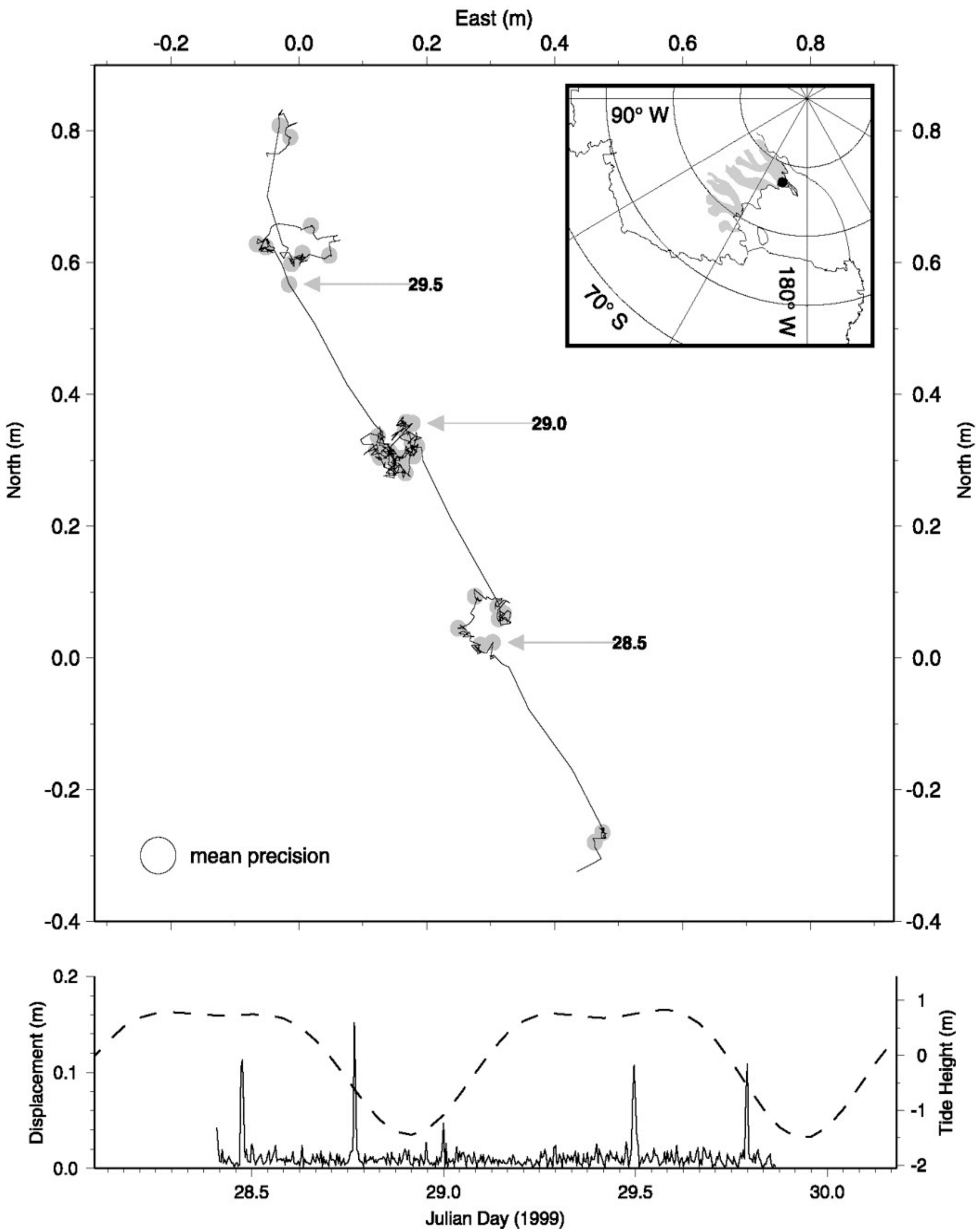
Saturation of till



Tulaczyk et al. 2000

Stick-slip ice stream variability

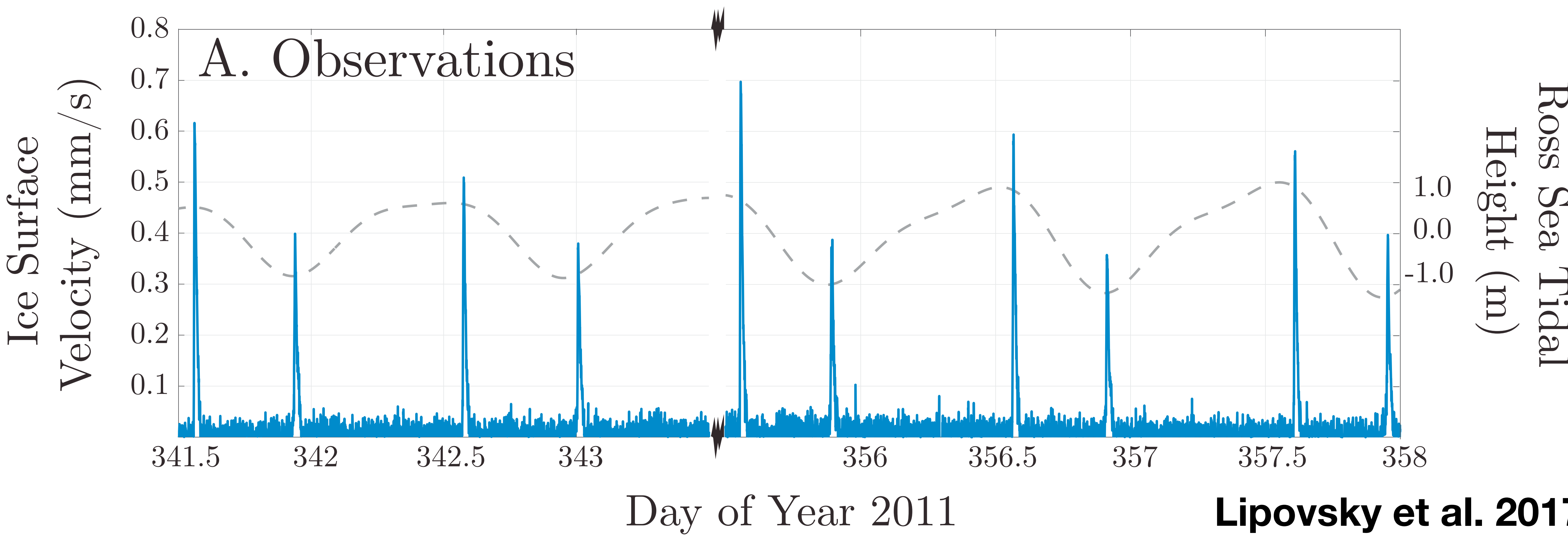
Whillans Ice Stream, West Antarctica



Stick-slip motion: ice is mostly static (stick), but periodically it moves very quickly over a short duration (slip). Similar to how faults move during and in-between earthquakes

