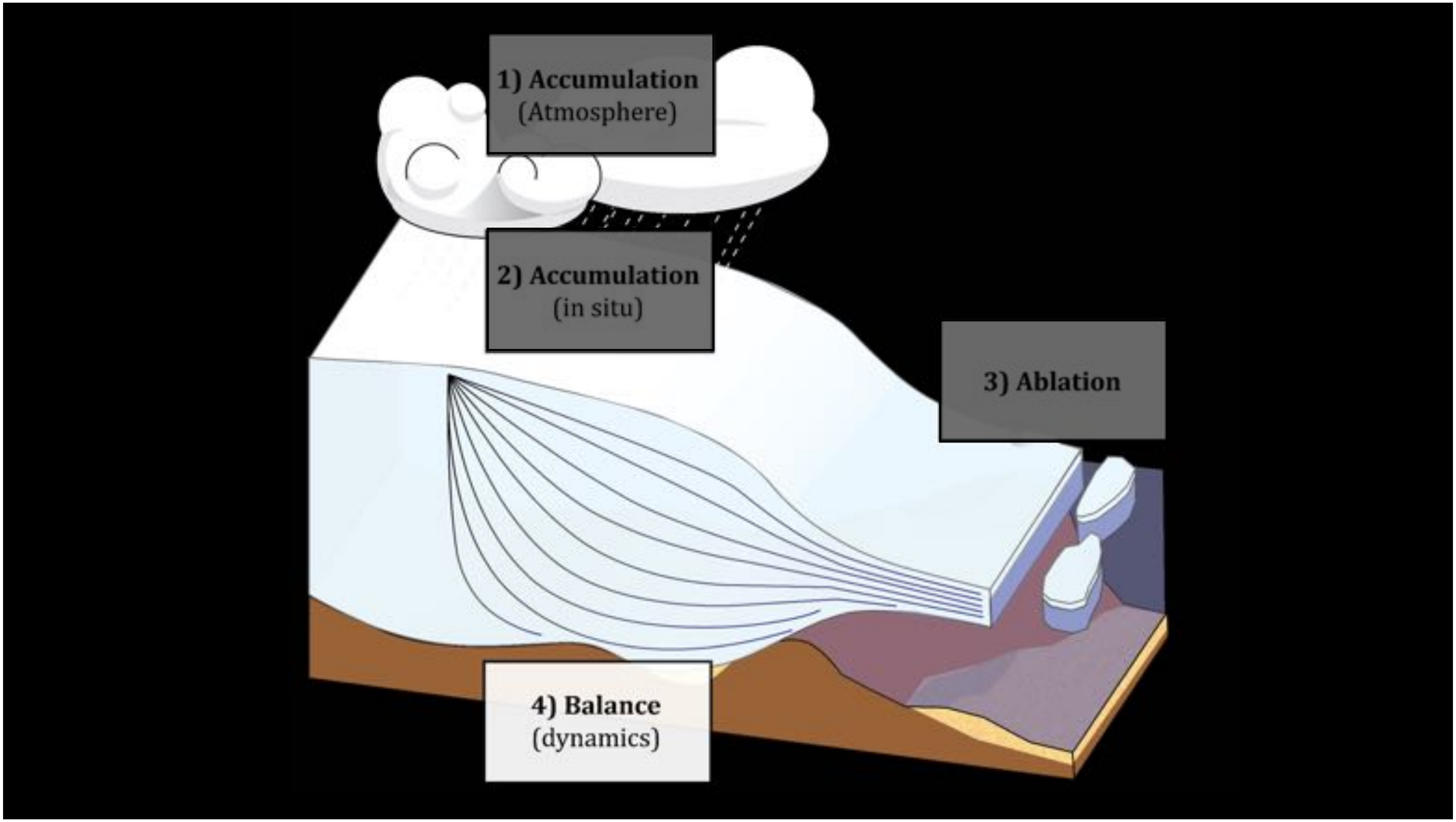
Ice Dynamics II:
Glacier Sliding and Hydrology

ESS431: Principles of Glaciology
ESS505: The Cryosphere

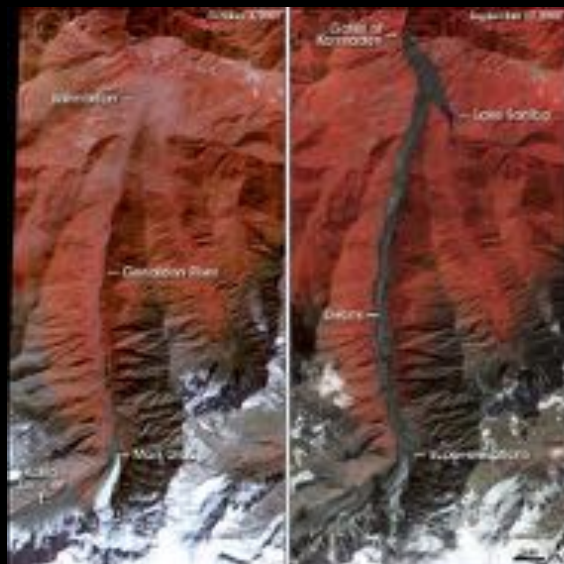
Monday, 10/22 – Knut Christianson



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

Ice Avalanche

NASA Earth Observatory



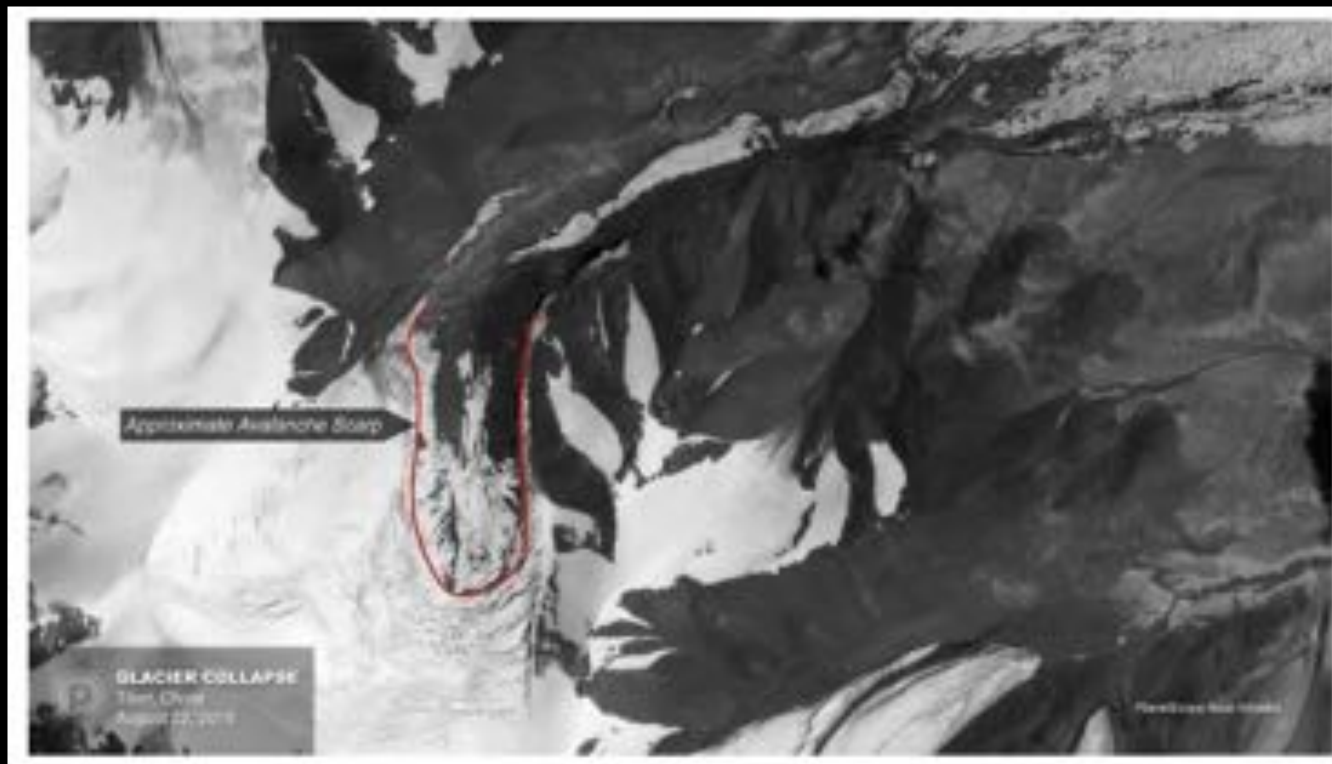
NASA Earth Observatory

September 20, 2002, North Ossetia, (Russian Caucasus)

- Part of Maili Glacier broke off and avalanched, ~100 km per hour
- 20×10^6 tonnes of ice, rock, mud swept ~16 km through Karmadon Gorge
- ~140 fatalities, village of Nizhny Karmadon destroyed

The glacier before its collapse in early July. Some crevasses, a sign of imminent surging, can be seen at its base. (Planet)

July 3rd, 2016



August 22nd, 2016

Today's Objectives:

