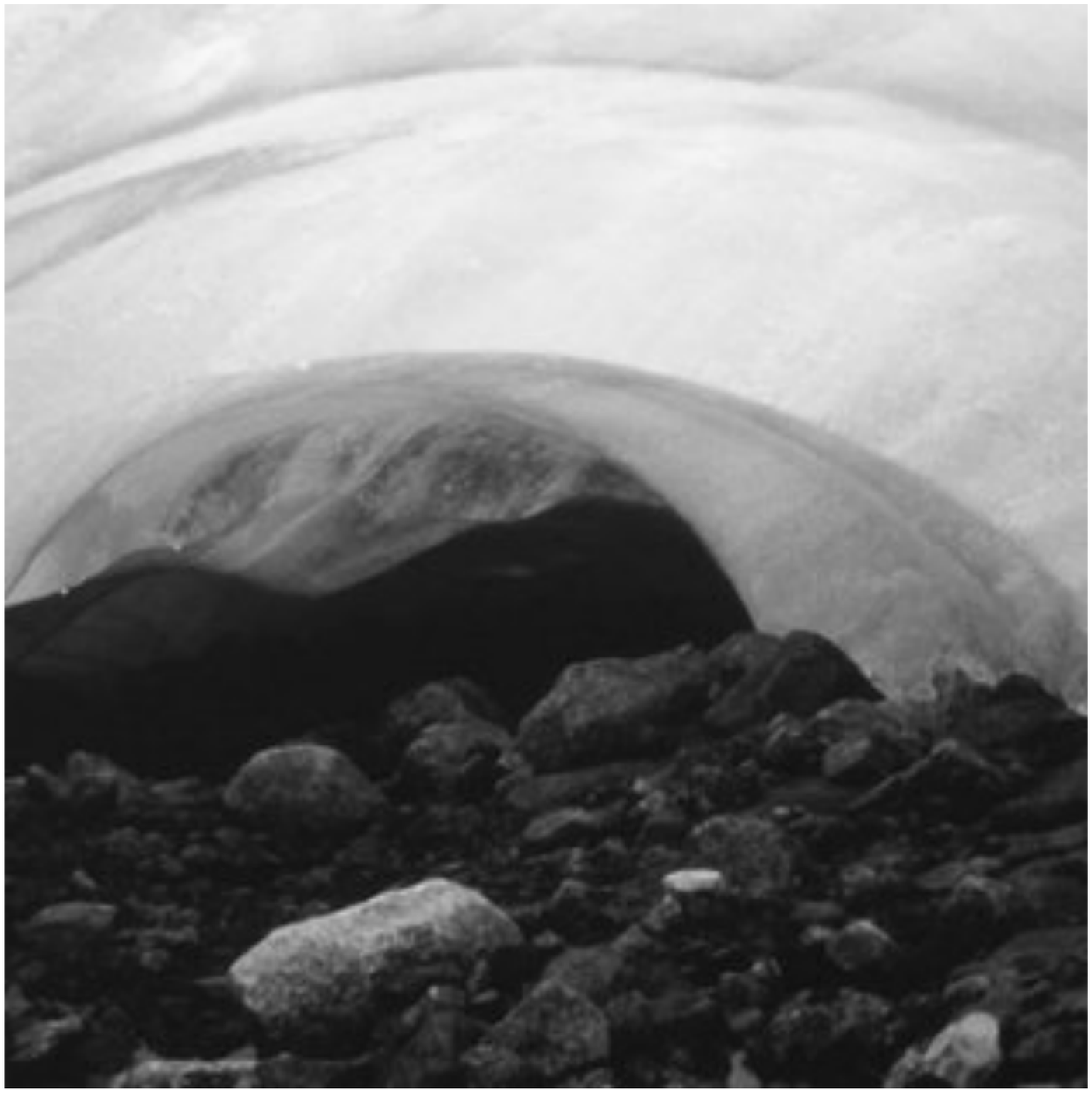
The Ice-Bed Interface

What is down there?

Hard obstacles of varying size

What is down there?

Hard obstacles of varying size



What is down there?

Till

(poorly sorted glacially-eroded sediment)

What is down there?

Till

(poorly sorted glacially-eroded sediment)

What is down there?

Water

What is down there?

Water

Why do we care?

Ice slides over the bed and/or the bed deforms under the ice

Why do we care?

Ice slides over the bed and/or the bed deforms under the ice

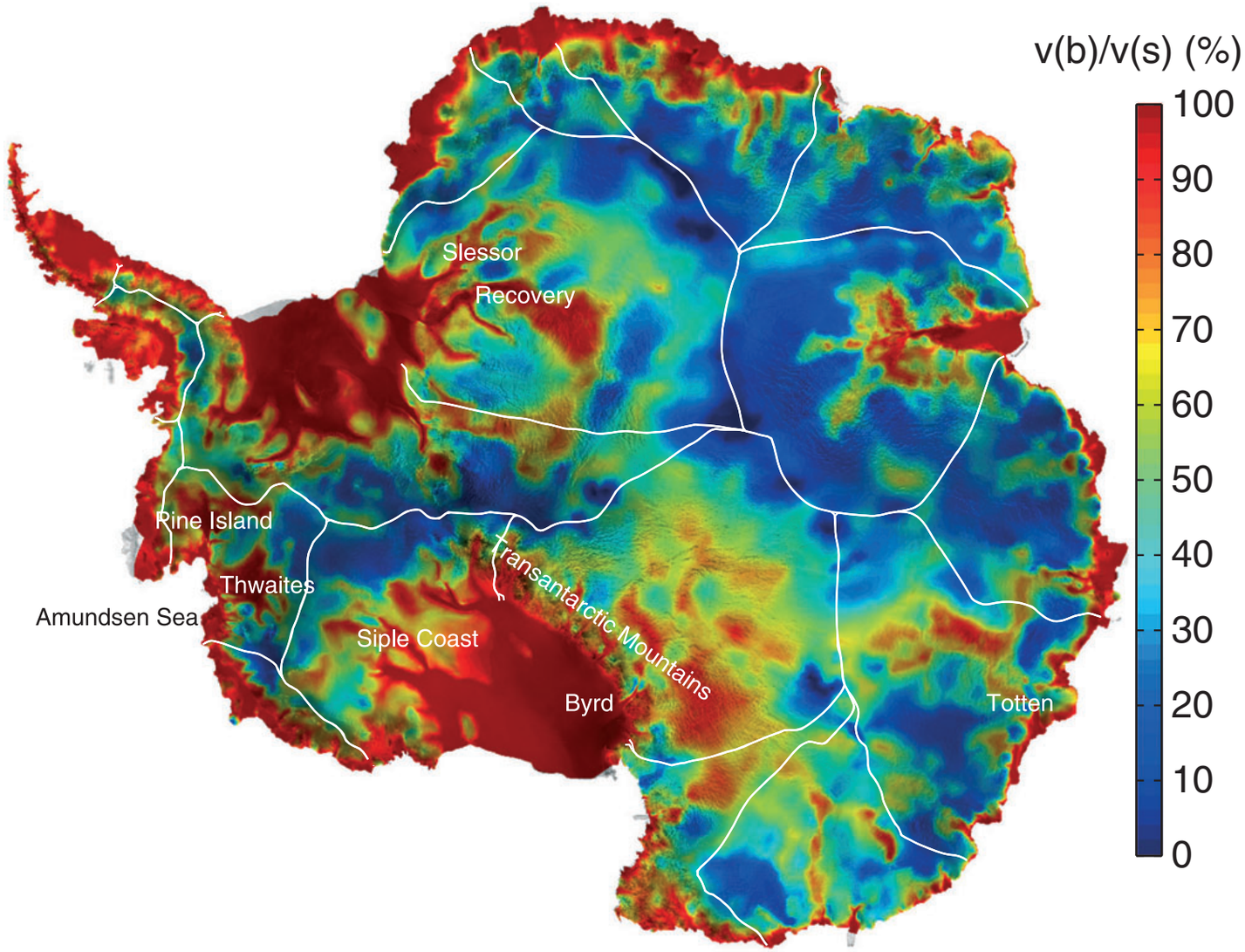
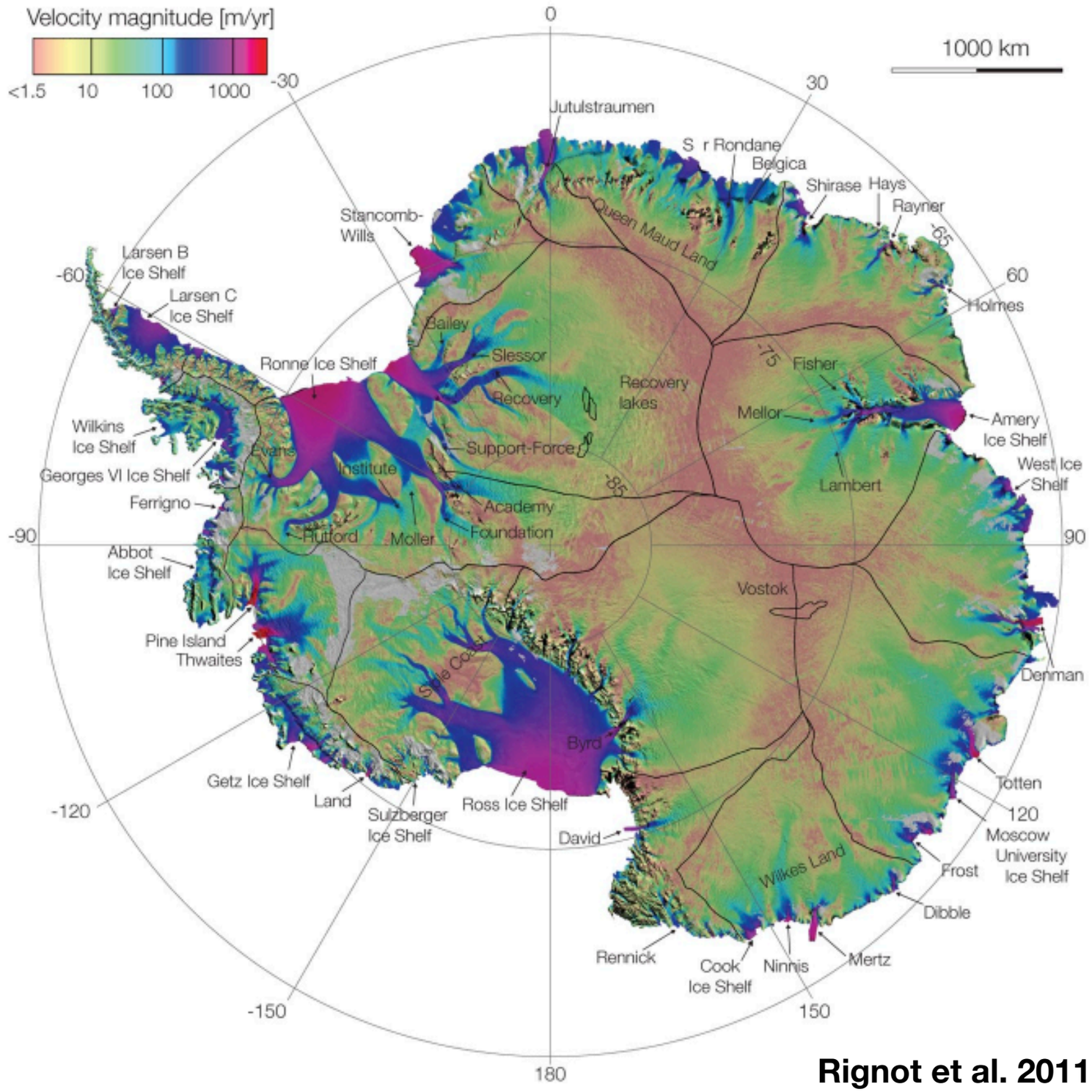


Figure 6. Ratio between modeled basal and surface velocity in %. The white lines indicate the location of ice topographic divides.

Morlighem et al. 2013

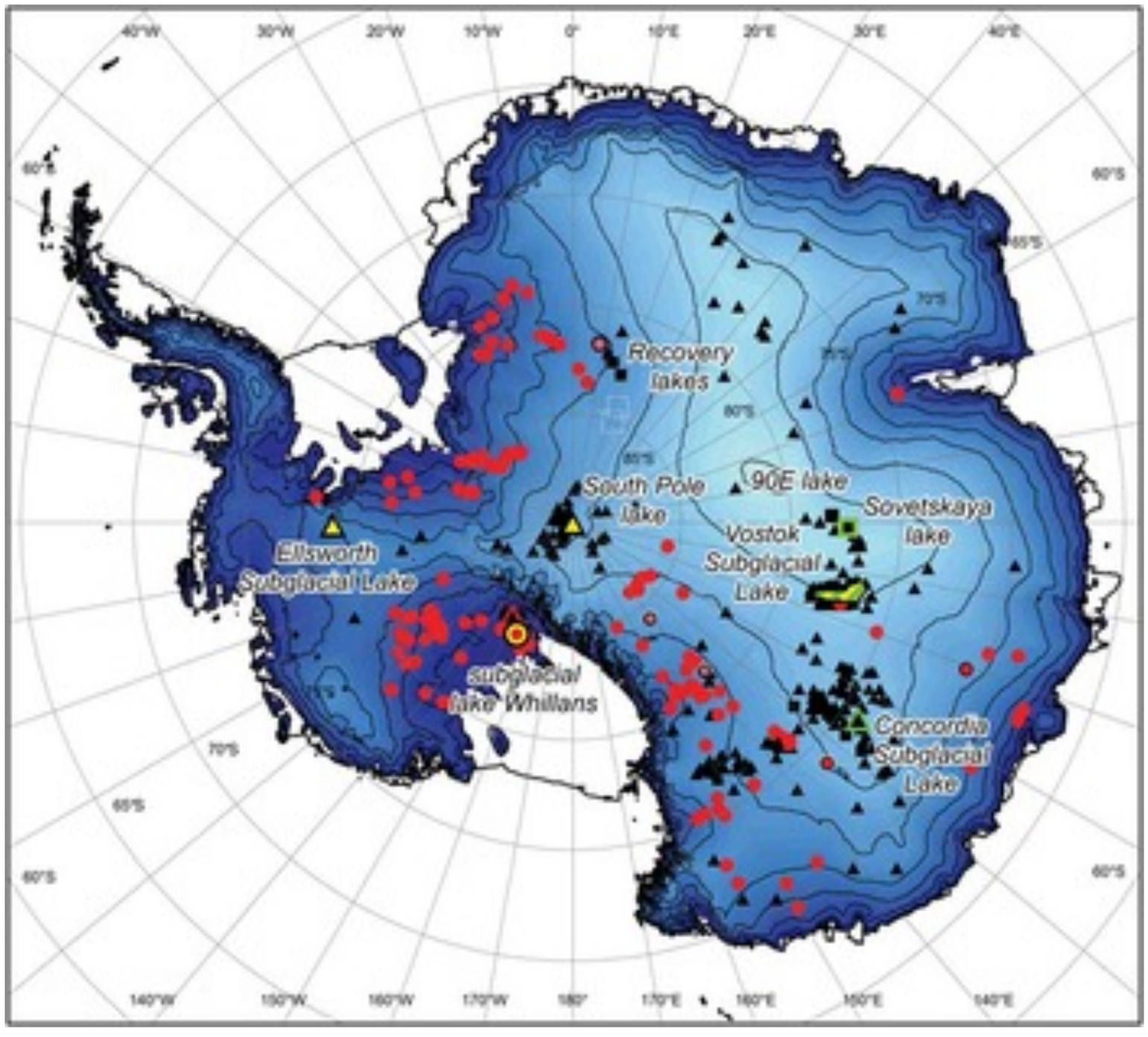
Why do we care?