Stick-slip ice stream variability

Whillans Ice Stream, West Antarctica

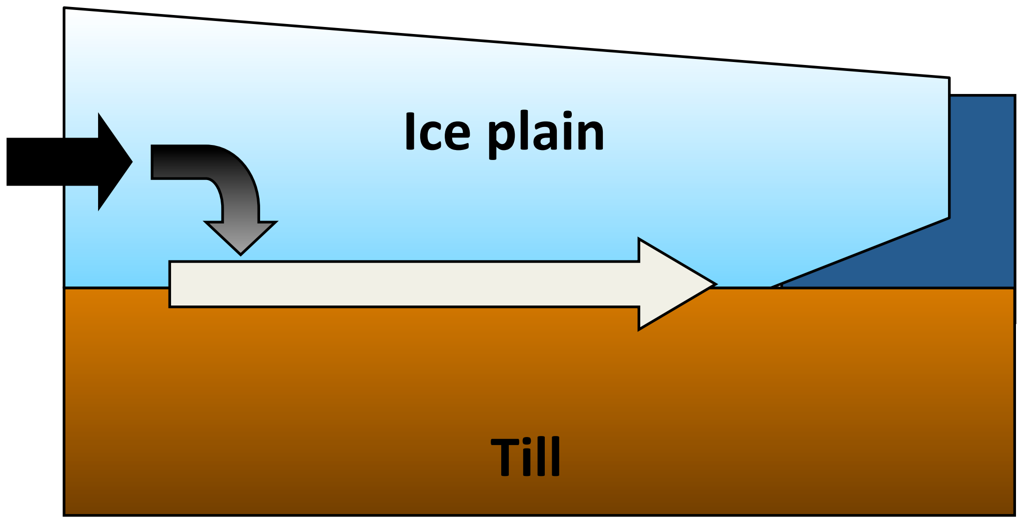


Lipovsky et al. 2017

The slip events at this one ice stream also seem to occur during high or low tide

Stick-slip ice stream variability

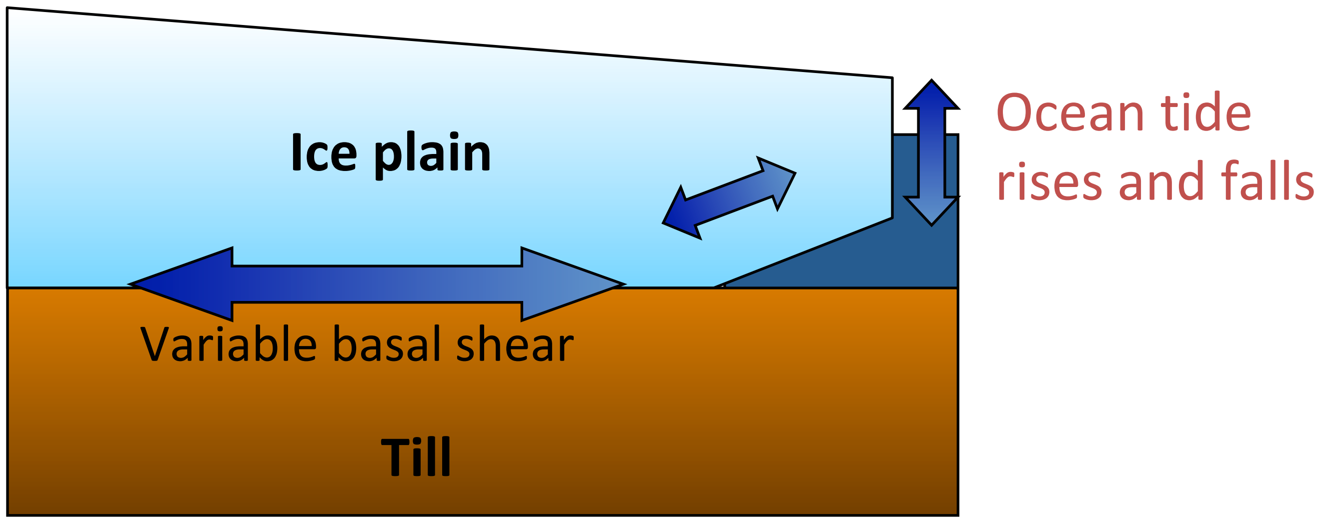
Whillans Ice Stream, West Antarctica



One idea: plastic till is below the “yield stress” that is required for deformation to occur in the till