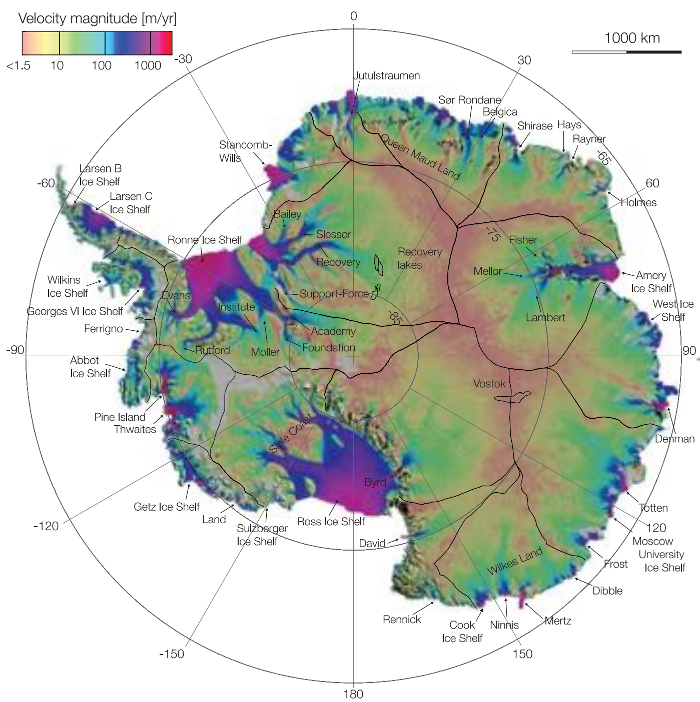
Basal Sliding:

- What are the controls on basal sliding? How do they compare with the physics of internal deformation?
- What are the two fundamental processes that allow sliding past bedrock obstacles? What is the role of water in each process?

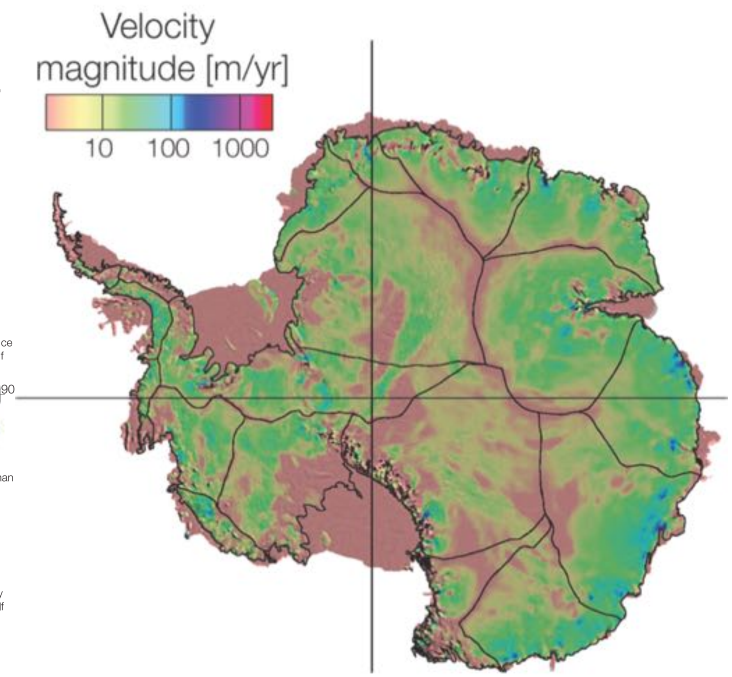
Hydrology:

- How is water transported in a glacial system?
- How does the amount of water in the system affect the water transport regime?

Importance of Sliding



Observed Surface Speed



Deformation Speed Only

Importance of Sliding

Internal deformation u_d is always present

Sliding contribution to ice transport:

$u_s = 0 \times u_d$ e.g. frozen bed

$u_s = 10^N \times u_d$ e.g. glacier surges and ice streams

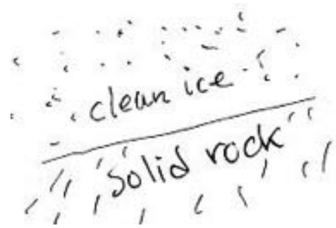
N can be as high as ~ 3

In "typical" temperate mountain glaciers, it is commonly supposed that

Ice transport due to sliding $\approx$ Ice transport due to internal deformation

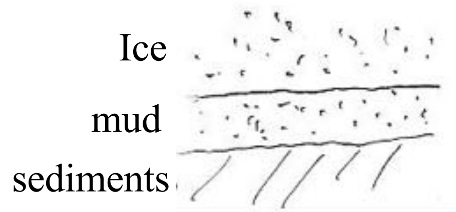
What's it like under a glacier?

Smooth clean bedrock



Frozen ground (tundra, gravel, till)

Soft marine mud

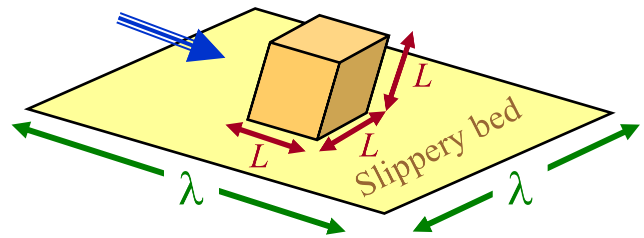


Glacial till – unsorted gravel, mud

- Soft, wet deformable
- Hard, overconsolidated
- Wet, thawing (geothermal flux, frictional heat)
- Wet, freezing (ice fingers into pores)

Tombstone Model

(J. Weertman, 1957)
A simple starting model for sliding



1) Regelation

2) Enhanced Deformation

Weertman, J. (1957), *J. Glac.* ***3***, 33.

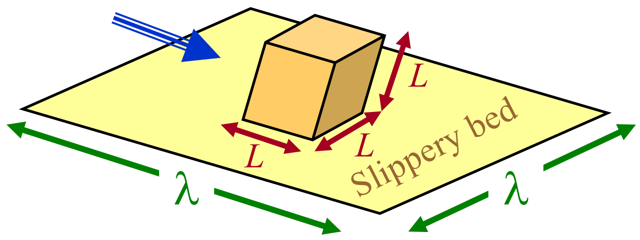
ON THE SLIDING OF GLACIERS

By J. WEERTMAN
(Naval Research Laboratory, Washington, D.C.)

ABSTRACT. A model is proposed to explain the sliding of any glacier whose bottom surface is at the pressure melting point. Two mechanisms are considered. One is pressure melting and the other is creep rate enhancement through stress concentrations. Neither of the mechanisms operating alone is sufficient to explain sliding. If both mechanisms operate together appreciable sliding can occur.

Regelation

Tombstone Model



(J. Weertman, 1957)

A simple starting model for sliding

If ice is not accelerating off the mountain (i.e. an ice avalanche), then there must be a restraining force to balance the down-slope driving shear stress

$\tau = \rho\, g\, h \sin(\theta)$ acting on area $\lambda\times\lambda$.

h = ice thickness

θ = surface slope

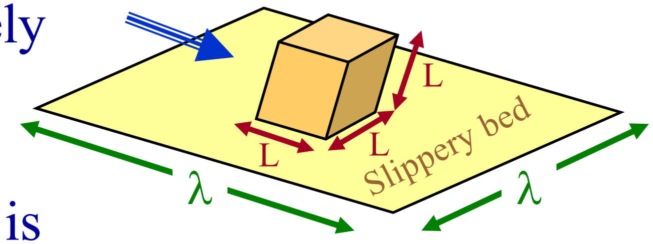
Force = stress ×Area on area $\lambda\times\lambda$:

$$F = \tau\lambda^2$$

- But there is no basal shear stress on slippery bed …

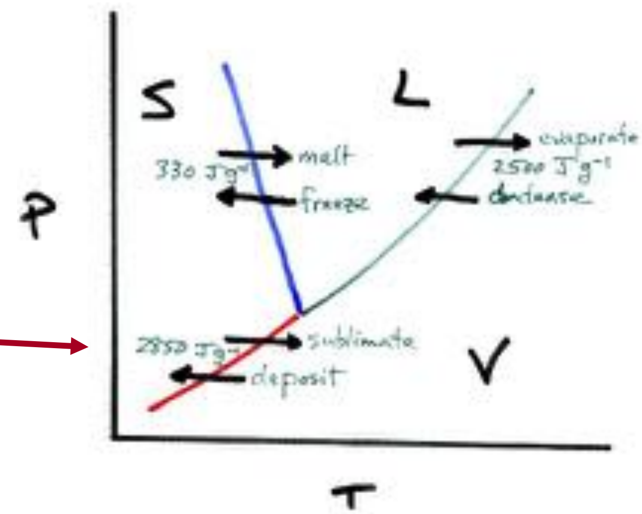
Tombstone face

- Force $\tau\,\lambda^2$ is supported entirely by uphill face of bump
- This face has area L^2
- Pressure (stress) on that face is $P = \tau\,\lambda^2 / L^2$ (force/Area)