Rignot et al. 2011

Why do we care?

Subglacial lakes!

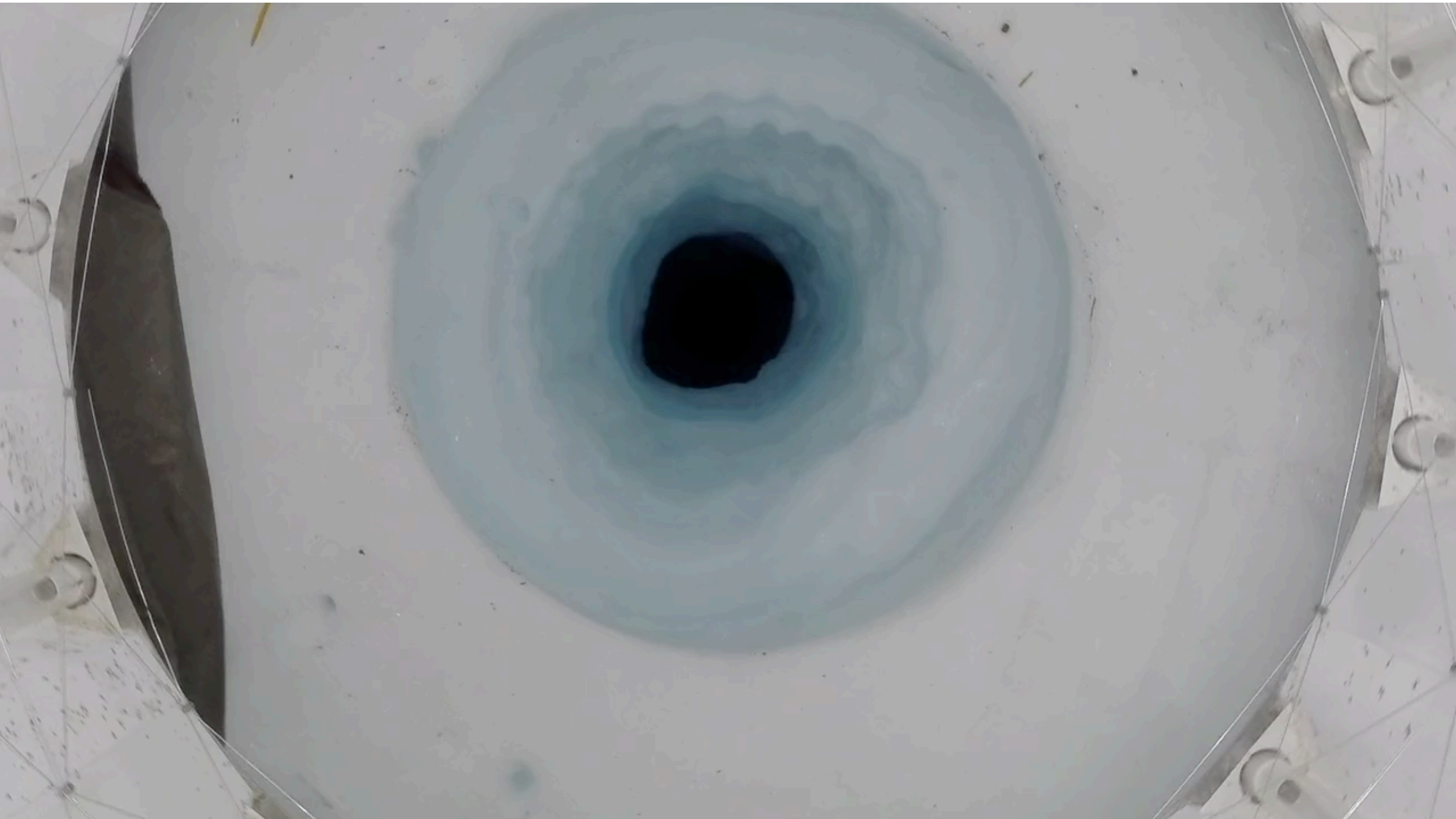


Wright & Siegert 2012

Why do we care?

Subglacial lakes!

Video from SALSA Project (Mercer Subglacial Lake in Antarctica)



What sets sliding velocity?

- Generally, two types of subglacial substrates are considered (where ice is grounded):
  - Hard bed
    - No motion beneath the interface
    - Impermeable to water
  - Soft bed
    - Can deform on its own (which in turns causes ice motion)
    - Water can permeate
- Whether one or the other is important depends on local geology, erosion over time (hard bed can become a soft bed and vice versa), whether basal ice is temperate or frozen (i.e. ice can be frozen to till)

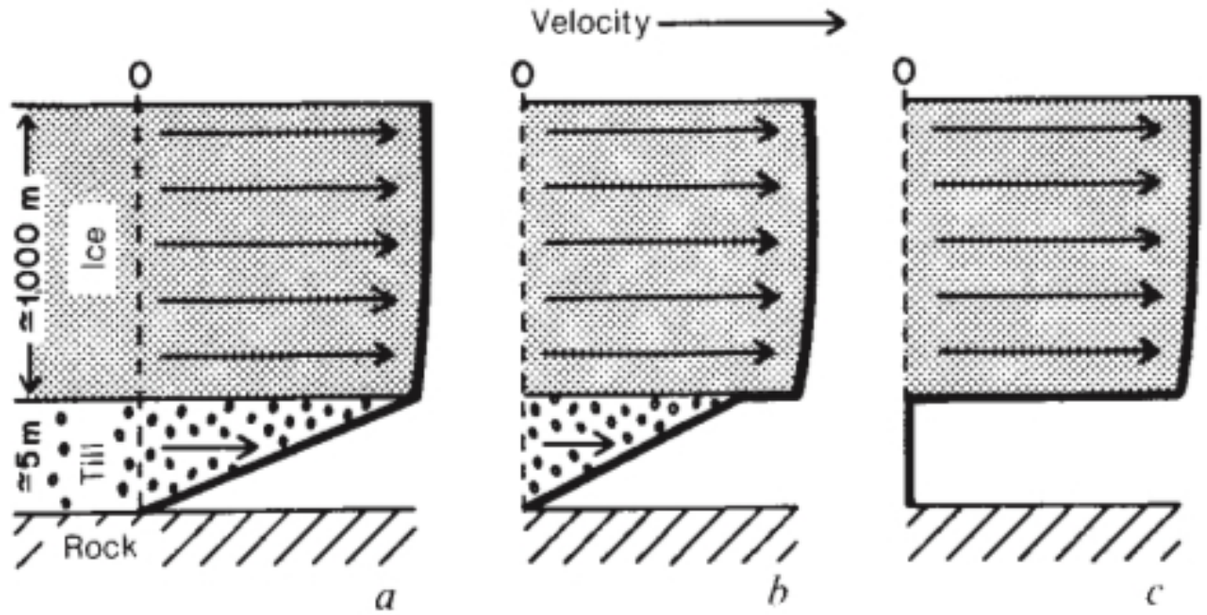
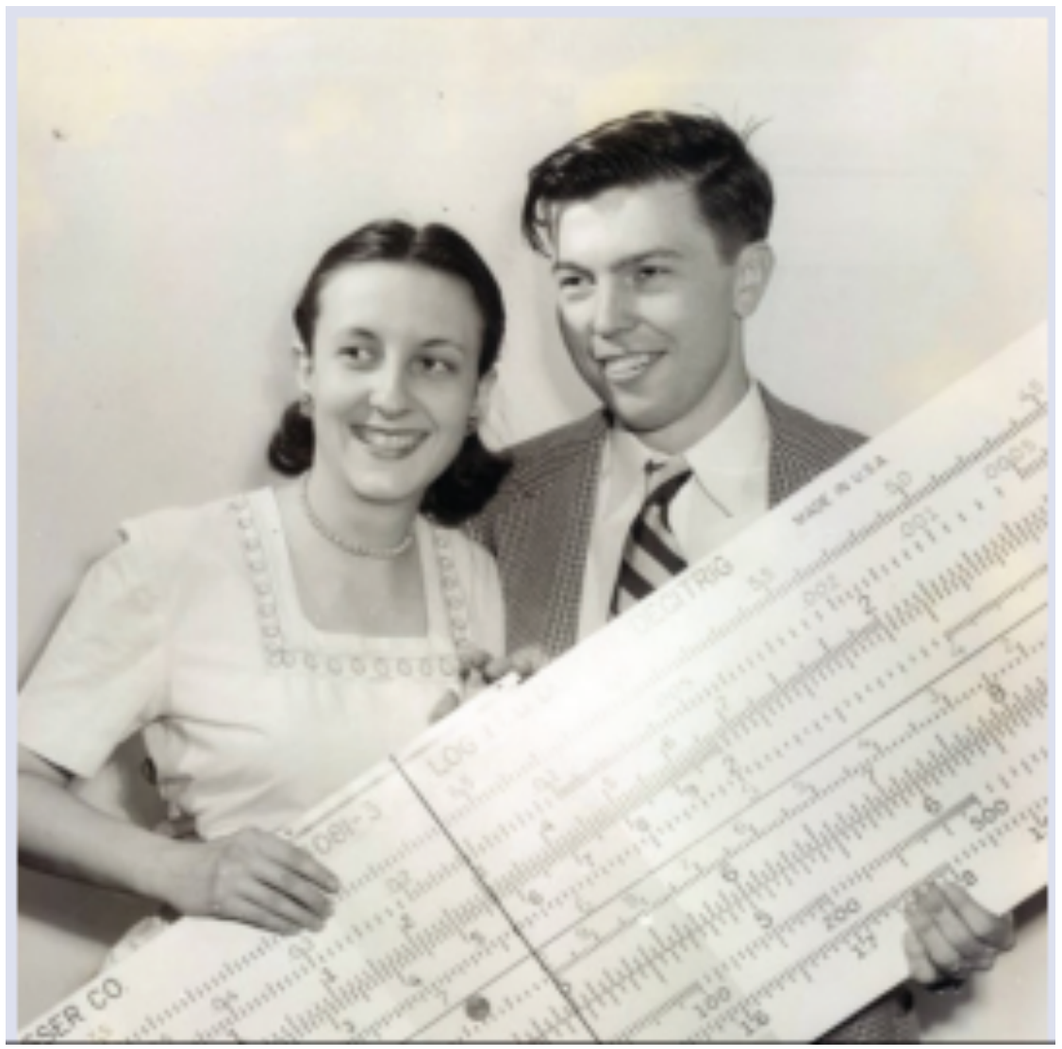


Fig. 1 Possible models for an ice-stream bed. *a*, Till deformation only; our model for UpB. *b*, Till deformation plus basal sliding; our model for near the grounding line of line stream B. *c*, Basal sliding only; not realized on ice stream B.

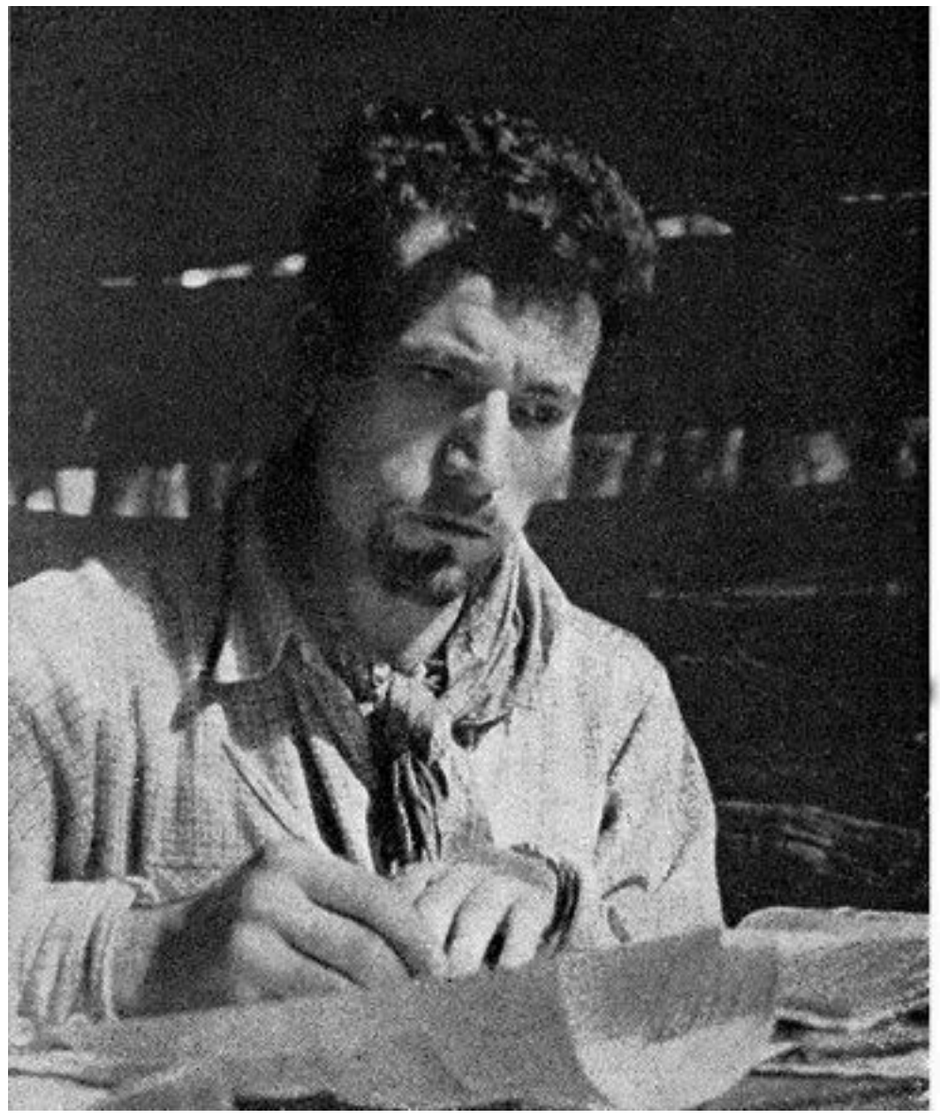
Sliding on Hard Beds: A Glaciological Battle

Julia & Johannes Weertman (and slide rule)



vs.