Stick-slip ice stream variability

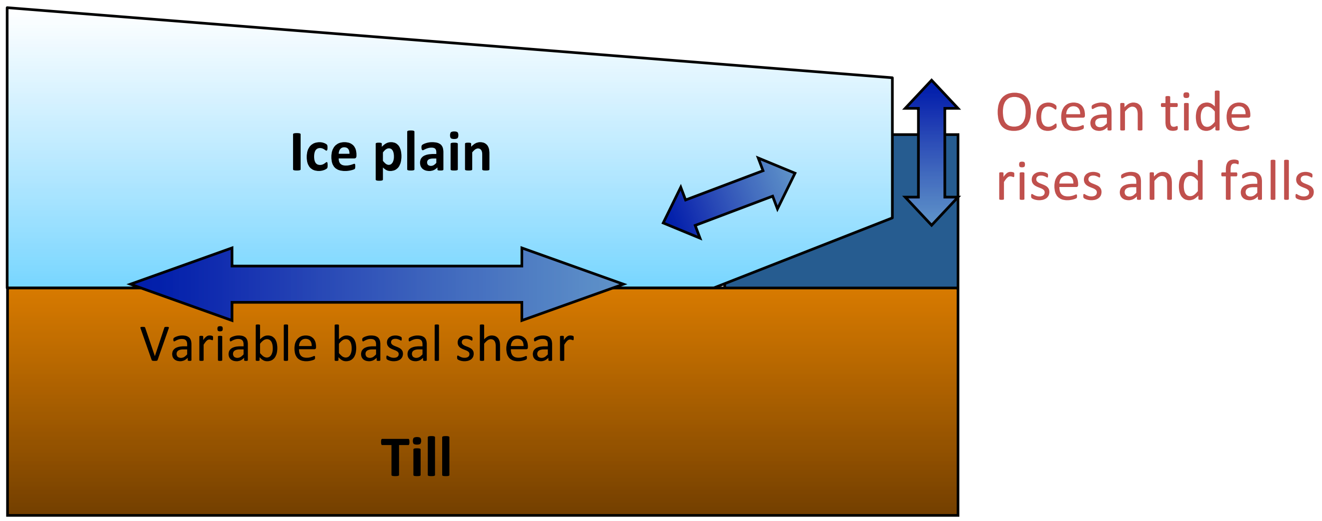
Whillans Ice Stream, West Antarctica



One idea: when the yield stress is reached, the till slips arbitrarily fast until stress is relieved