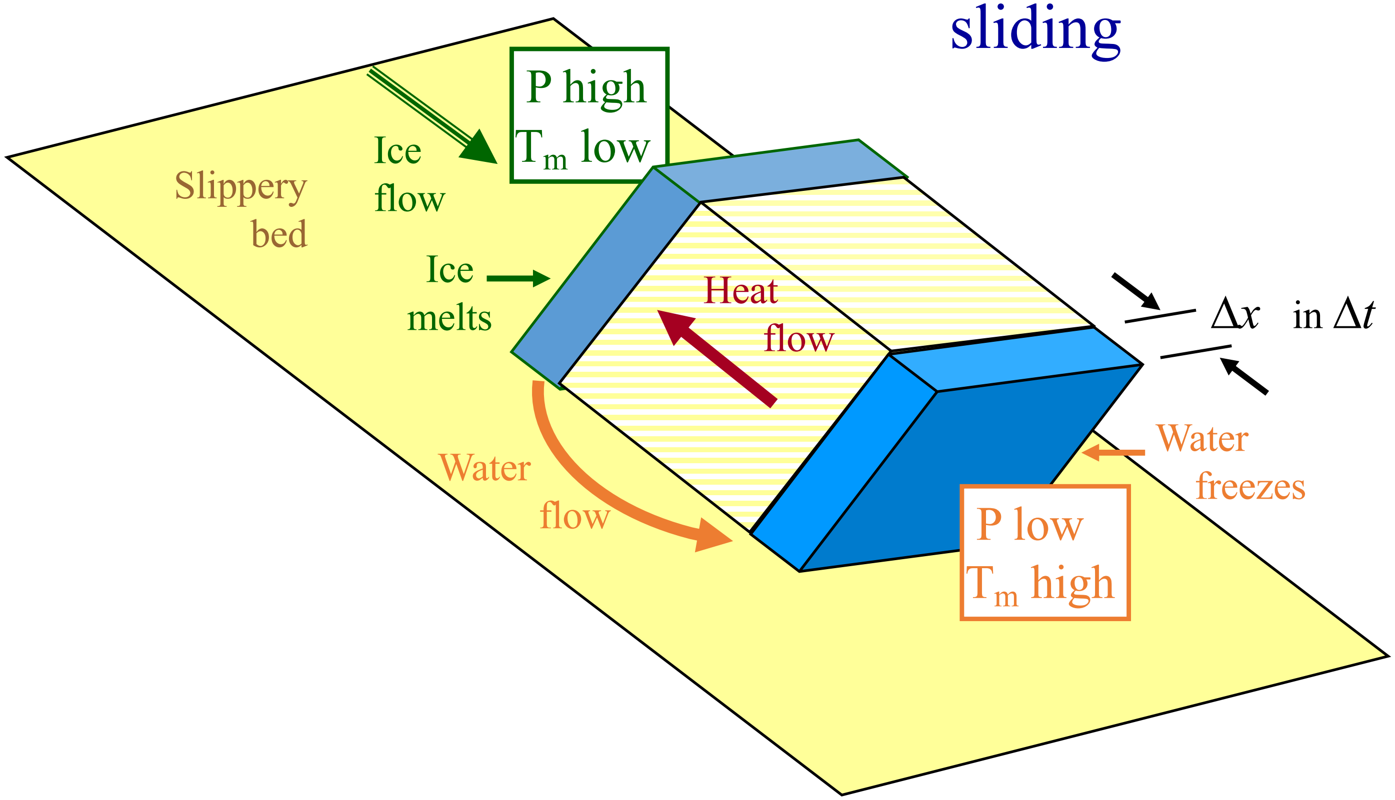
High pressure depresses freezing point

- $\Delta T = c\,P$
- c = -7 ×10^{-8} °C Pa^{-1} (slope on phase boundary)

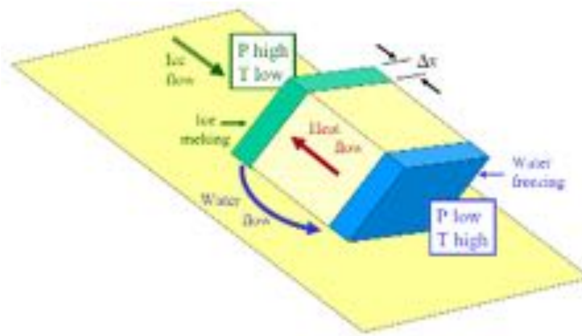


$$\Delta T = c\,\tau\,\lambda^2 / L^2$$

Regelation sliding



Can ice slide past a Bump?



- How fast ice can move past bump depends on how fast heat can get back through bump.
- Heat flux Q depends on temperature gradient $\Delta T/L$ (Fourier's Law).

$$Q = -K\,\Delta T / L$$

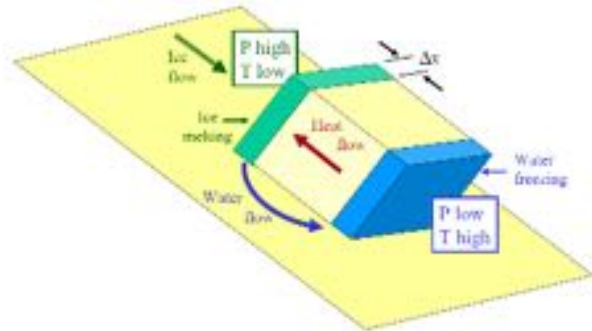
K = rock conductivity ≅2 W m^{-1} deg^{-1}

L = rock scale length (m)

$$\Delta T = c\,\tau\,\lambda^2 / L^2$$

$$Q = -\left(\frac{Kc\tau}{L}\right)\left(\frac{\lambda^2}{L^2}\right)$$

Sliding Speed by Regelation



In time Δt, heat flux Q (W m^{-2}) delivered to Area $=L^2$ of rock face can melt a volume V of ice given by: $V = L^2 \times \Delta x$ (1)

V = (energy delivered)/(energy to melt 1 m^3)

$V = (Q \times L^2 \times \Delta t) / (\rho H)$ (2)

H = heat of fusion = 331 kJ/kg

ρ = ice density = 900 kg/m^3

Equating (1) and (2) and using

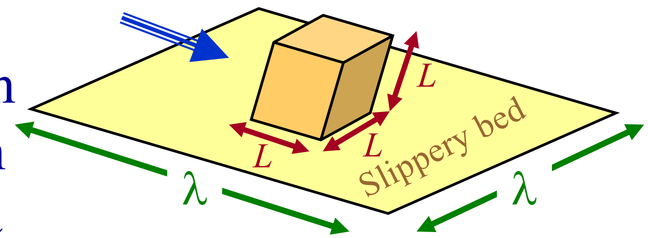
$$Q = -\left(\frac{Kc\tau}{L}\right)\left(\frac{\lambda^2}{L^2}\right)$$

$$U_{slide} = \frac{\Delta x}{\Delta t} = \frac{Kc\tau}{\rho HL}\frac{\lambda^2}{L^2}$$

Example of sliding speed

$$U_{slide} = \frac{Kc\tau}{\rho HL}\frac{\lambda^2}{L^2}$$

If $L = 0.02$ m
$\lambda = 0.2$ m
$\tau = 10^5$ Pa



$$U_{slide} = \frac{2W\,m^{-1}\deg^{-1}\,7\times10^{-8}\deg Pa^{-1}10^{5}\,Pa}{900kg\,m^{-3}\,3.3\times10^{5}\,J\,kg^{-1}\,0.02m}\,\frac{0.2^2\,m^2}{0.02^2\,m^2}$$

$$\approx 2\times10^{-7}\,m\,s^{-1}$$

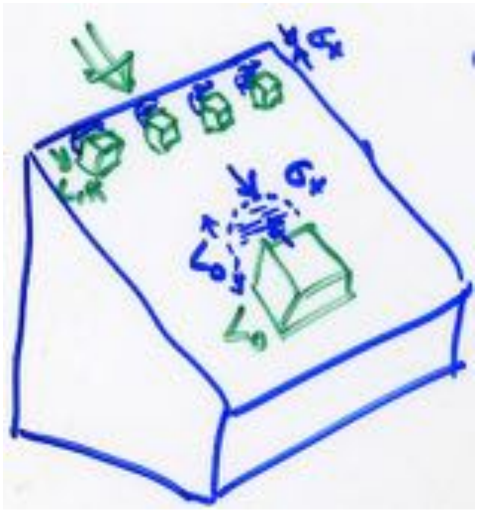
$$\approx 2\times10^{-7}\,m\,s^{-1}\times 3\times10^{7}\,s\,yr^{-1} \approx 6m\,yr^{-1}$$

How will sliding speed change if bumps are bigger?

Regelation Demonstration – on Friday

Enhanced Creep

Can ice flow around bumps?