Louis Lliboutry



Hard Bed - Regelation

Regelation - the process of pressurized melting and depressurized freezing
- or, one way ice can move over obstacles in the bed (i.e. a rock)

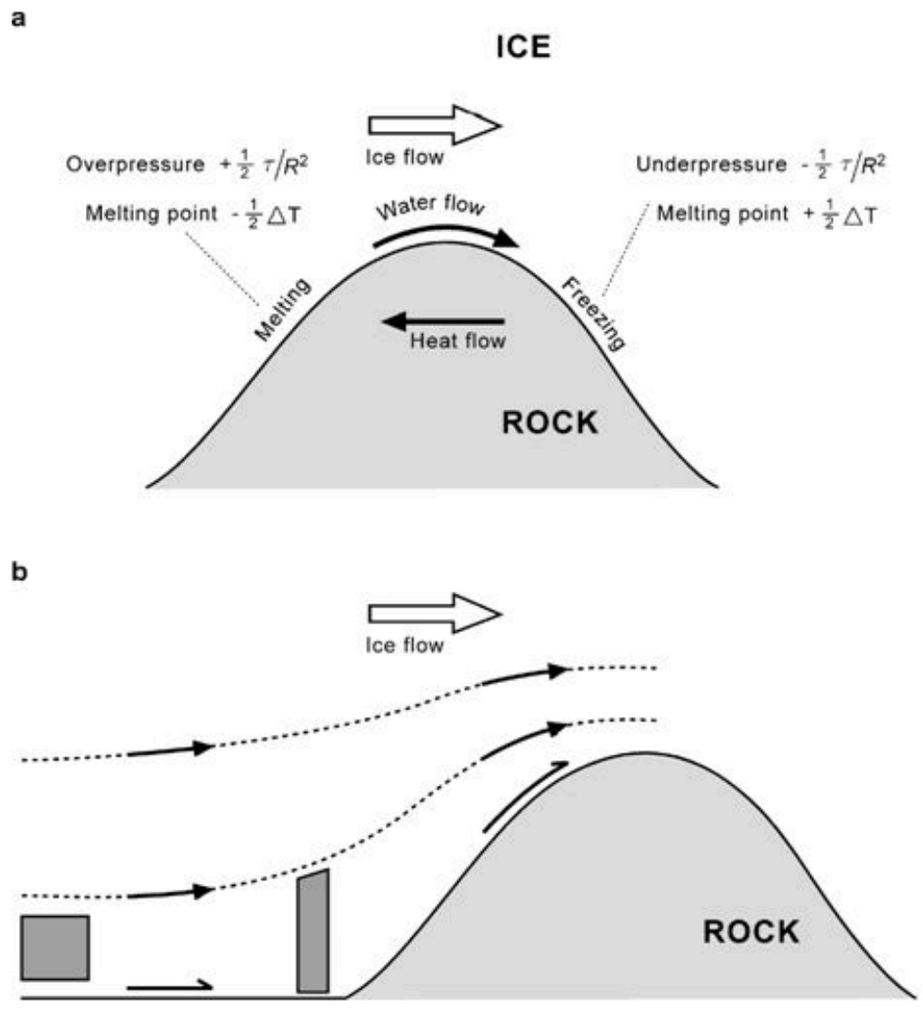


FIGURE 7.1

(a) The regelation mechanism of glacier sliding. Symbols are defined in the text. (b) The creep mechanism of sliding. Dashed curves represent flowlines. A parcel of ice first compresses longitudinally as it approaches the bump, as shown. In general, the parcel also shears.

Cuffey & Paterson Ch. 7

Hard Bed - Regelation

Regelation - the process of pressurized melting and depressurized freezing
- or, one way ice can move over obstacles in the bed (i.e. a rock)

Weertman's theory of sliding - to the board and demo!

Issues with Weertman (and others) regelation theory for sliding

- Glacier velocity is observed to change on short time scales (how does roughness change so quickly?)
- Constraining the parameters using physical measurements is hard - in practice velocity is inverted to get parameter C (not a physical measurement)
- Ice-obstacle interface is often not clean - lots of debris in the ice
- Largest obstacles will get eroded over time - should narrow rough obstacle size distribution
- The upshot: ice-water interfaces are very complicated

Hard bed - cavitation

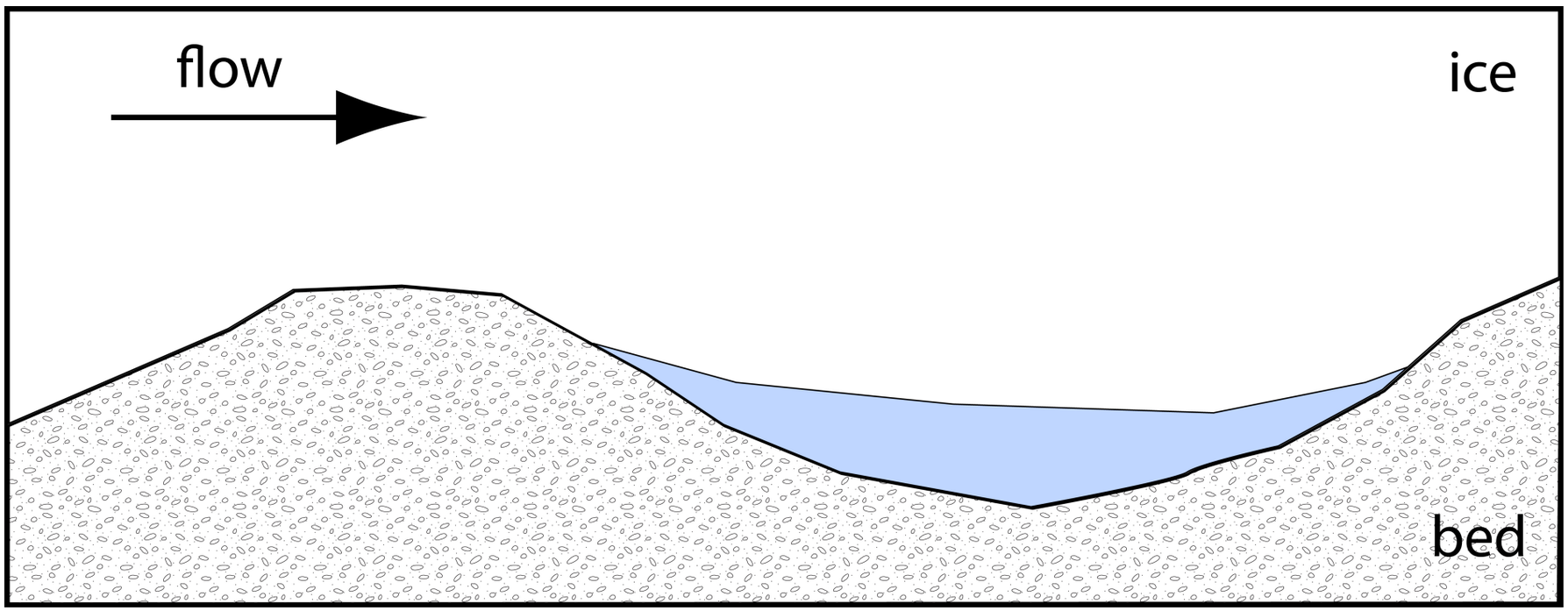
Cavitation - formation of a cavity downstream of obstacle

Hard bed - cavitation

Cavitation - formation of a cavity downstream of obstacle

Hard bed - cavitation

Cavitation - formation of a cavity downstream of obstacle



Hard bed - cavitation

Cavitation - formation of a cavity downstream of obstacle

Lliboutry's problem with Weertman - to the board!

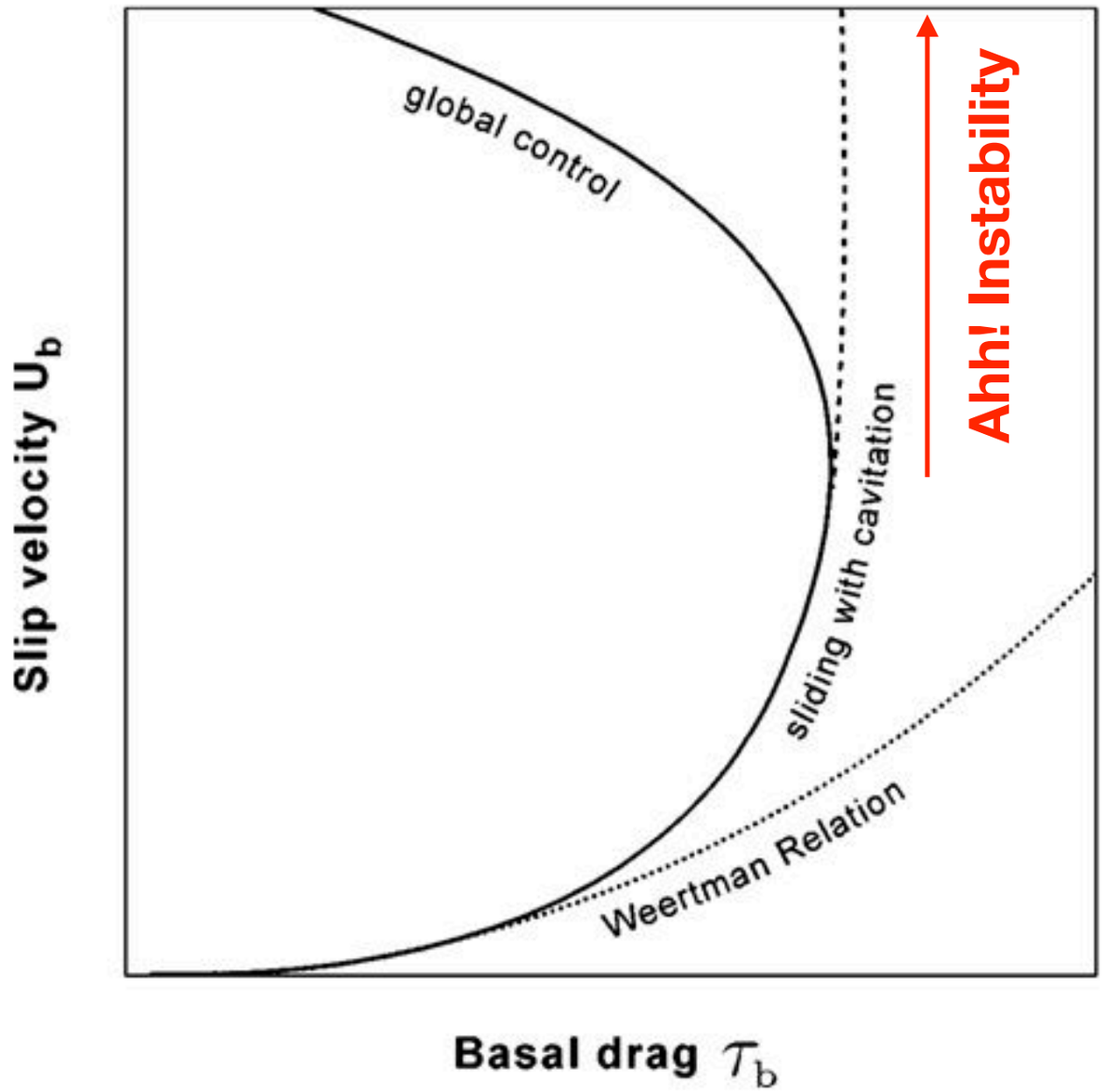
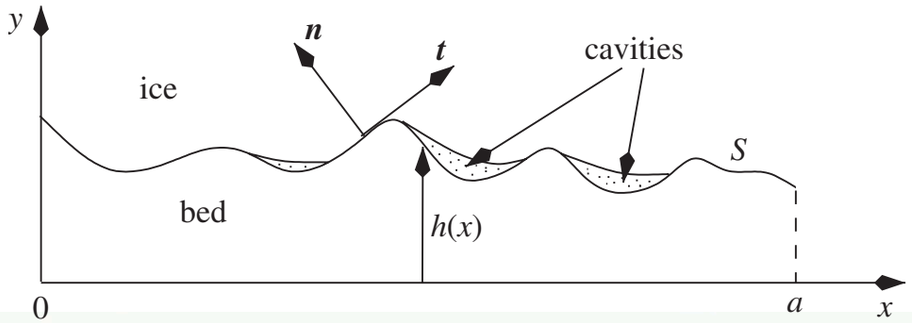
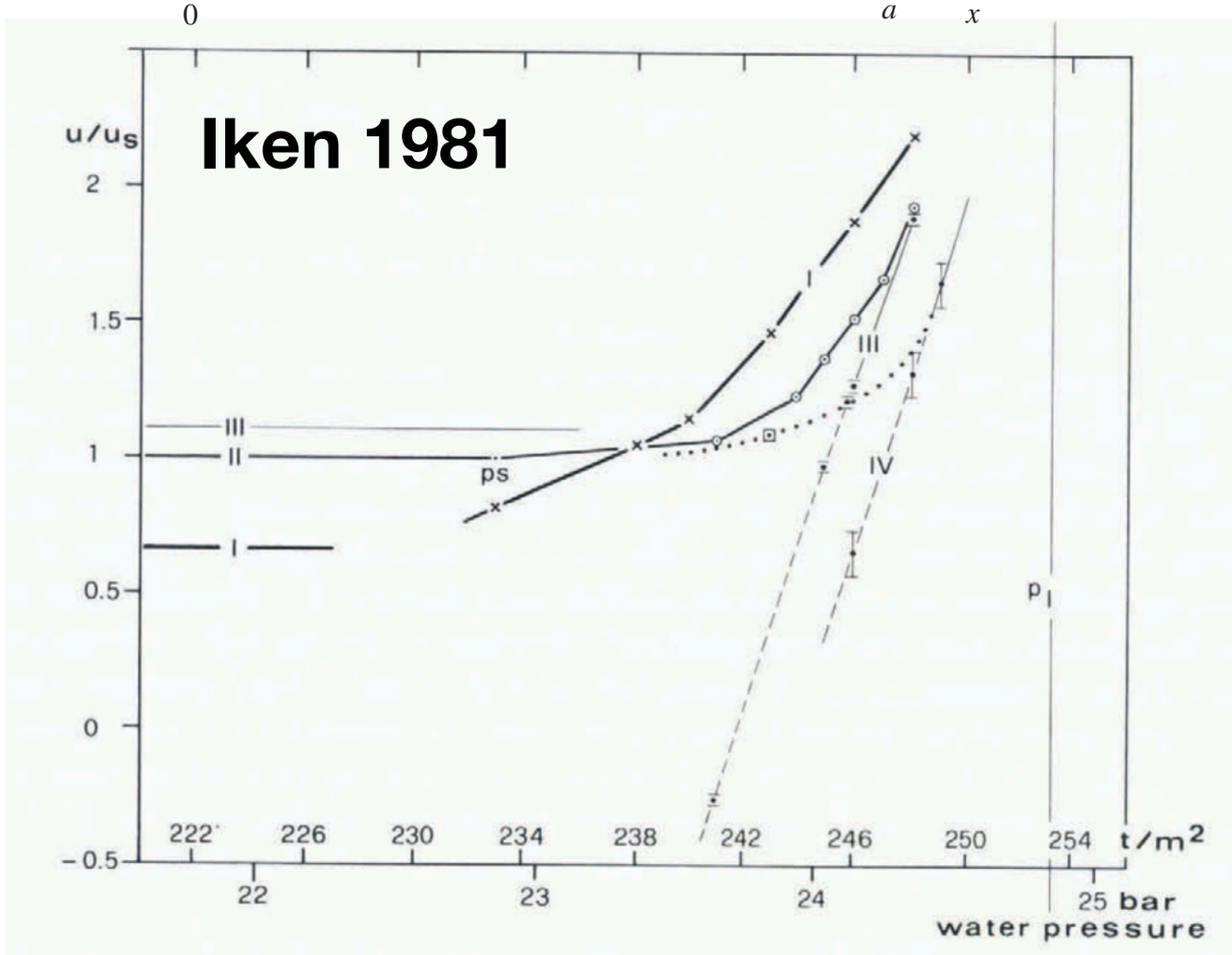