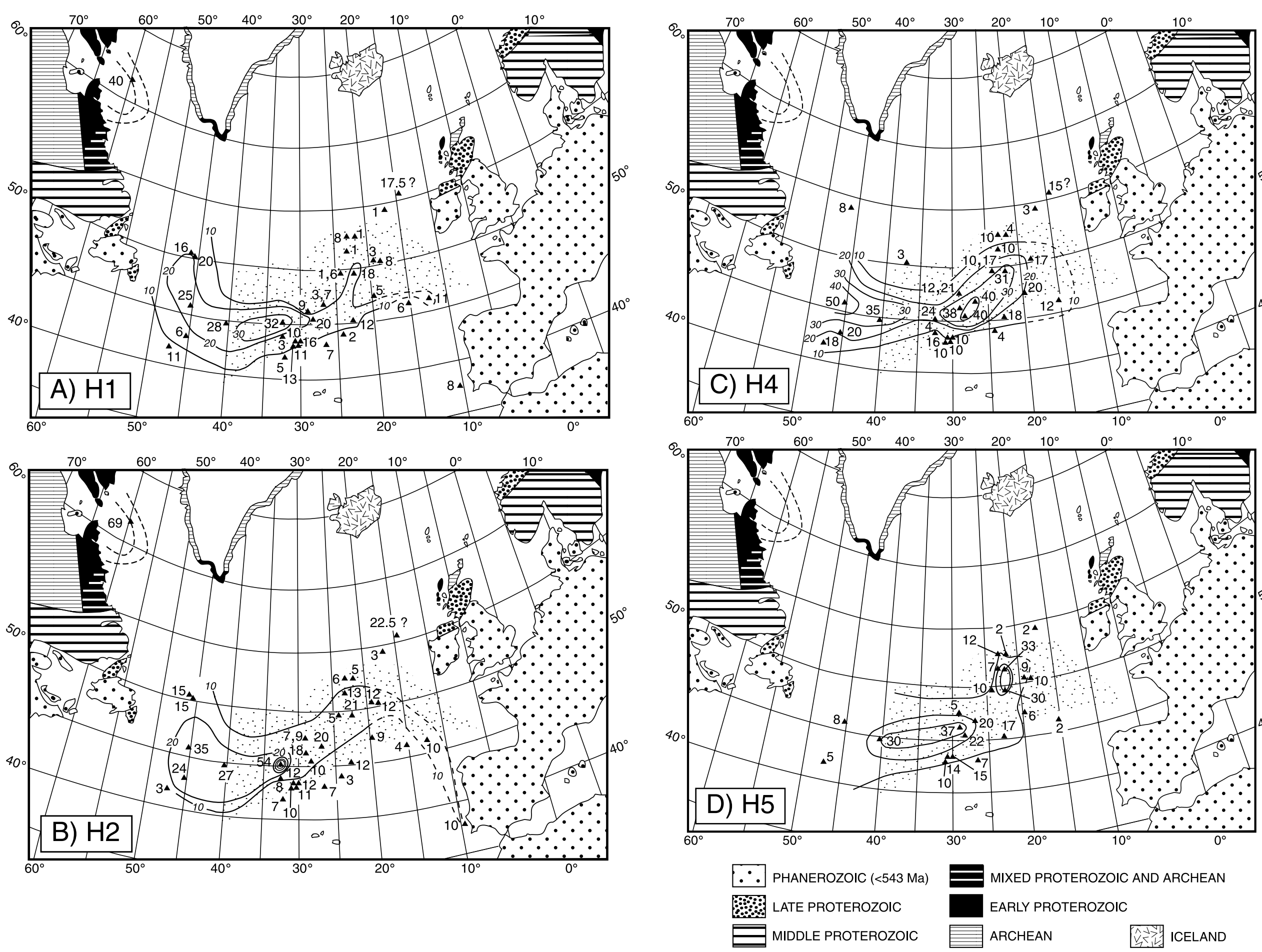
Stick-slip ice stream variability

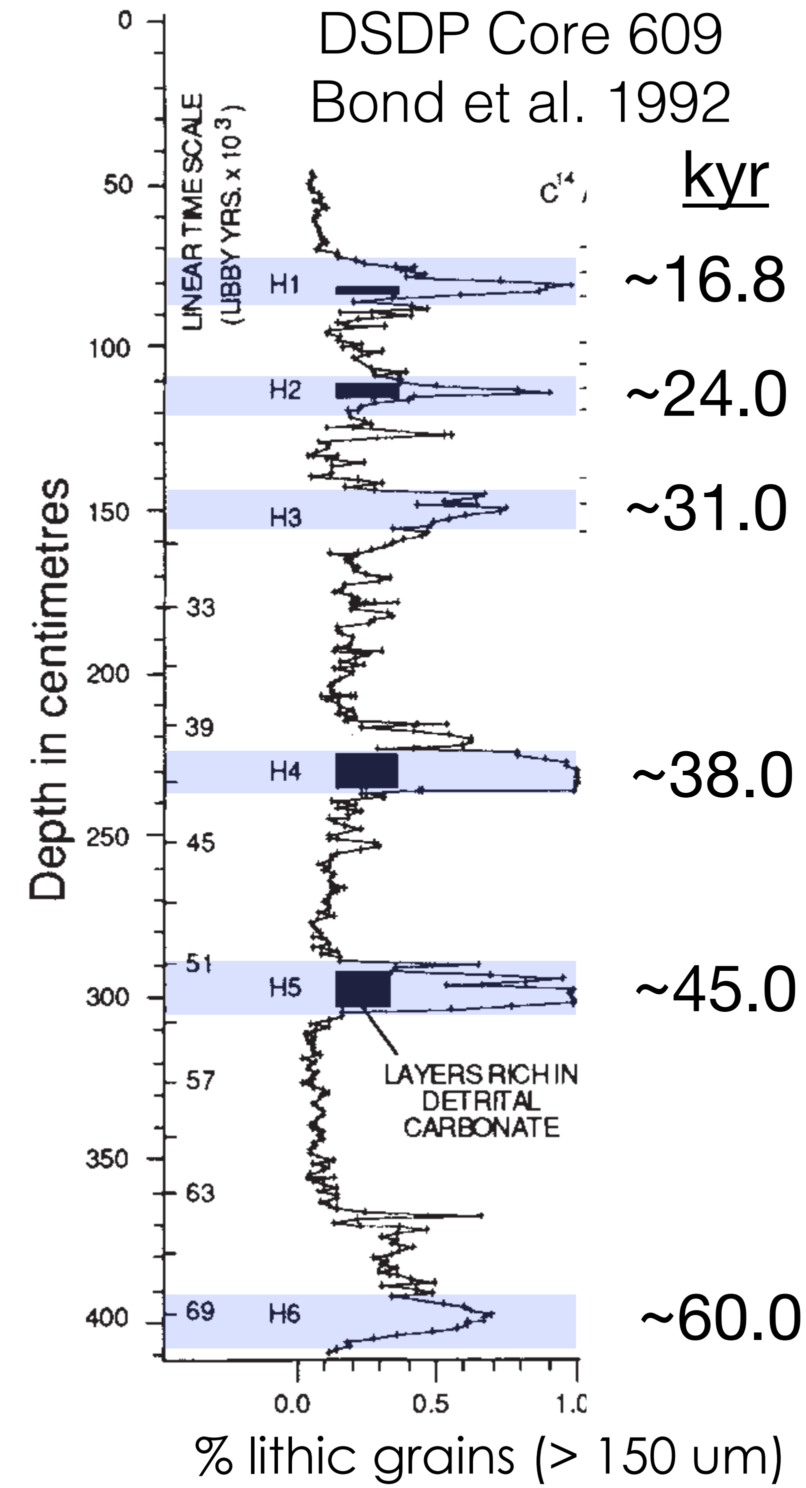
Whillans Ice Stream, West Antarctica



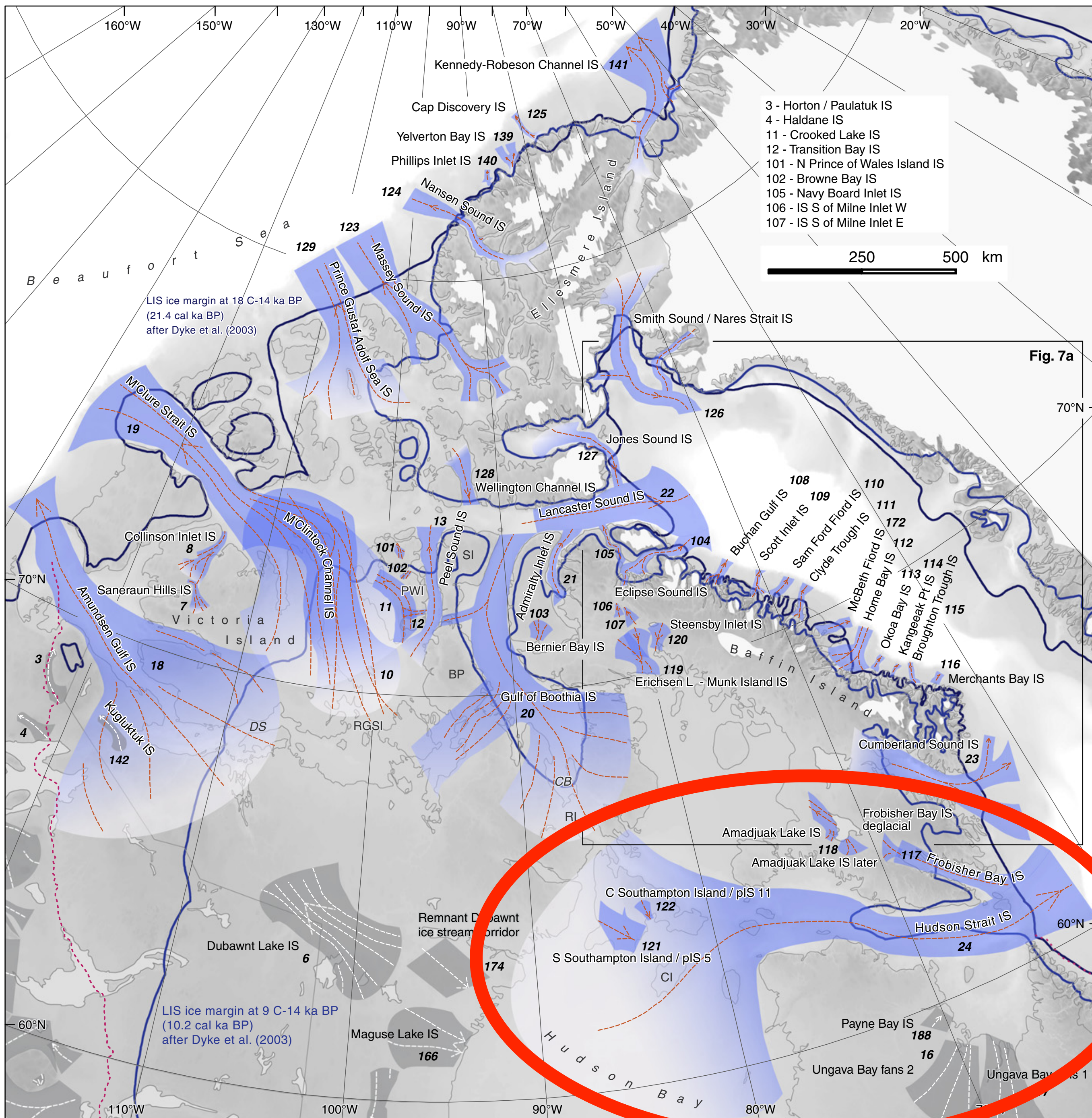
However, to explain the particular phasing and time scale of stick-slip behavior of ice streams (such as Whillans) requires more complicated models than just plastic till (i.e. rate and state behavior, see Lipovsky et al. 2017)