σ_x is compressive stress in ice upstream of bump

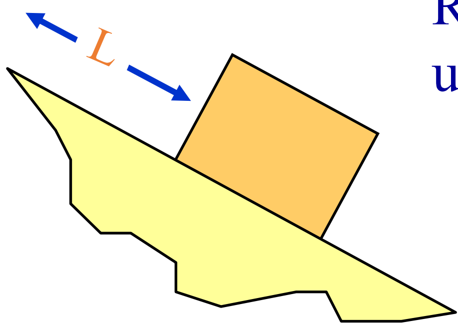
•Ice "knows" that bump is there for a distance ~L_0 upstream

•one large bump stresses a bigger volume of ice compared to many smaller faces with the same total restraining face area (as required for force balance)

Ice deforms in response to stress (Glen Flow Law)

$$\dot{\varepsilon}_x = A\sigma_x^3$$

Strain near bumps



Rate of shortening of a line upstream from bump

$$\dot{\varepsilon}_x = \left(\frac{\Delta L}{L}\right)\frac{1}{\Delta t}$$

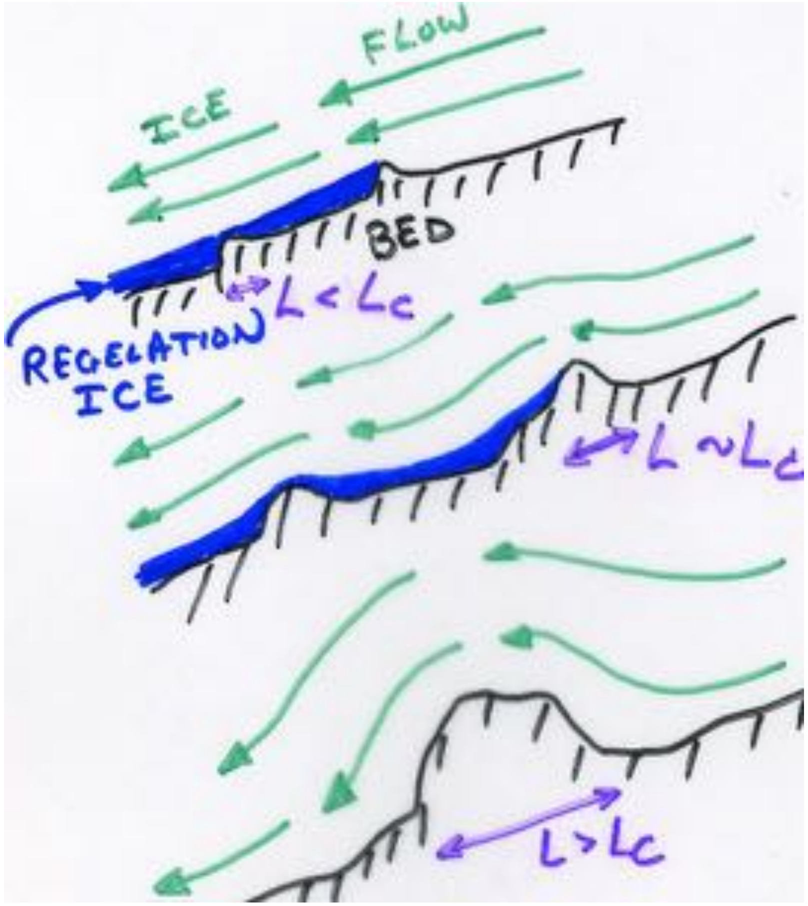
$$U_{slide} = \frac{\Delta L}{\Delta t} = L\dot{\varepsilon}_x = LA\sigma_x^3$$

We used Glen flow law:

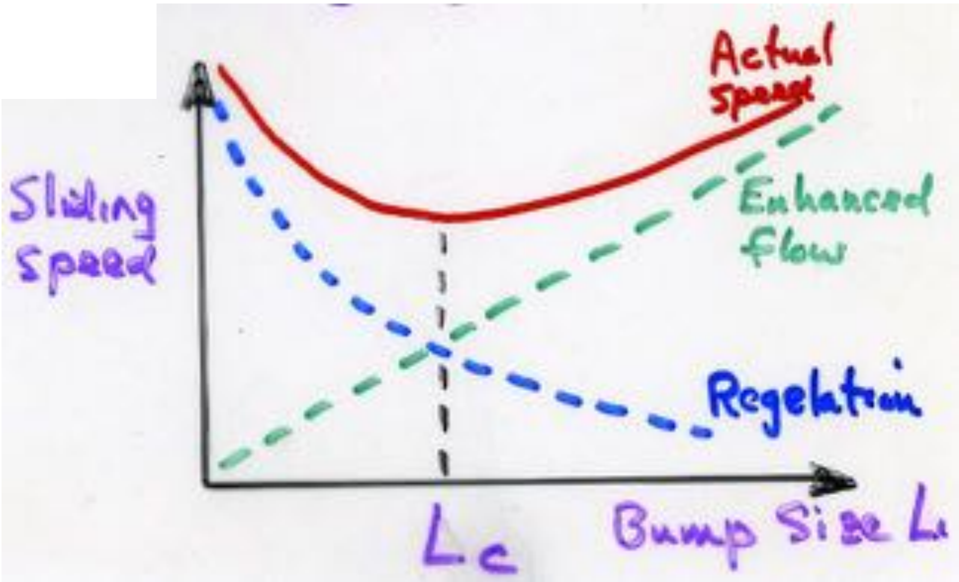
Ice can move faster around larger bumps

Regelation-Deformation Tradeoff

- Regelation allows ice to slide past small bumps easily.
- Enhanced strain gets ice past large bumps easily.
- At some intermediate scale $L = L_c$, both processes are equally effective (or ineffective).



Controlling-Obstacle Size

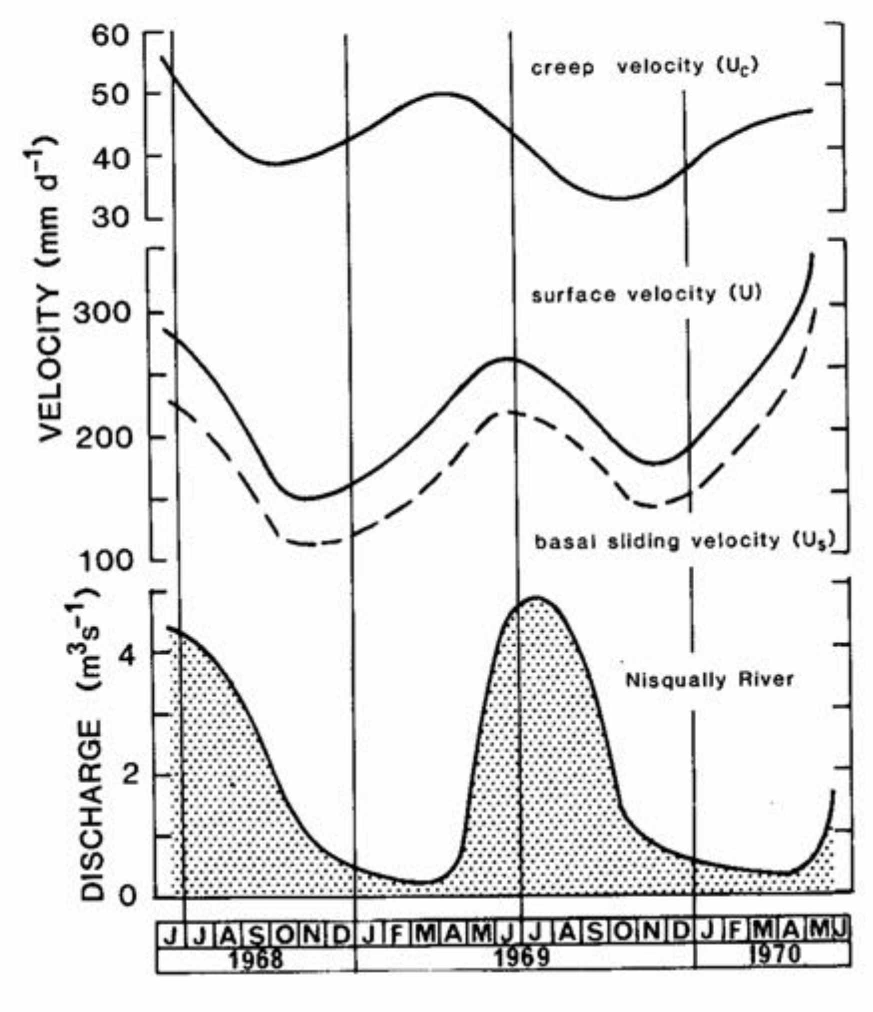


- Actual sliding speed is sum of 2 processes
- At $L=L_c$, U_{slide} is minimum
- Bedrock bumps with size L_c control sliding speed.

What assumptions are built into this concept?

Flow on Nisqually Glacier

Can Tombstone Model explain these data?