FIGURE 7.5

Covariation of basal drag and sliding rate: a schematic view. A similar relation applies for deformable beds, so the vertical axis can be regarded as the slip velocity in general.

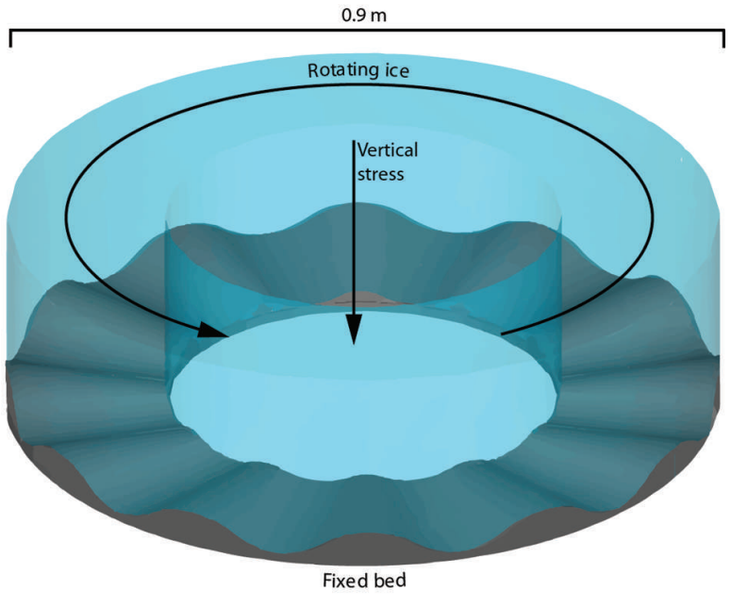
Late entrants - Almut Iken

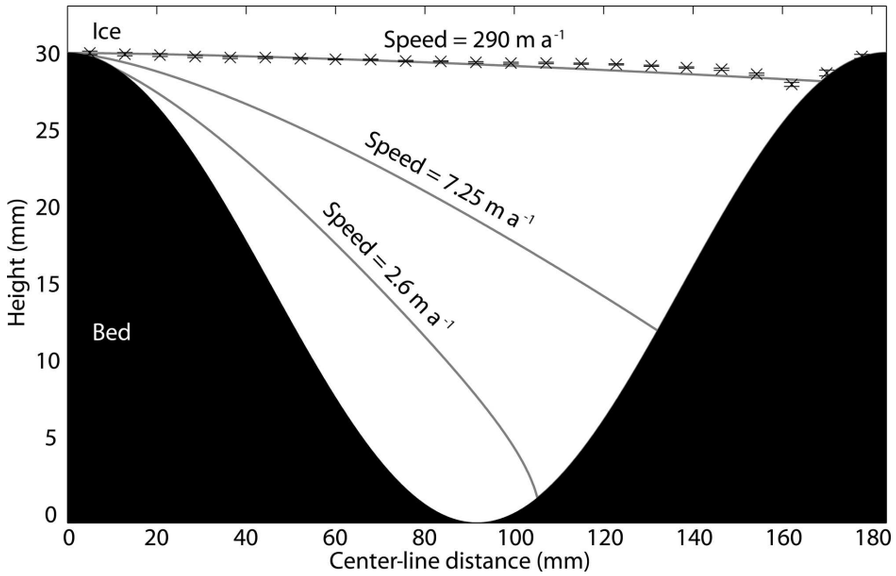


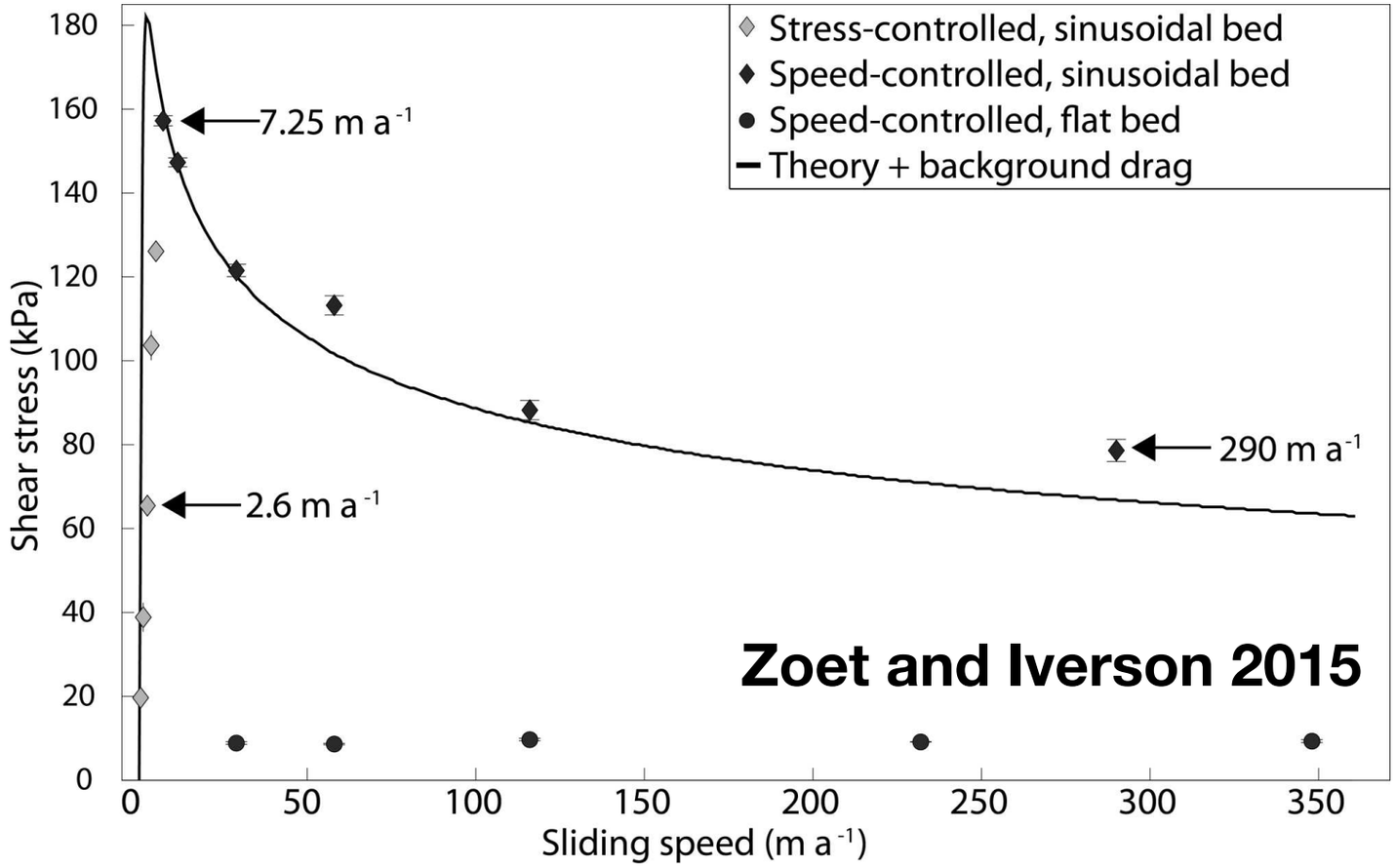


“Iken’s bound” - below a certain water pressure, cavitation is not important, but in practice many places exceed this pressure and water is important!

Late entrants - Lucas Zoet







For a sinusoidal bed (one of Lliboutry's assumptions) - Lliboutry seems to be right