Centennial/millennial scale ice stream variability



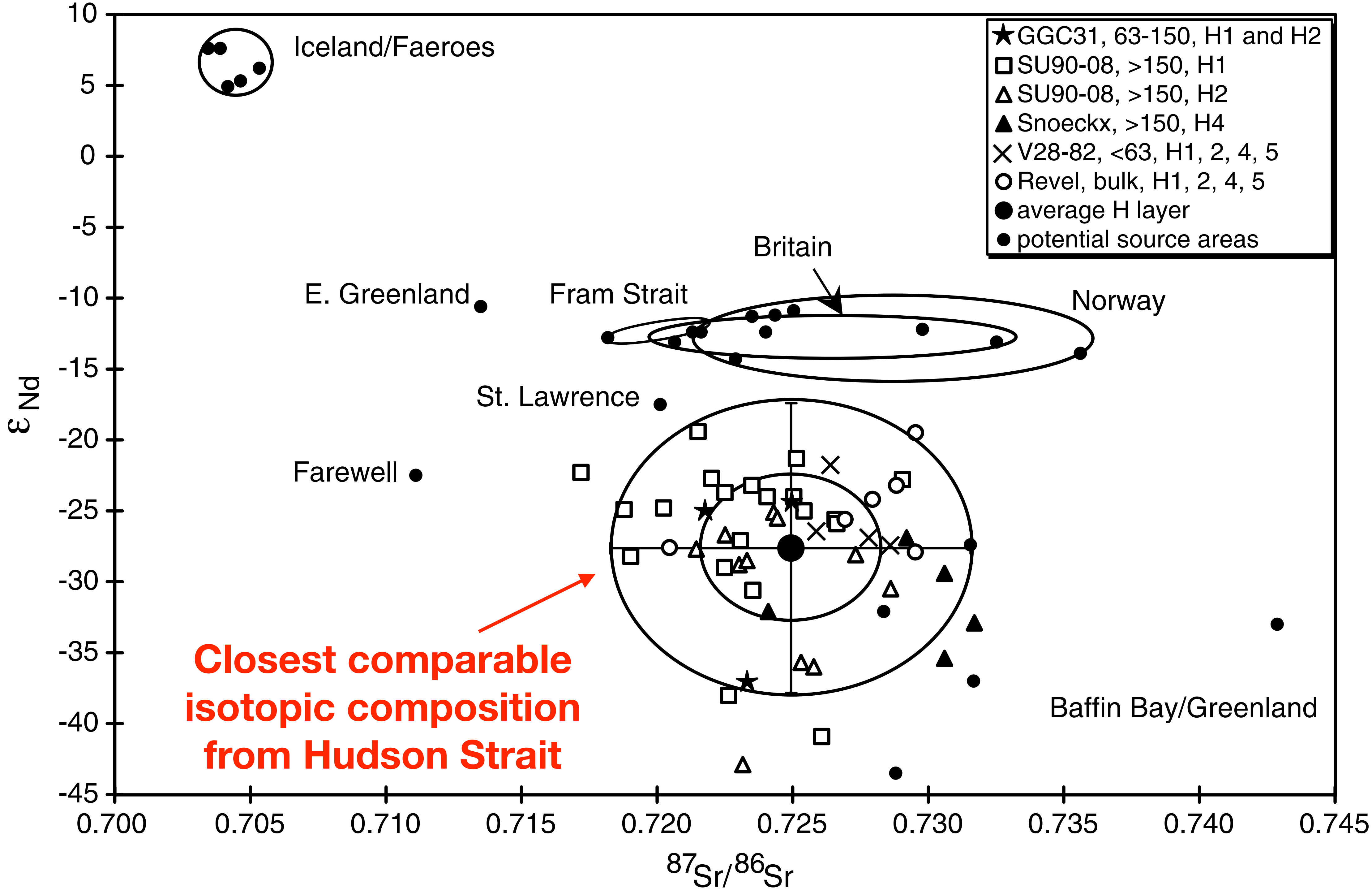


Centennial/millennial scale ice stream variability



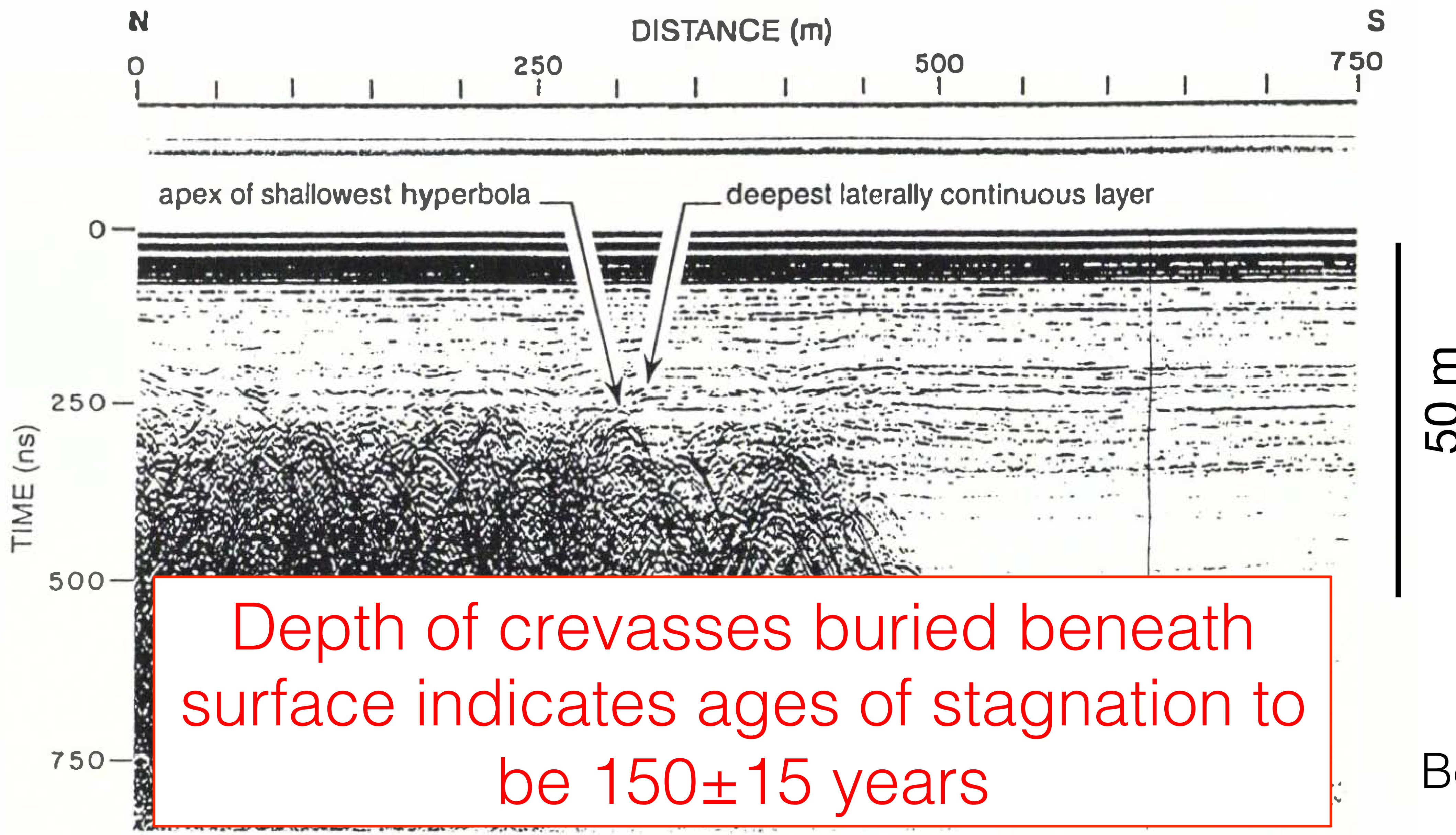
Hudson Strait Ice Stream - potentially the largest ice stream existing in the geological record (about as long as the distance from Atlanta to Texas), drained the heart of the Laurentide Ice Sheet - variability in ice flow thought to play a role in generating Heinrich events through discharge of icebergs

Centennial/millennial scale ice stream variability



Hemming 2004

Centennial/millennial scale ice stream variability



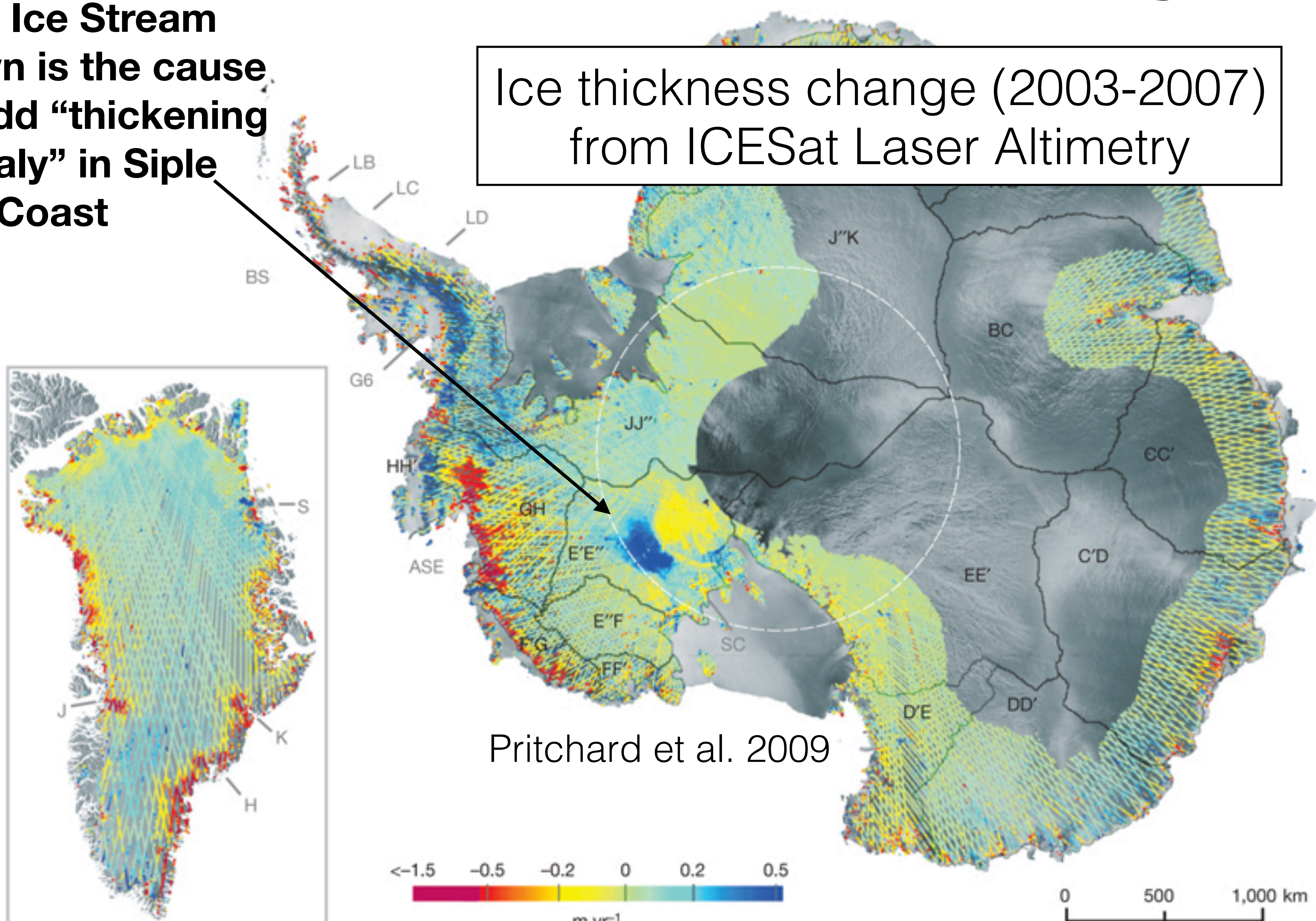
Retzlaff & Bentley 1993

Ice streams in West Antarctica also seem to exhibit flow variability on time scales of centuries