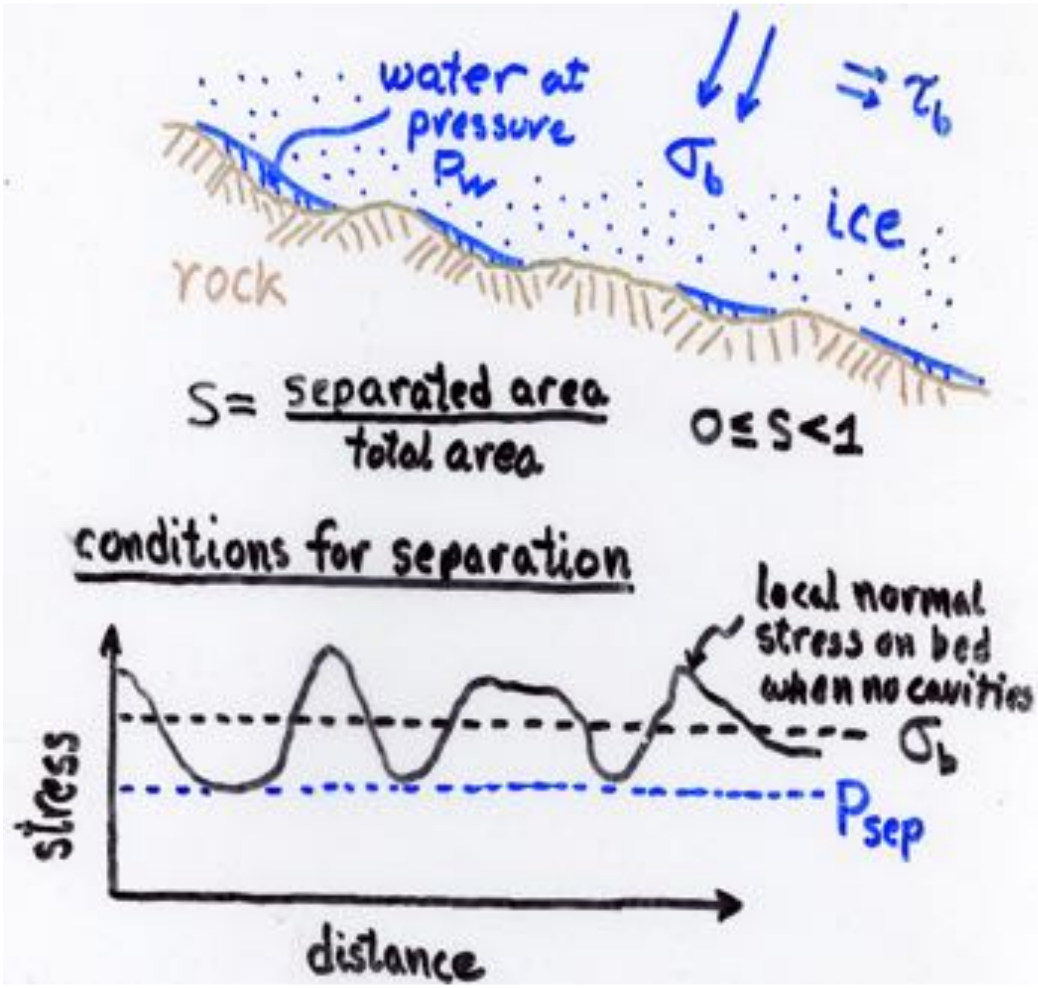
Based on Hodge, S.M. 1974 *J. Glaciol*. 13(69) 349-369.

Water is very important

- Meltwater from surface
- Meltwater from the bed

- Drainage through till?

- What does water do in a glacier?



Bed Separation and Sliding

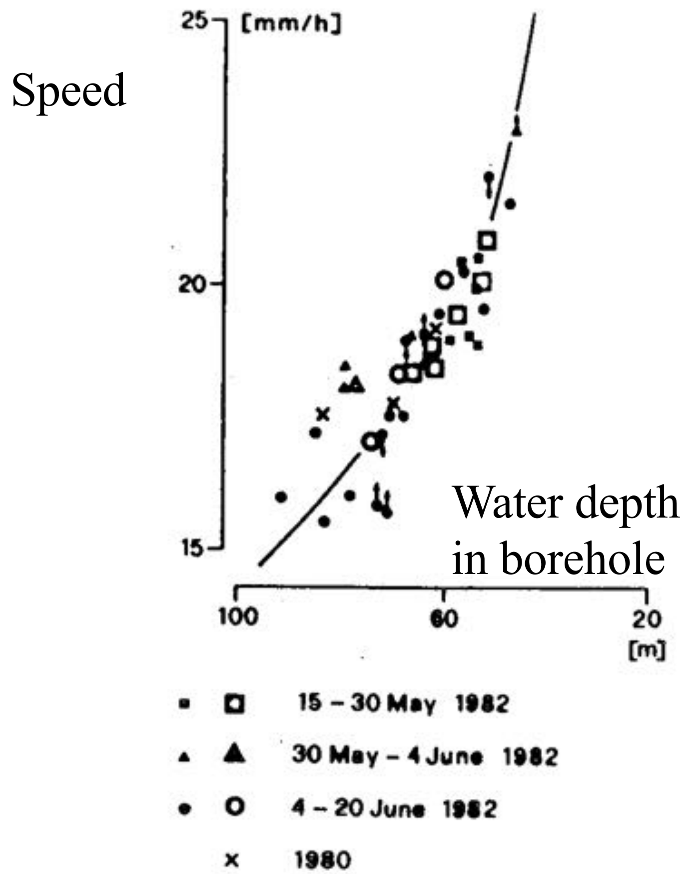
$P_w < P_{sep}$

- $S = 0$
- Cavities cannot form

$P_w > P_{sep}$

- $S > 0$
- Cavities can open

Sliding and Water Pressure



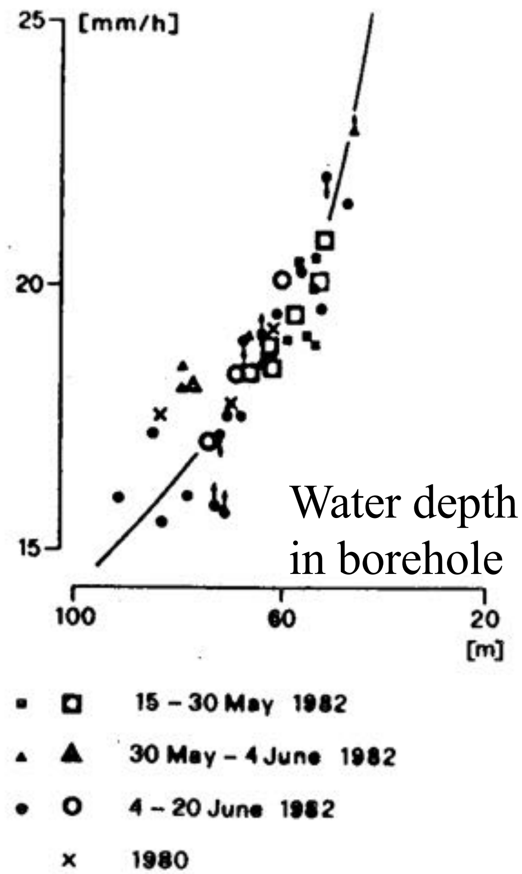
Glacier moves faster when water level rises in a hole to bedrock

- Why?

(Almut Iken)

Sliding and Water Pressure

Speed



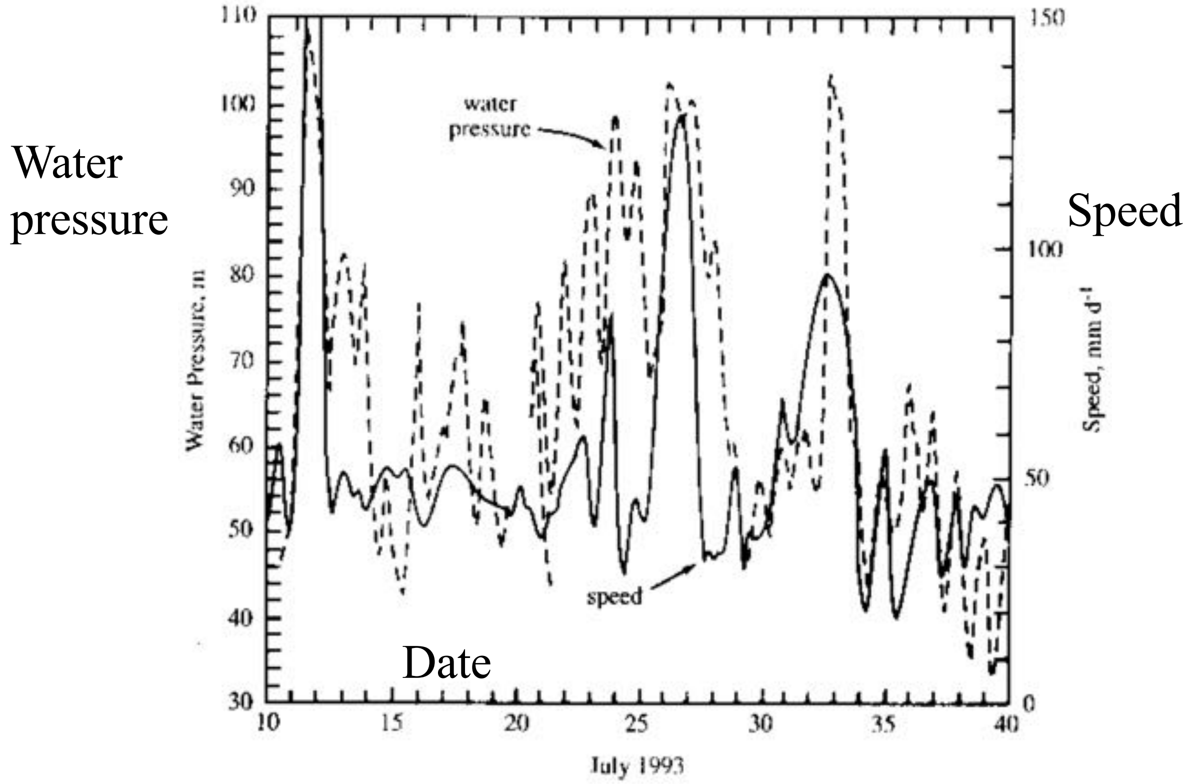
Water depth in borehole

Glacier moves faster when water level rises in a hole to bedrock

- Borehole is acting as a manometer; water level tells us about water pressure at the base of the glacier