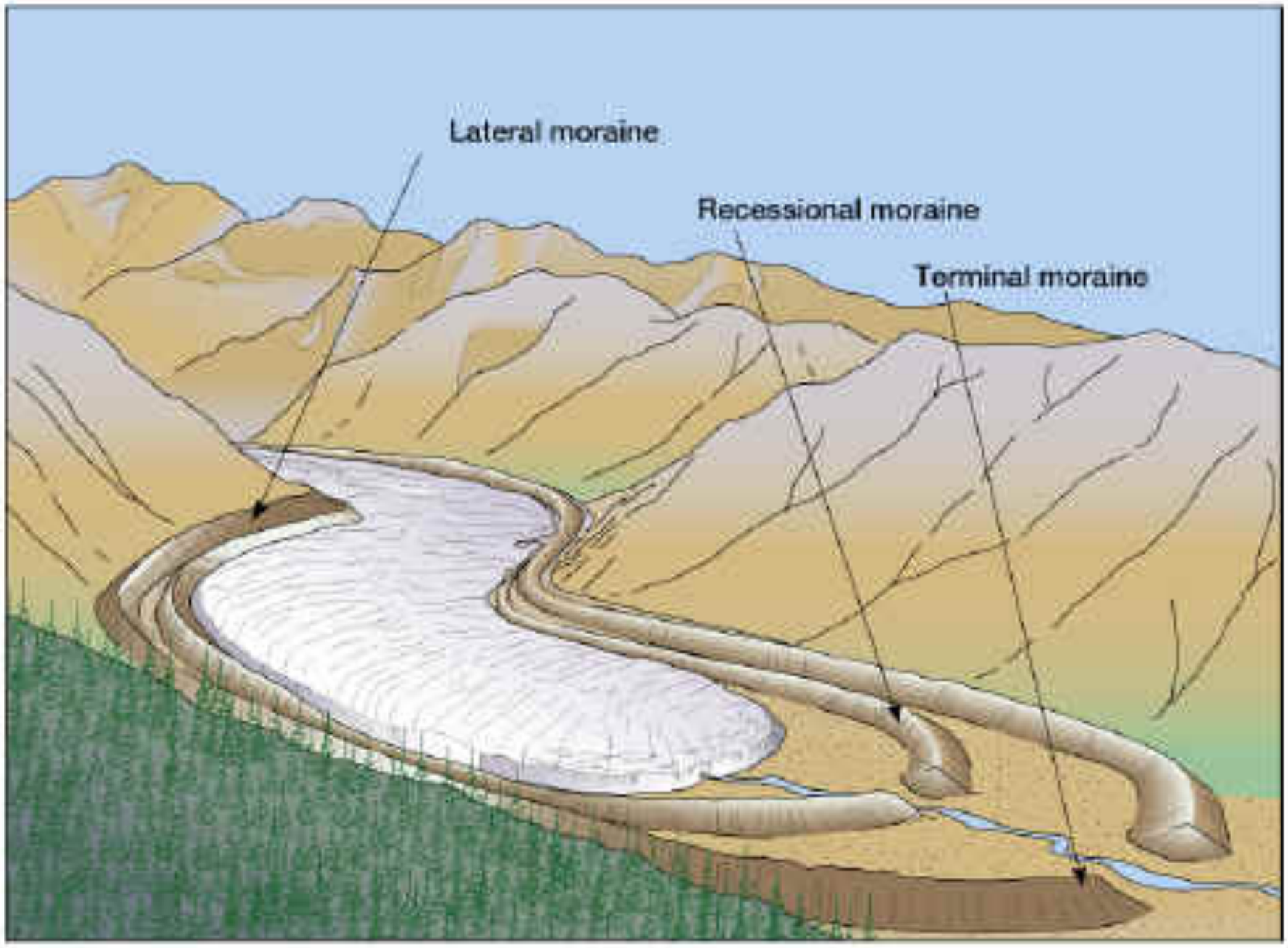
Soft beds

What glaciers leave behind

Erratics

What glaciers leave behind

Moraines



What glaciers leave behind

Moraines

Terminal

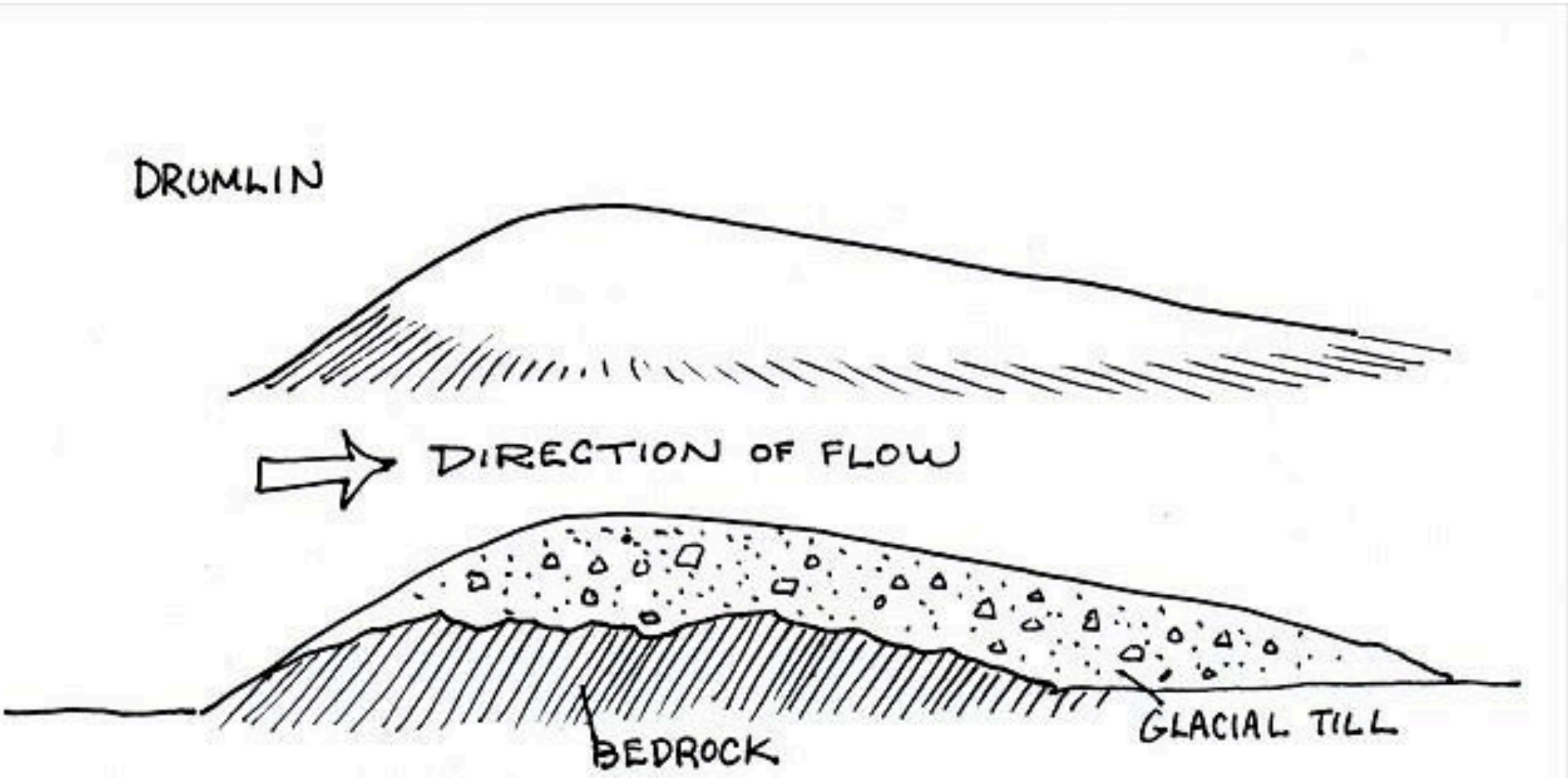
Flute Moraine -
signature of cavities!

What glaciers leave behind

Drumlins

What glaciers leave behind

Drumlins



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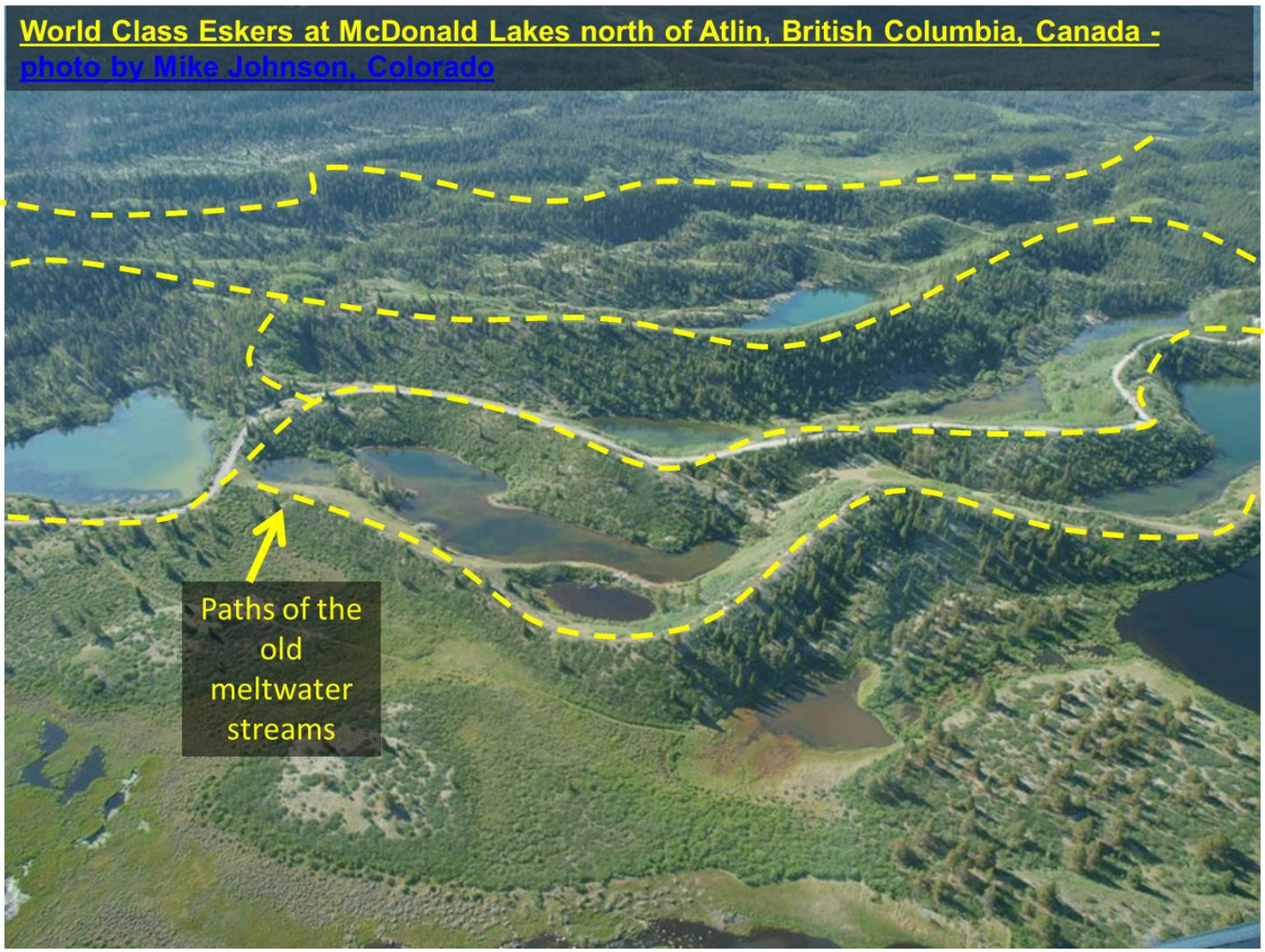
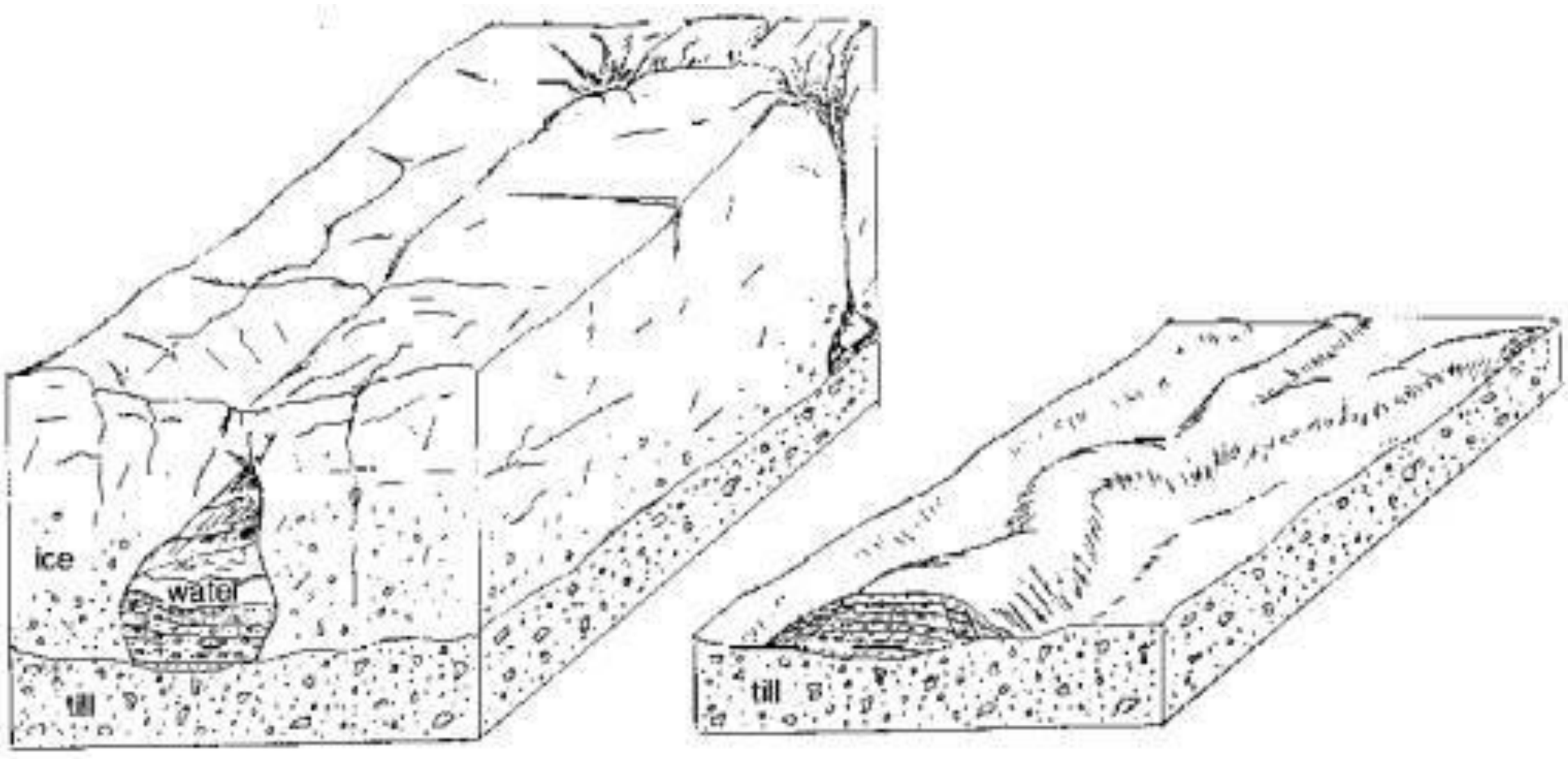
What glaciers leave behind

Eskers



What glaciers leave behind

Eskers



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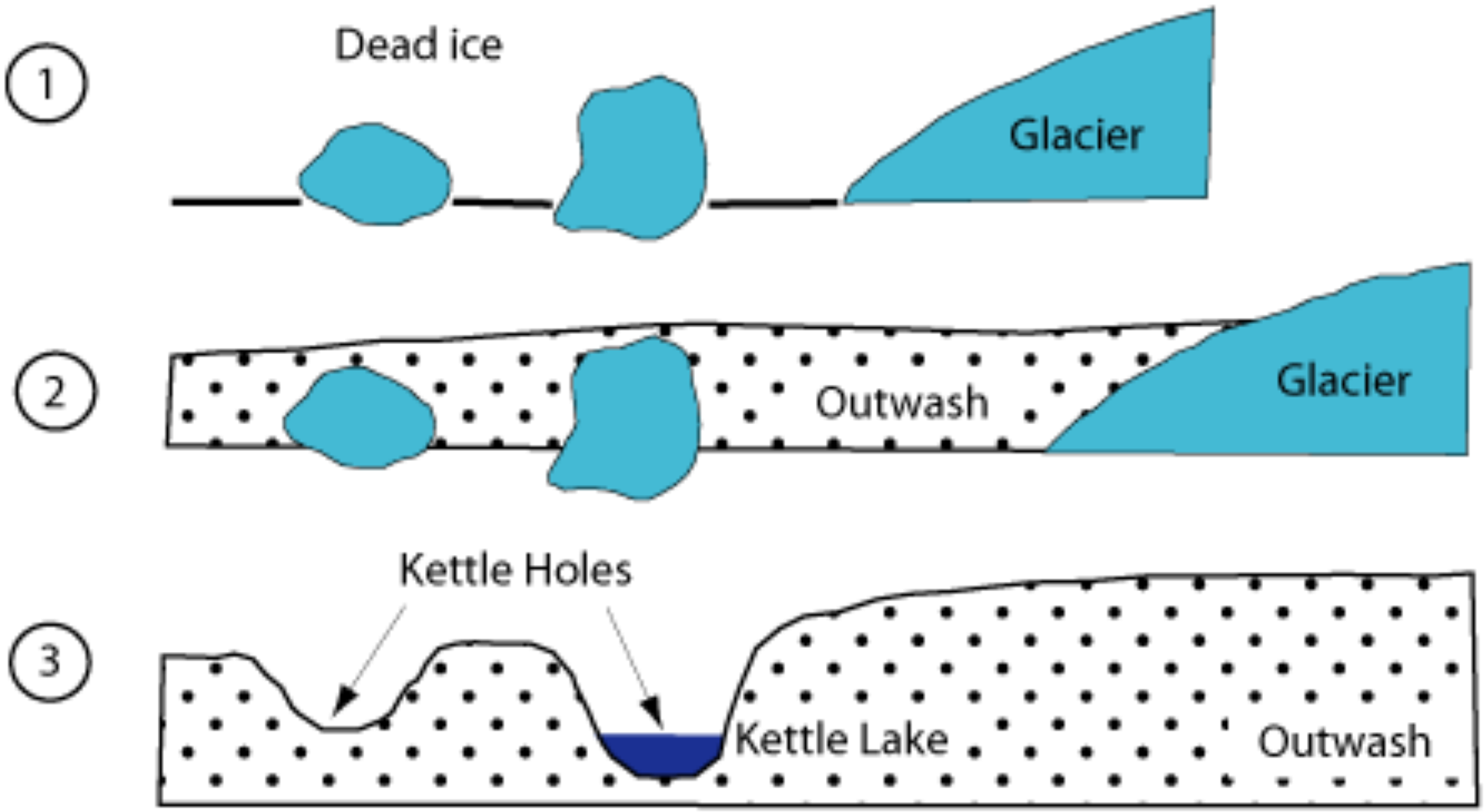
What glaciers leave behind