Centennial/millennial scale ice stream variability

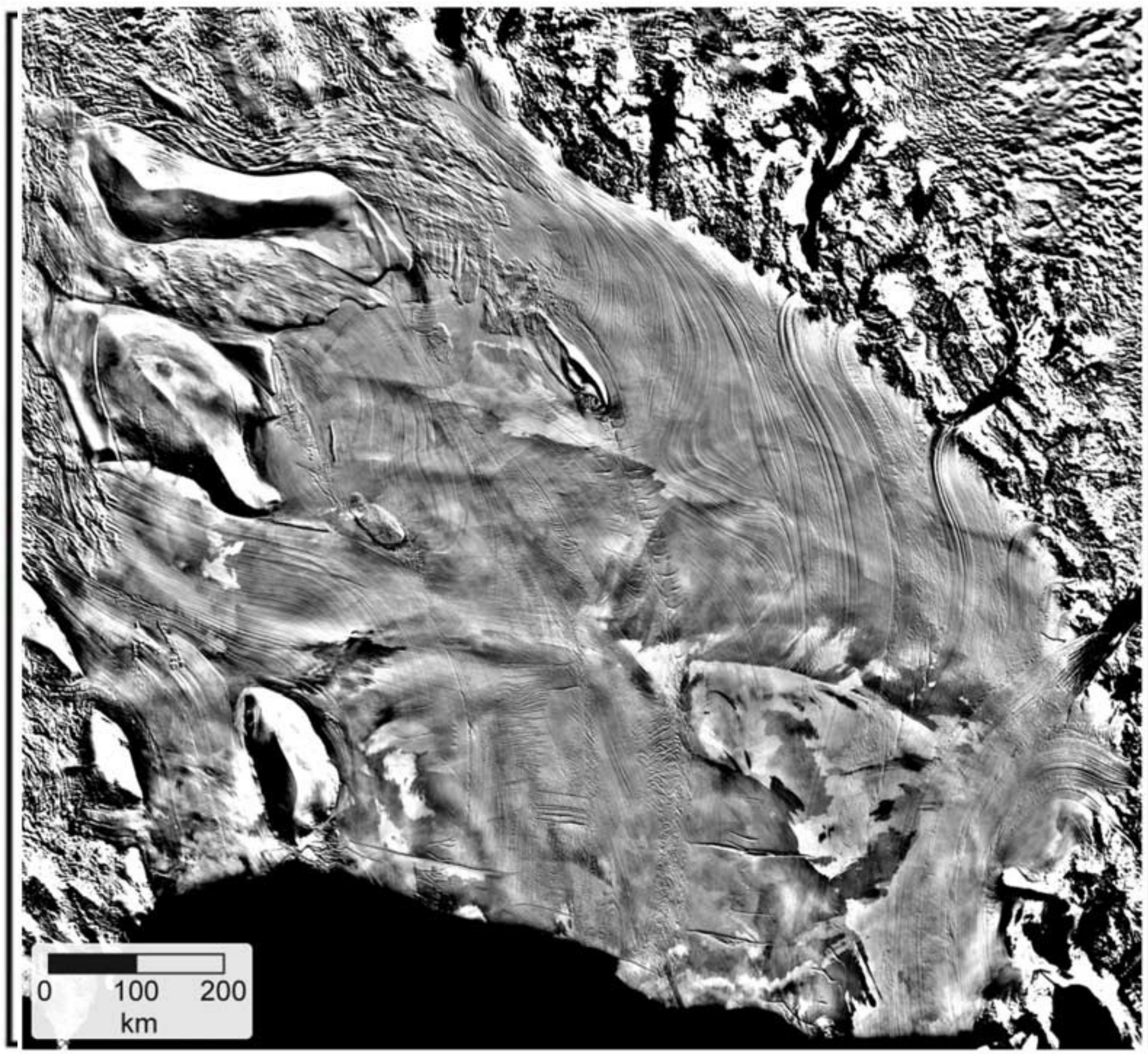
Kamb Ice Stream shutdown is the cause of this odd "thickening anomaly" in Siple Coast

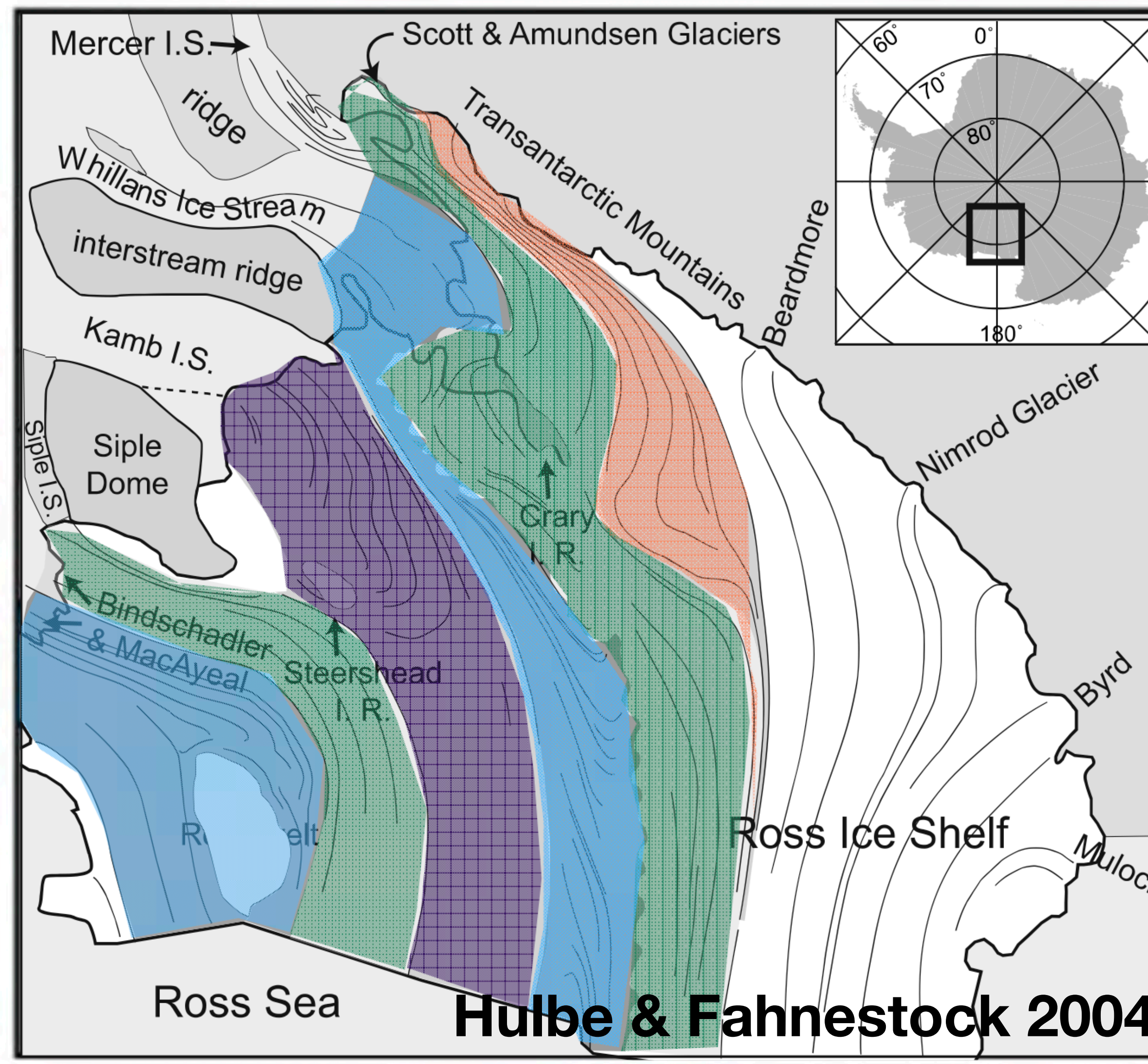
Ice thickness change (2003-2007) from ICESat Laser Altimetry