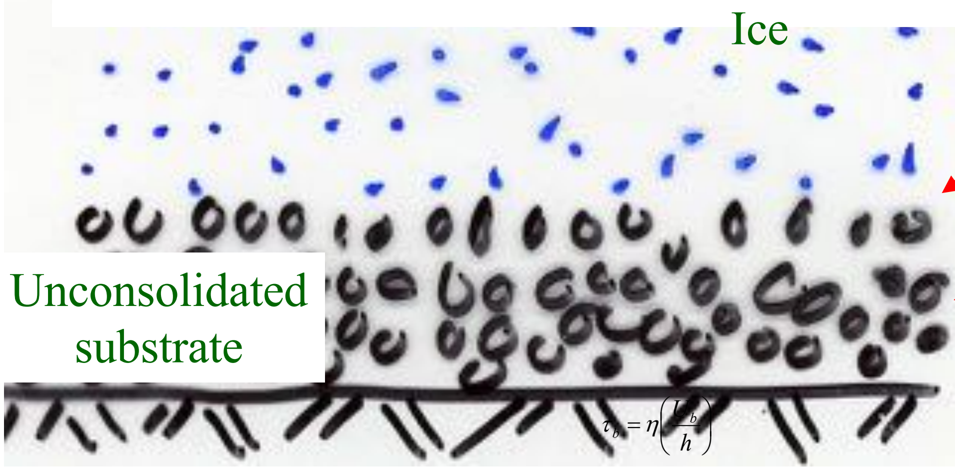
(Almut Iken)

Sliding and Water Pressure - Storglaciaren



(Hanson et al., 1998. *J. Glaciol.* 44(147) 359)

Sliding and Soft Beds



Factors:

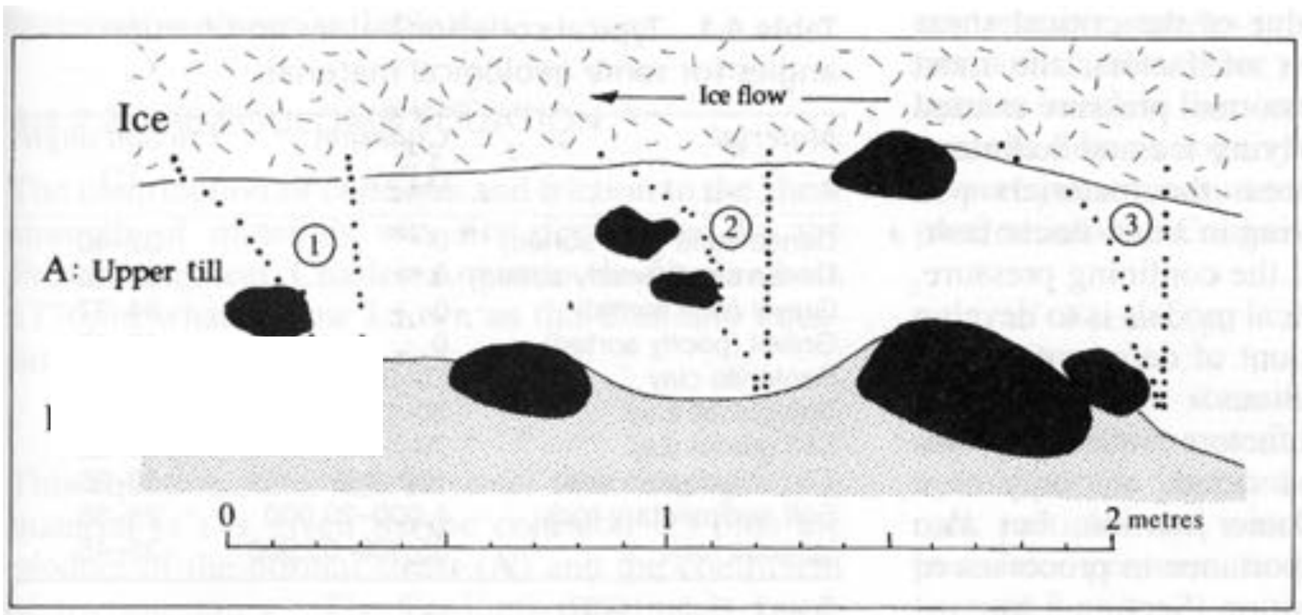
•Thickness *h* and composition of material (till viscosity η)

•Pore-pressure distribution

$$U_b = \frac{h}{\eta}\tau_b$$

But … what is viscosity η ???

Deformable Bed in Iceland



Breiðamerkerjøkull, Iceland

•Segmented rods left in subglacial till were moved forward by glacier over 10 day interval.

(Benn and Evans, *Glaciers and Glaciation*, adapted from Boulton and Hindmarsh)

Rock Friction

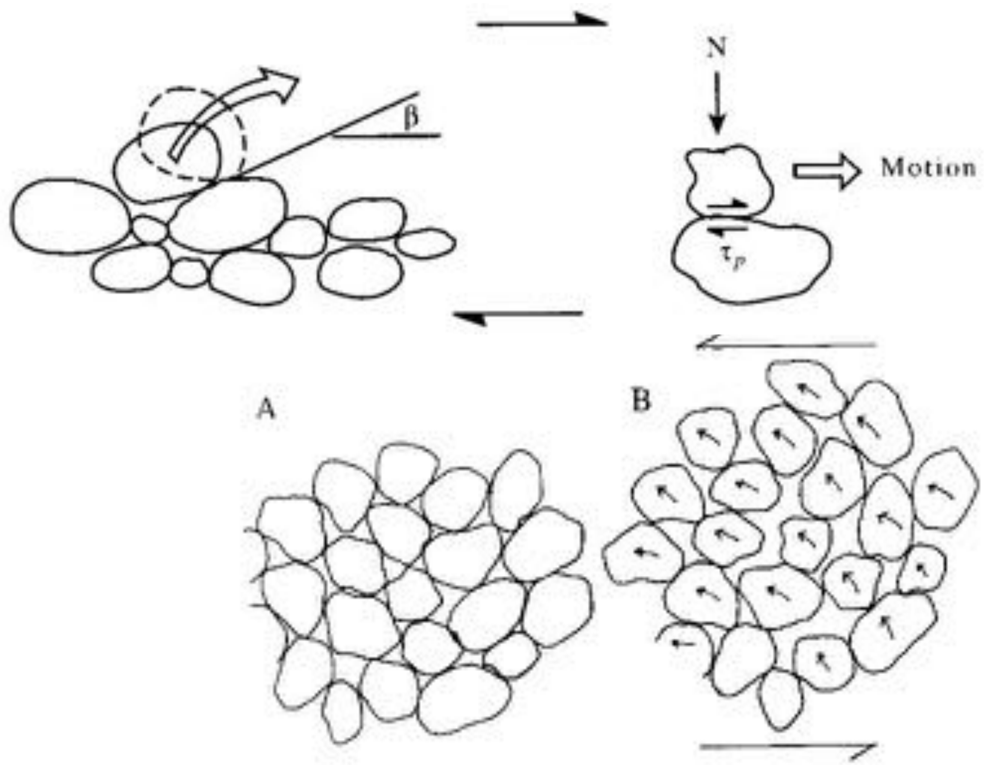
Pressure difference

Rocks pressed against bed

Water pressure reduces rock-to-rock friction

Geothermal flux

Rock Friction – Till Dilation



- Till must swell so that clasts can move past one another

- Water at high pressure helps to dilate till

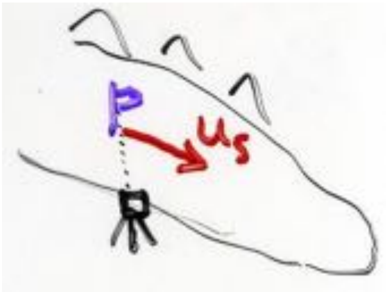
(Hooke, *Fundamentals of Glacier Mechanics*; Benn and Evans, *Glaciers and Glaciation)*

Questions, Questions, Questions …

1. Can speed U_d due to internal deformation change rapidly?
- Consider hours, days, seasons.

2. Can sliding speed U_b change rapidly, e.g. in a few hours?
- Consider Tombstone model, Deforming-till model, (others?)