Kettles

What glaciers leave behind

Kettles



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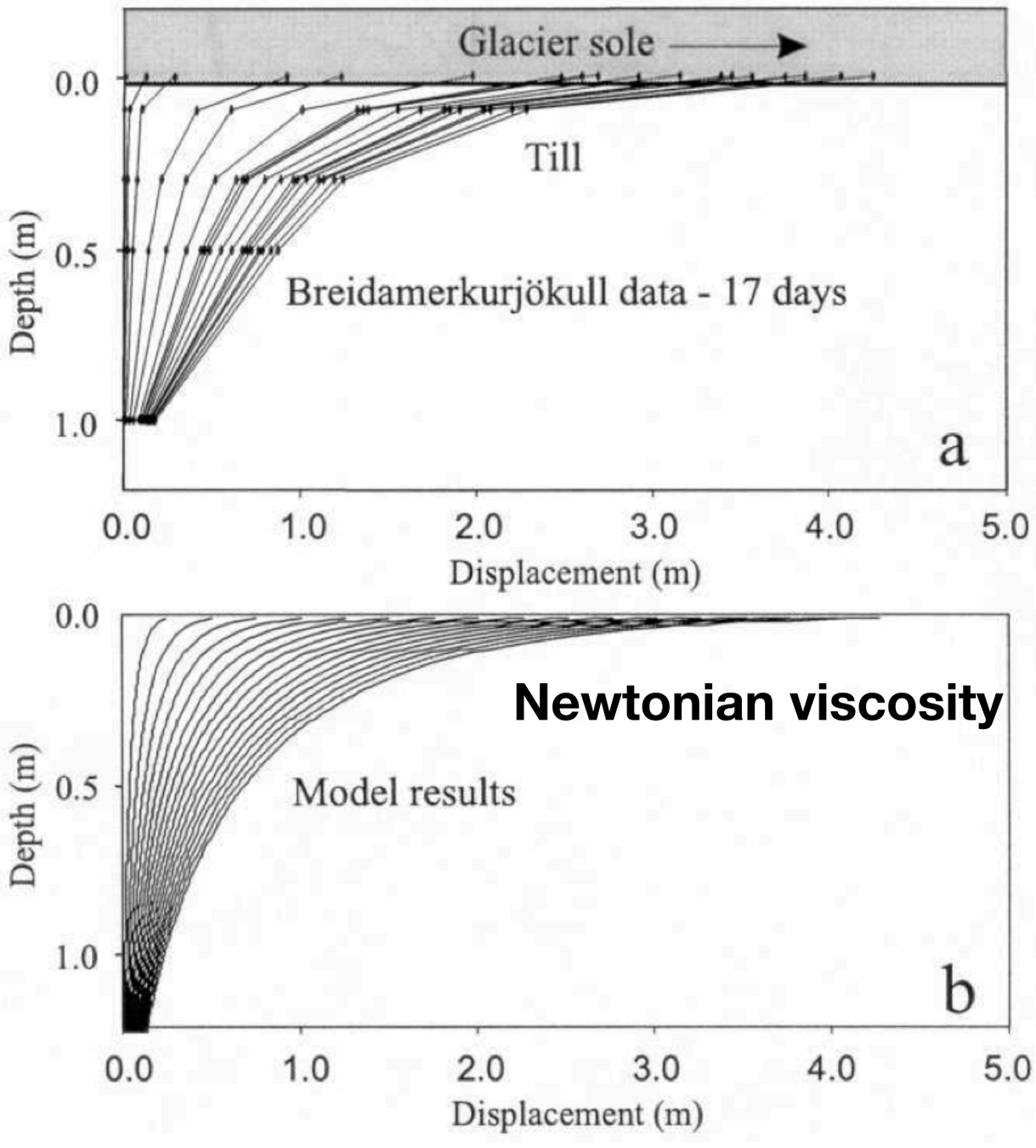
What happens where the bed is soft and can deform?

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

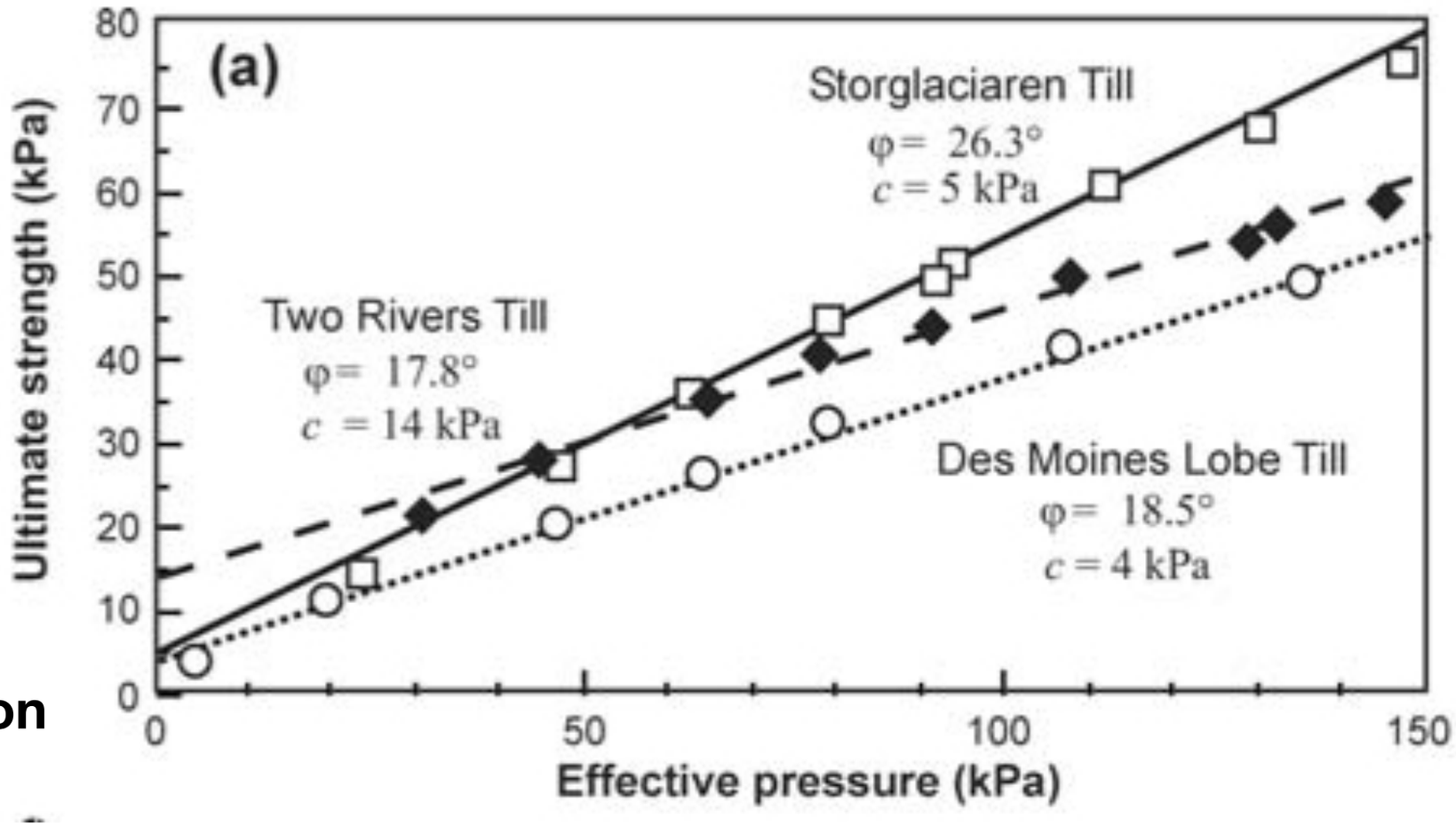
$$\tau = N\tan(\phi) + c$$

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

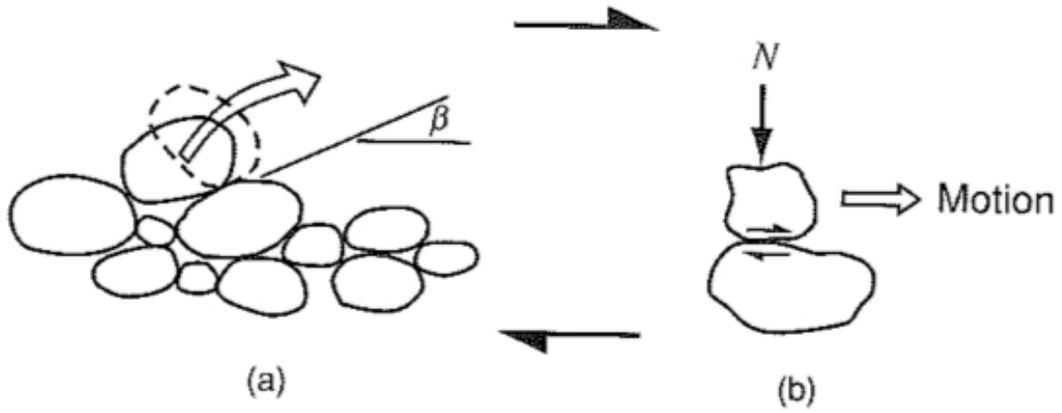
Sand grains are not very cohesive. They will only stick to one another if there is some water in the sand, but <u>not too much</u>

Cohesion

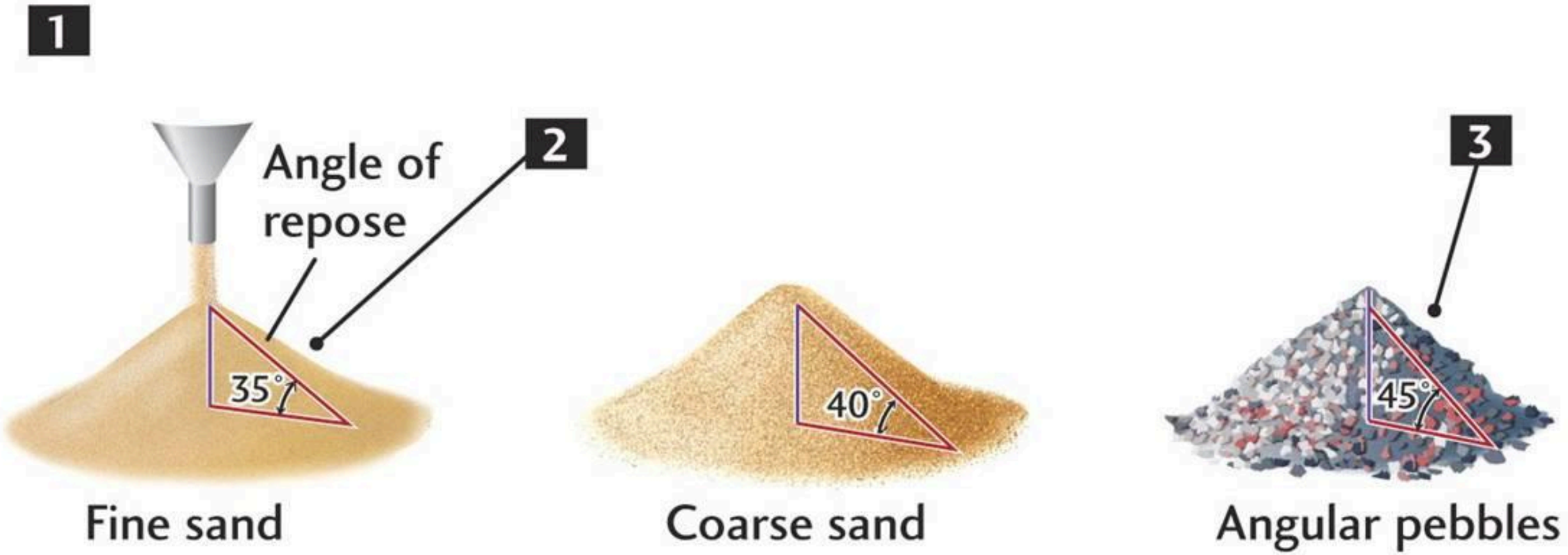
Cohesion - the attraction of grains to each other - depends on the grain properties and what's in between the grain