Pritchard et al. 2009

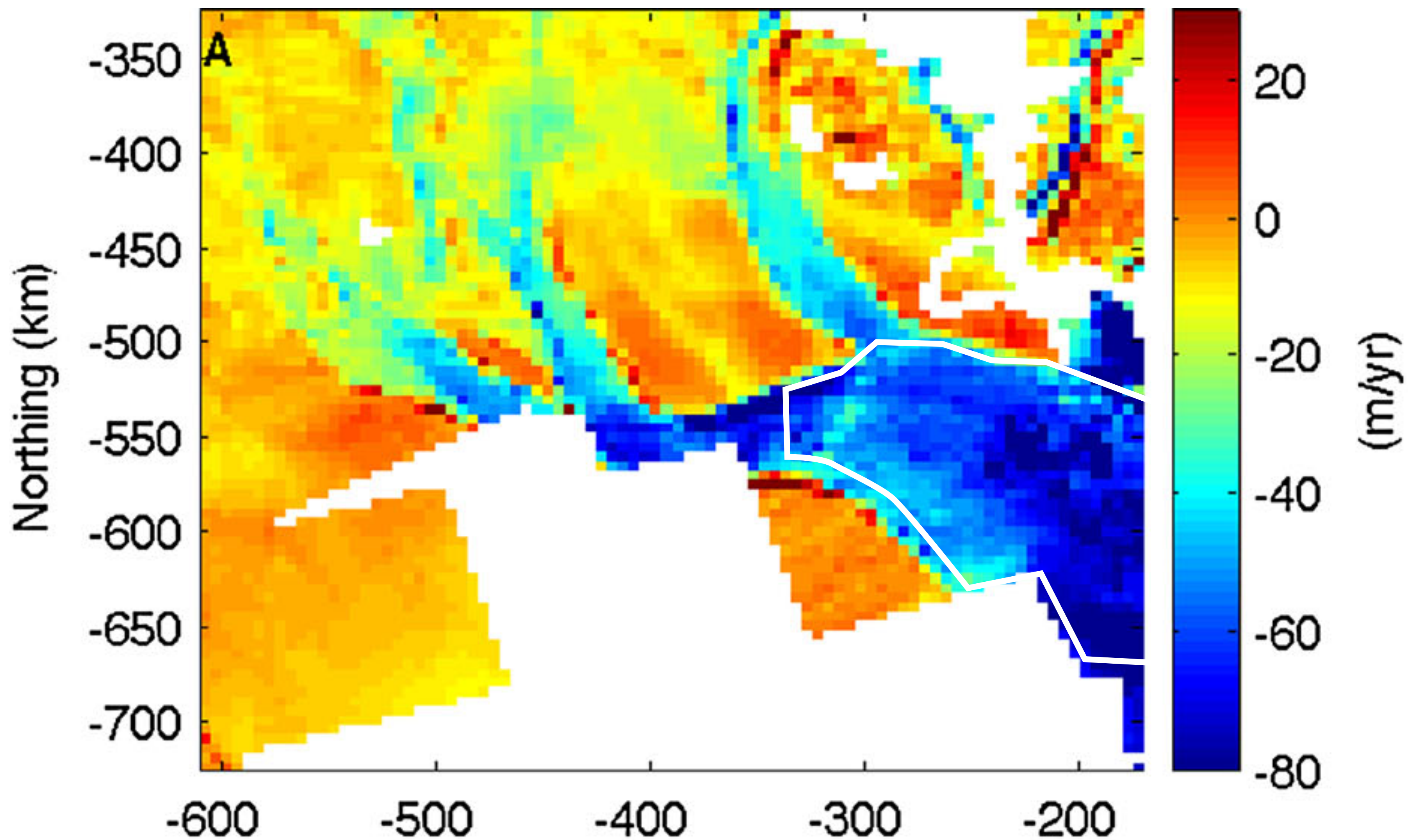
Centennial/millennial scale ice stream variability





Folds/undulations in streamlines the Ross Ice Shelf (in the absence of other obstructions) indicate that the relative flow speed of adjacent ice streams has changed over time

Centennial/millennial scale ice stream variability



Beem et al. 2014

Difference in Whillans ice stream velocity between 1997 and 2009

Ice stream variability

Water in till

Stress lowers till
deforms more

What else affects
the heat budget
at the ice-bed
interface?

More heat generated by friction
at interface (velocity x friction)

Water generated by friction heat

Positive feedback?