3. You are measuring the surface speed U_s of a pole in the center of a glacier in the Cascades. You just had the hottest 3 days of the summer. What might happen to U_s?



Today's Objectives:

Basal Sliding:

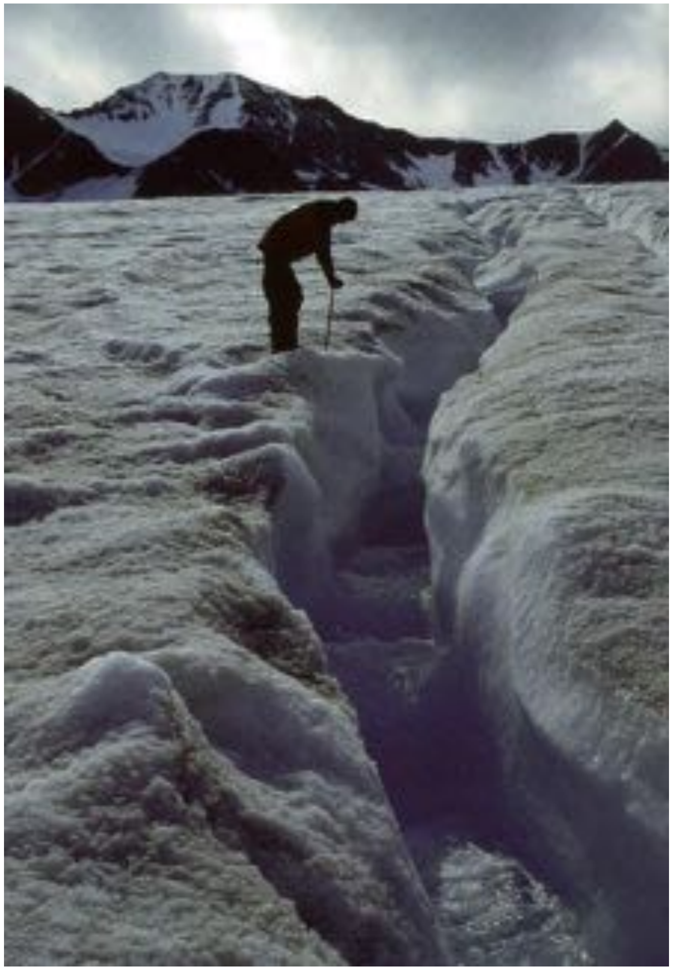
- What are the controls on basal sliding? How do they compare with the physics of internal deformation?
- What are the two dominant processes that allow sliding past bed features? What is the role of water in each process?

Hydrology:

- How is water transported in a glacial system?
- How does the amount of water in the system affect the water transport regime?

Glacial Outburst Flooding

- South Tahoma Glacier, Mount Rainer, WA, USA
- Since 1985, over 30 have occurred



Streams on Glaciers

Water can melt channels into glacier ice

- Lower albedo than ice
- Dissipating potential energy as it loses elevation

Austre Lovenbreen, Spitsbergen
Hambrey and Alean. ***Glaciers***.

Rivers on the Greenland Ice Sheet

Vibeke Gletscher,
East Greenland

~300 m

Hambrey and Alean, ***Glaciers***.

Moulins

Water will find a way to move down into a glacier

• a supraglacial stream will typically flow into a crevasse

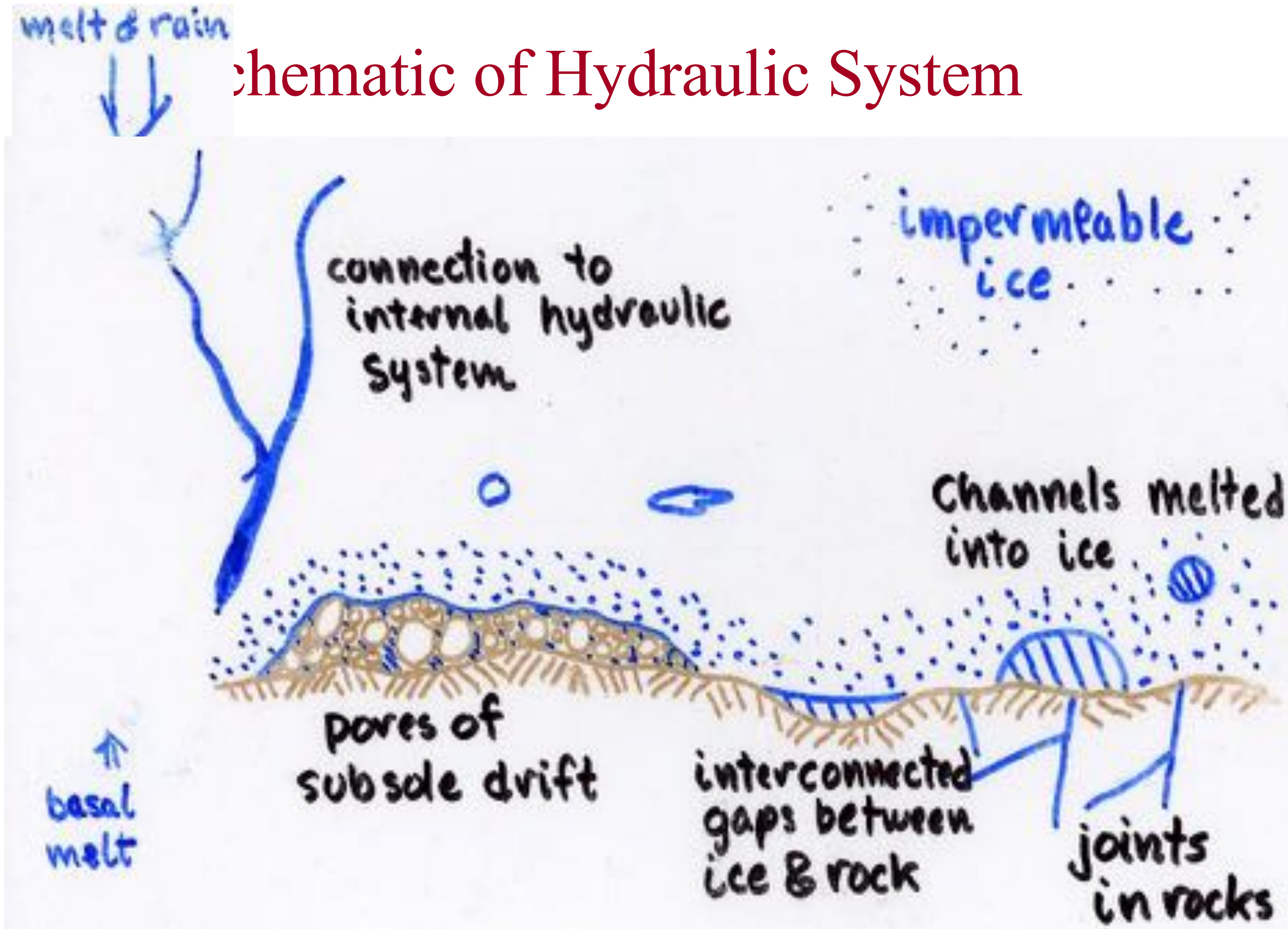
Tunnels

We can see the water coming out at a glacier terminus

- But where has it been?

Fox Glacier, NZ.
Hambrey and Alean. ***Glaciers***.

chematic of Hydraulic System

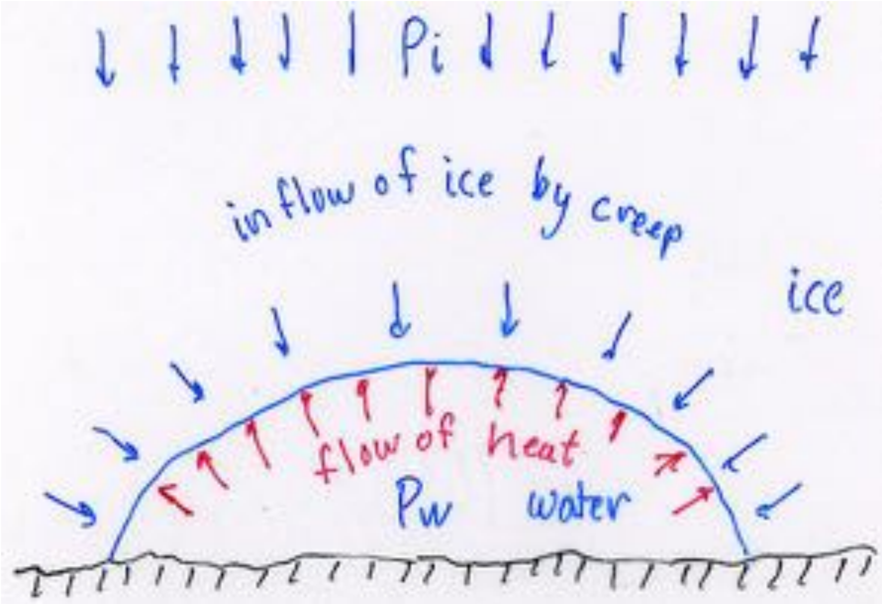


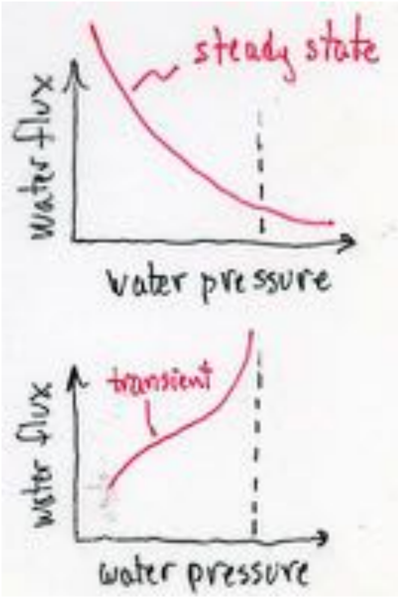
Tunnels in Winter

Water can stop flowing in winter
- where does a tunnel lead?
- What happens over the winter?