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

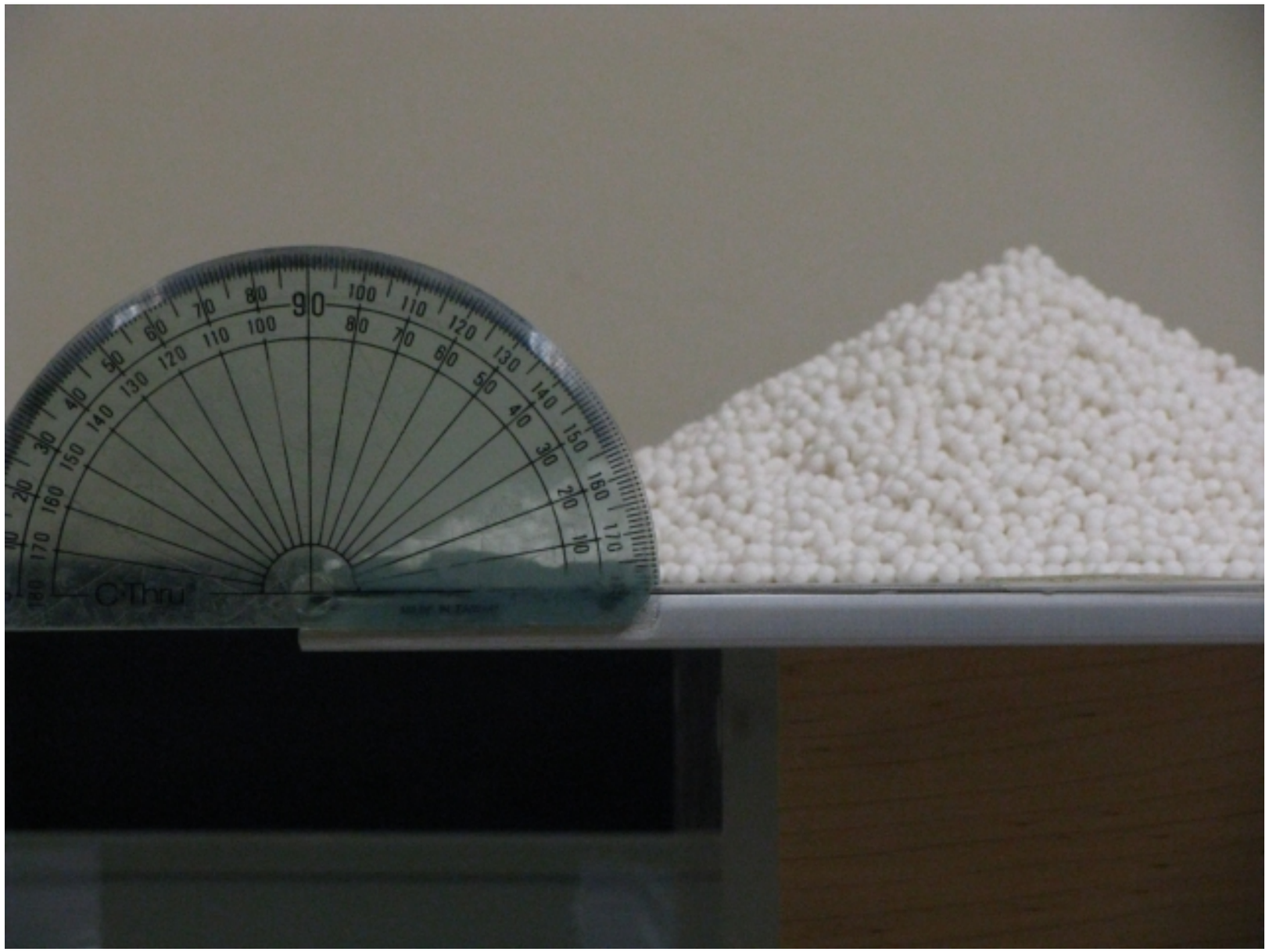
Friction angle and the angle of repose



MASS MOVEMENT DEPENDS ON THE NATURE OF MATERIAL, WATER CONTENT, AND SLOPE STEEPNESS

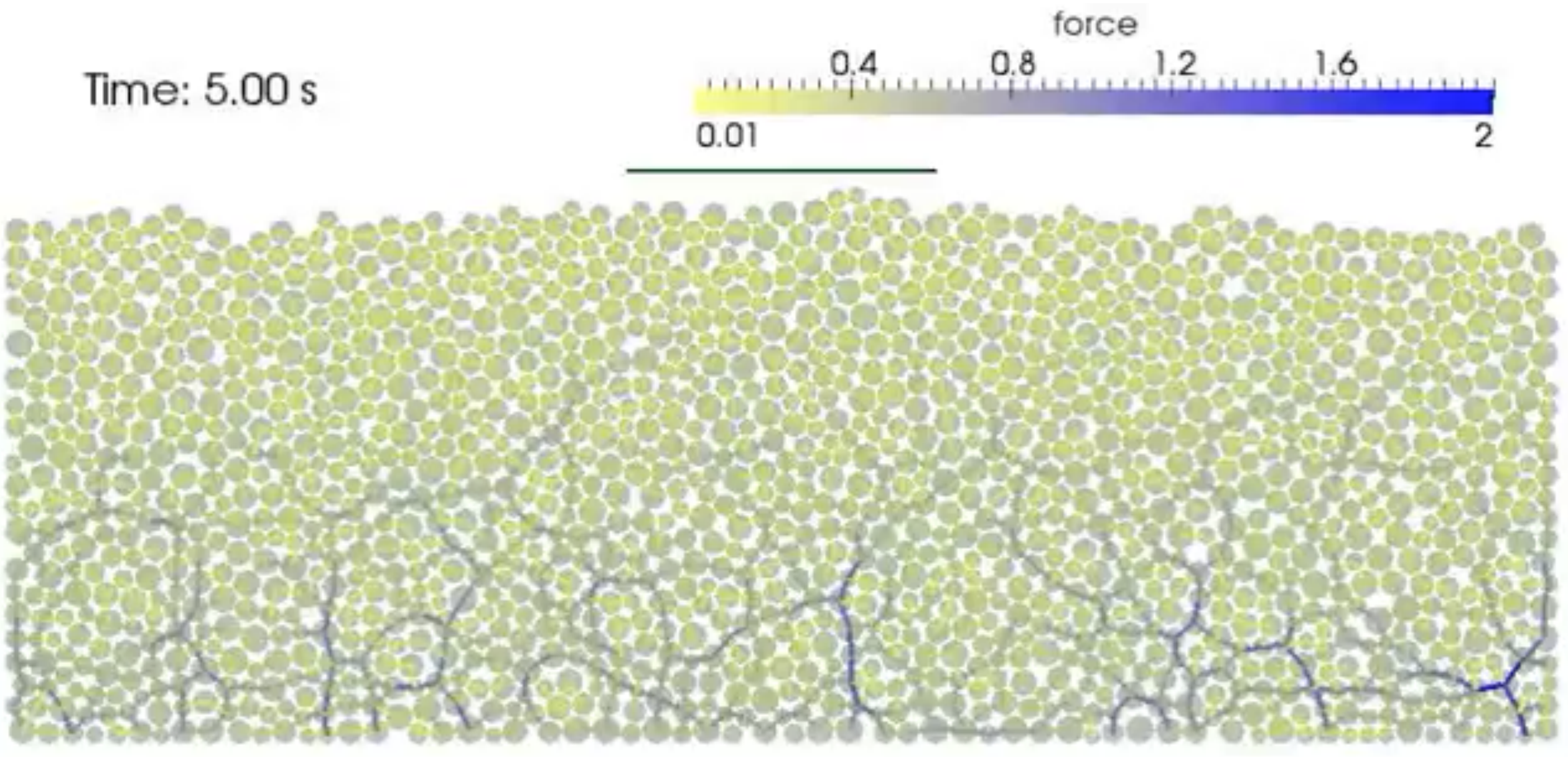


Friction angle and the angle of repose

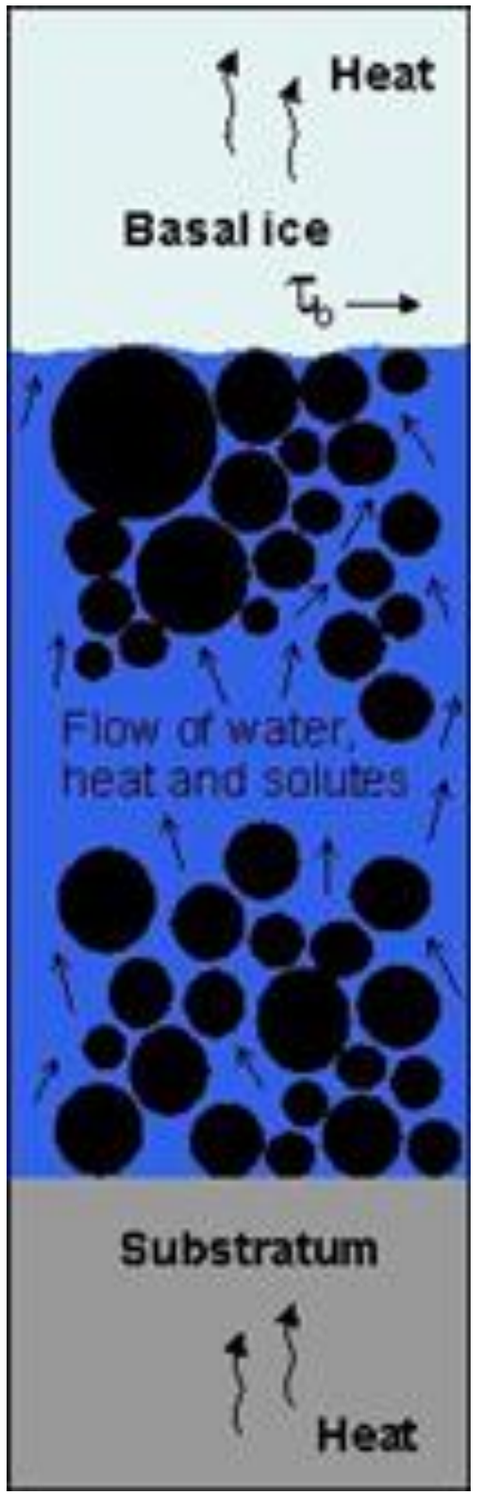


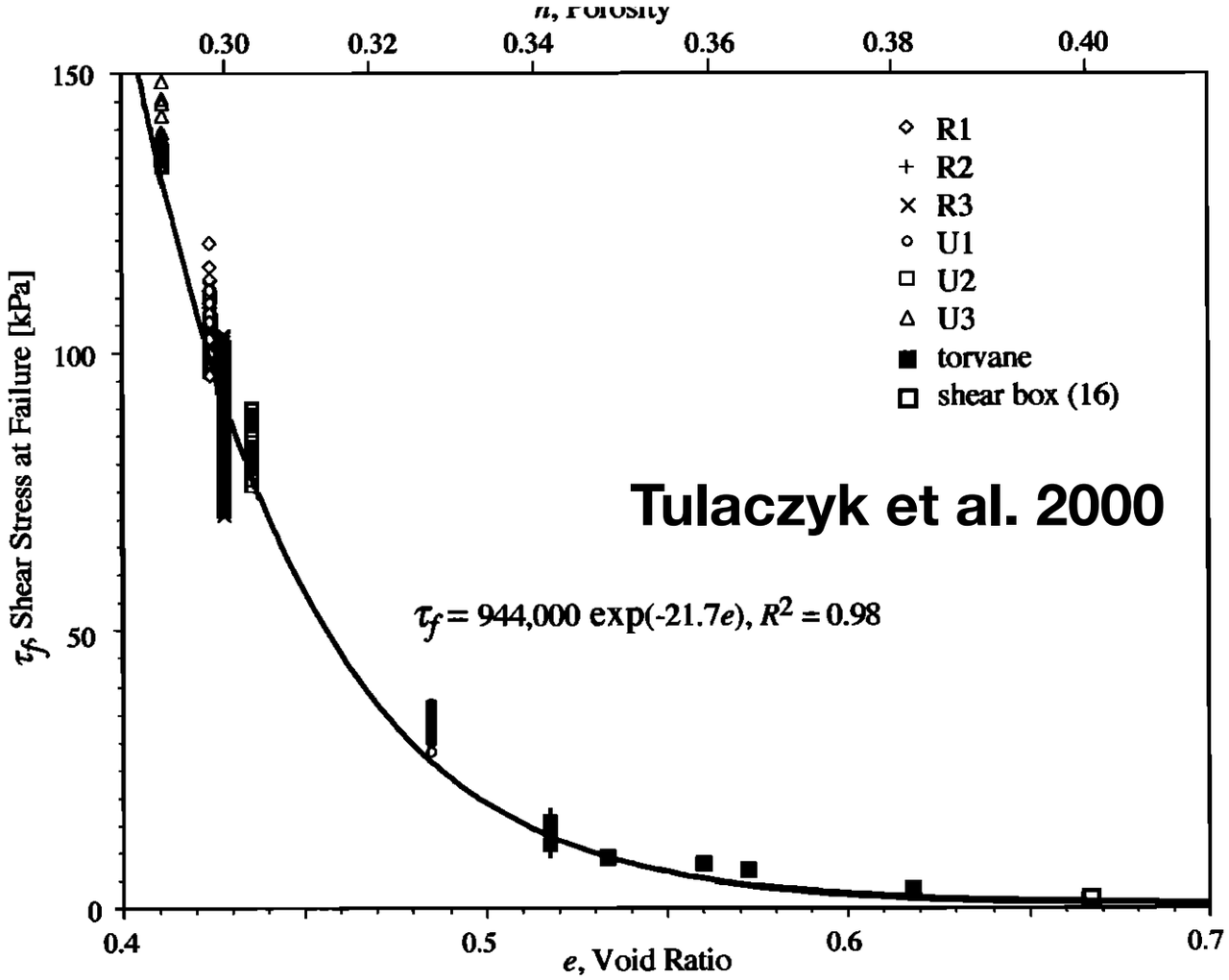
Grain contacts transmit stress from boundaries over long distances

Grain contacts transmit stress from boundaries over long distances



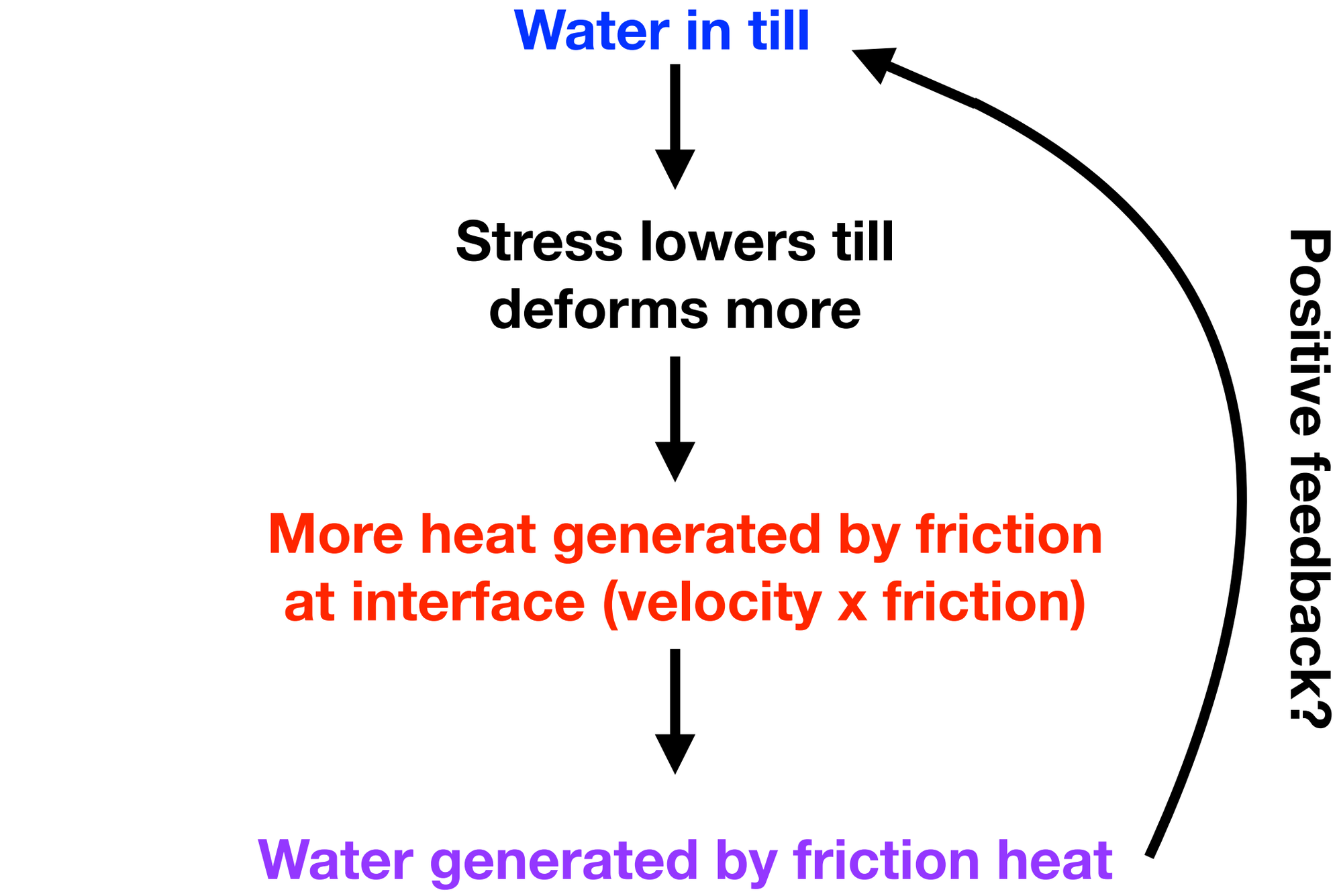
Saturation of till



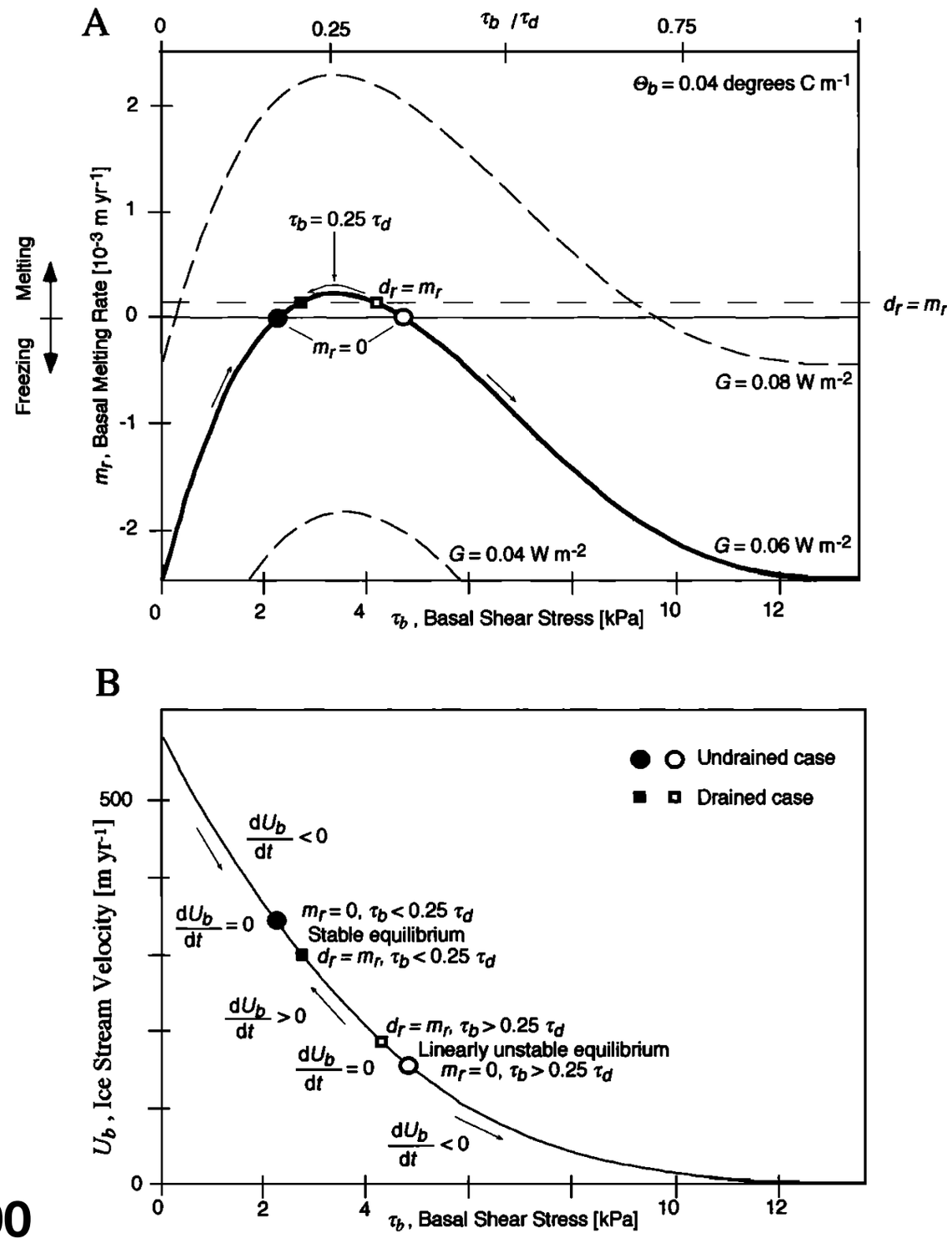


In water-rich tills, the addition of more water beyond the consolidation threshold of till causes a reduction in contact between grains within the till, lowering the basal shear stress require for plastic yielding of the till

Saturation of till

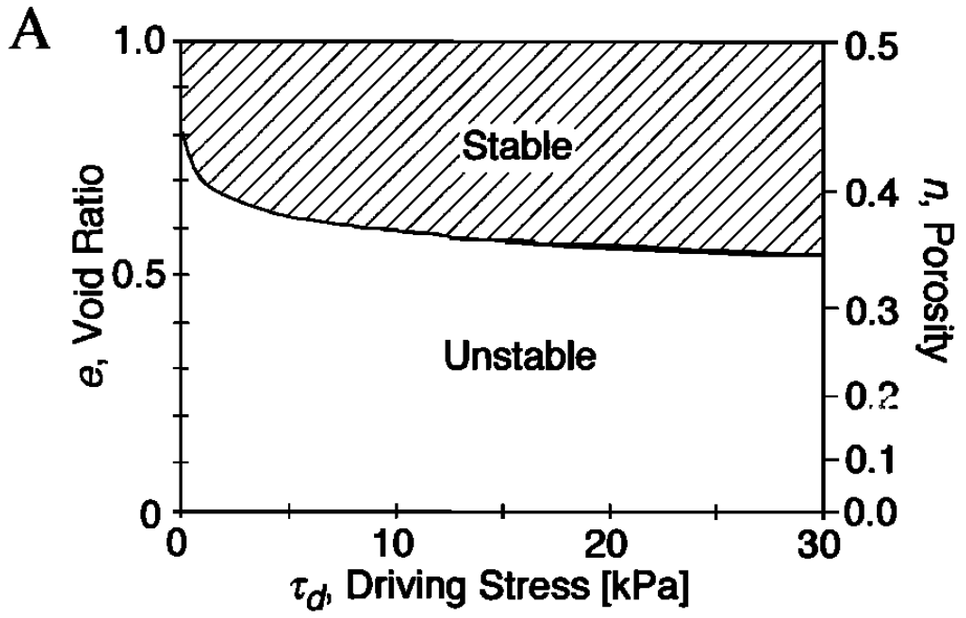


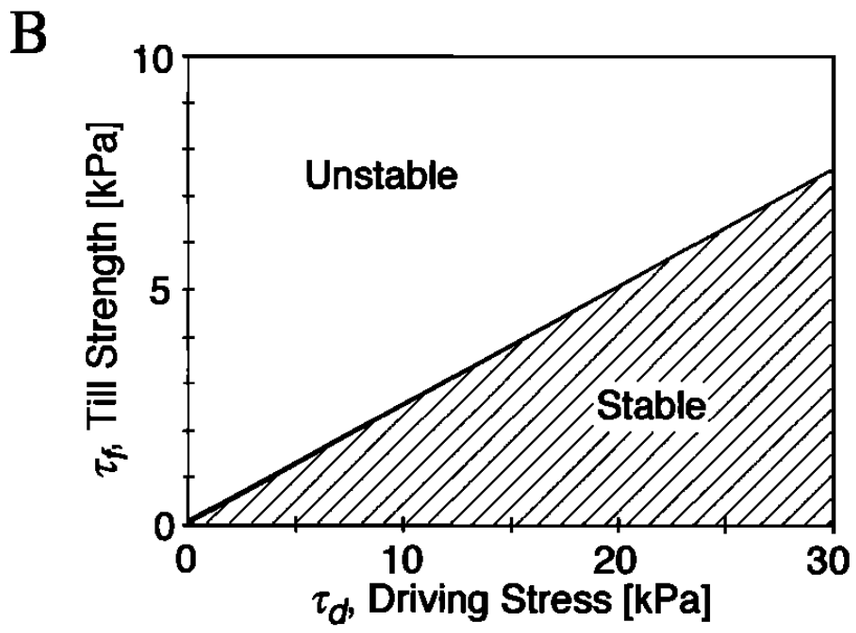
Saturation of till

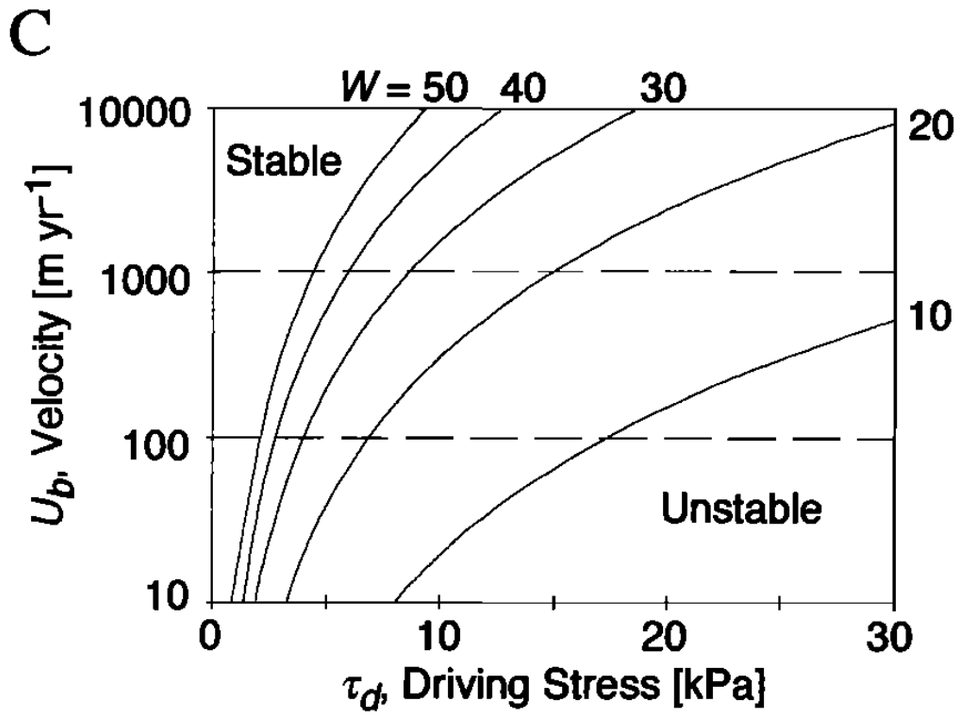


Tulaczyk et al. 2000

Saturation of till

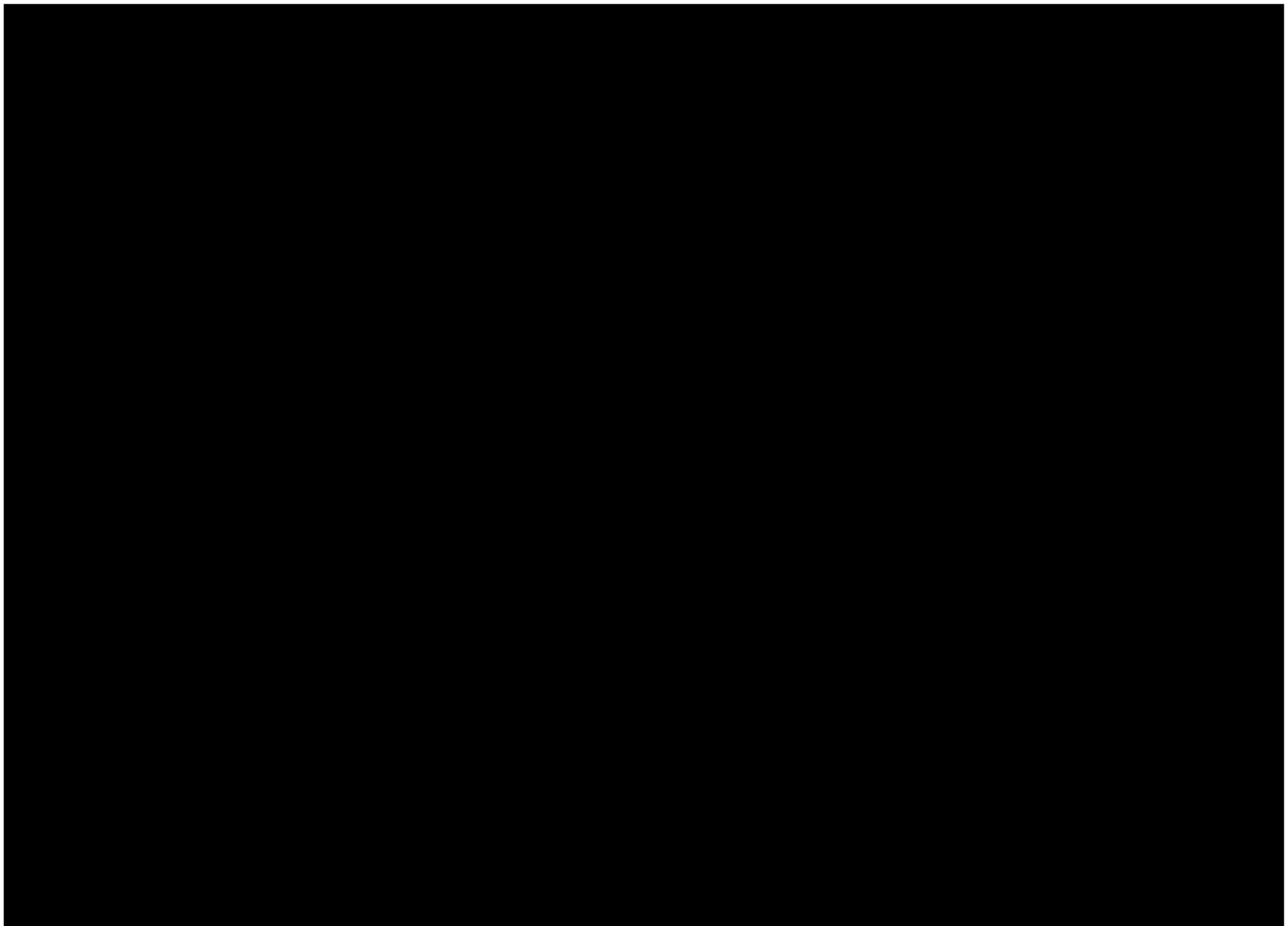






Tulaczyk et al. 2000

Cause for glacier surging?



Cause for glacier surging?

To the board? Depending on time - simplified thermal model for glacier surging