Matanuska Glacier.
Andersen and Borns.
Ice Age World.

Tunnels Transporting Water





Rothlisberger (1972)
Nye (1976)

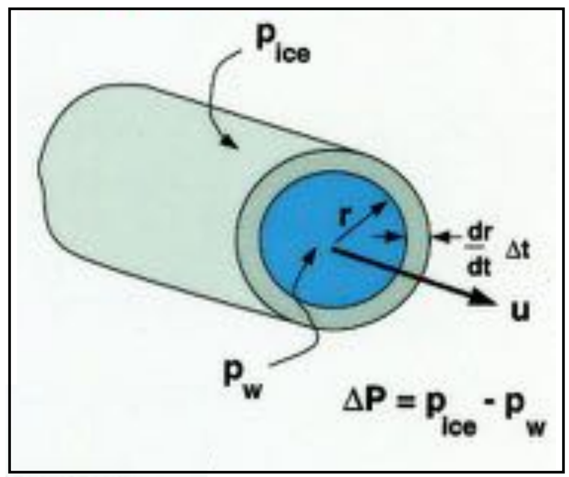
In steady state, higher water pressure ↔ lower water flux (in smaller tunnel)

Pressure in Steady Tunnels

Two competing influences:

- Creep closure of the tunnel, through ice deformation
- Tunnel growth, through melting from turbulent heat transfer

Creep Closure:



Pressure in Steady Tunnels

Two competing influences:
- Creep closure of the tunnel, through ice deformation
- Tunnel growth, through melting from turbulent heat transfer

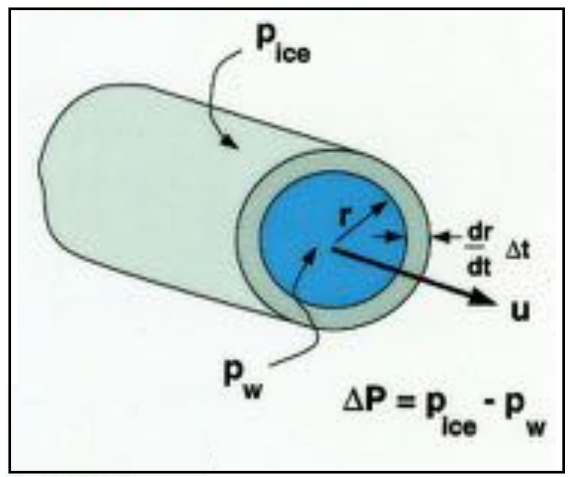
Creep Closure:

$$\dot{\epsilon} = \mathrm{A}\sigma^3$$

$$\frac{1}{r}\frac{\Delta r}{\Delta t} \approx \mathrm{A}[p_i - p_w]^3$$

$$\frac{\Delta r}{\Delta t} \propto \Delta p^{\,3}$$

$$\frac{\Delta V}{\Delta t} \propto 2\pi r * r\Delta p^{\,3}$$



Pressure in Steady Tunnels

Two competing influences:

- Creep closure of the tunnel, through ice deformation
- Tunnel growth, through melting from turbulent heat transfer

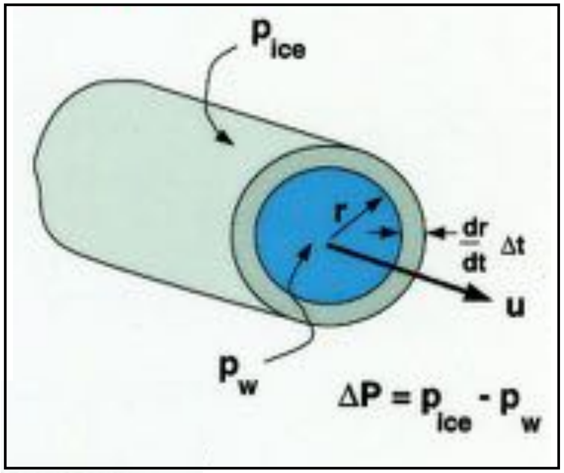
Turbulent Melting:

$$\frac{\Delta V}{\Delta t} \propto \frac{\Delta E}{\Delta t} \propto Q_w$$

$$Q_w = \pi r^2 u$$

$u \propto r^{2/3}$ - (pipe flow theory)

$$\boxed{\frac{\Delta V}{\Delta t} \propto r^{8/3}}$$



Pressure in Steady Tunnels

Two competing influences:

- Creep closure of the tunnel, through ice deformation
- Tunnel growth, through melting from turbulent heat transfer

Creep

$$\frac{\Delta V}{\Delta t} \propto r^2 \Delta p^{\,3}$$

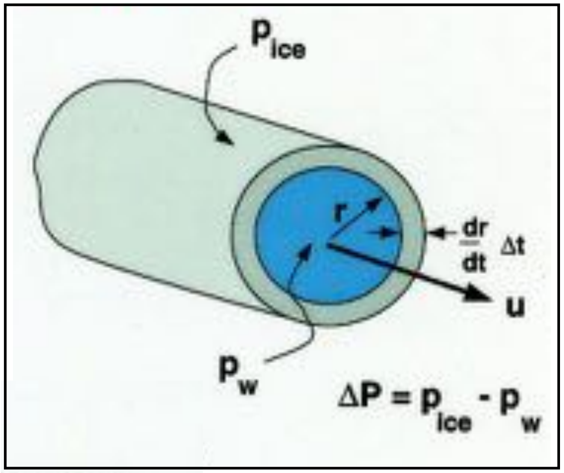
Melt

$$\frac{\Delta V}{\Delta t} \propto r^{8/3}$$

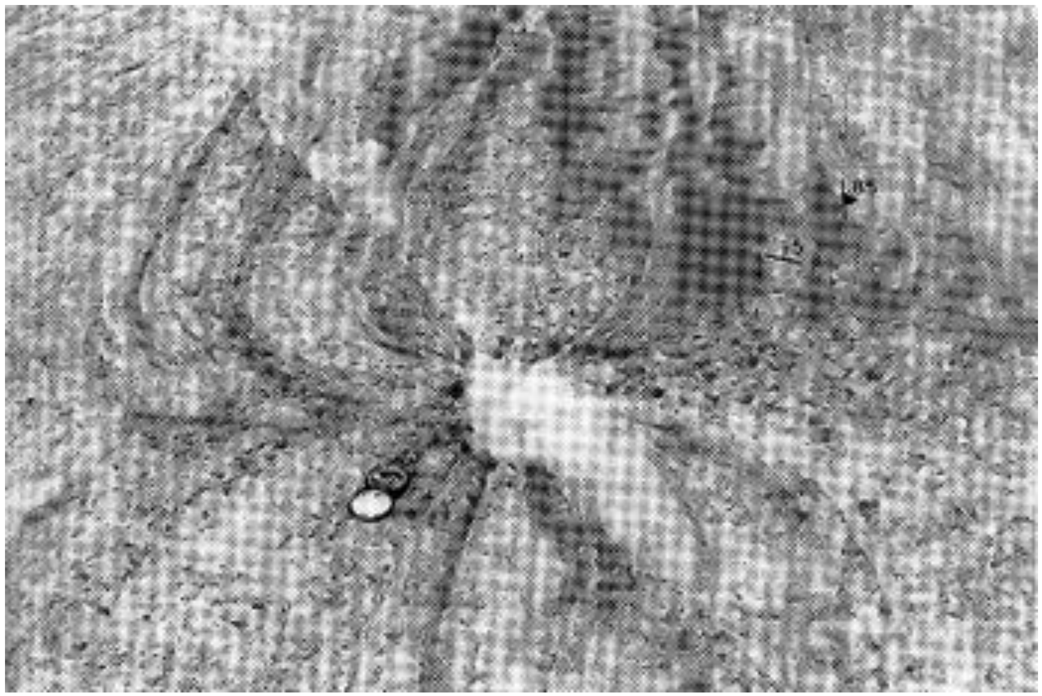
$$\Delta p \propto r^{2/9}$$

$$\Delta p \propto Q^{1/12}$$

As radius grows, Δp grows, p_w falls



Under-pressurized conduit

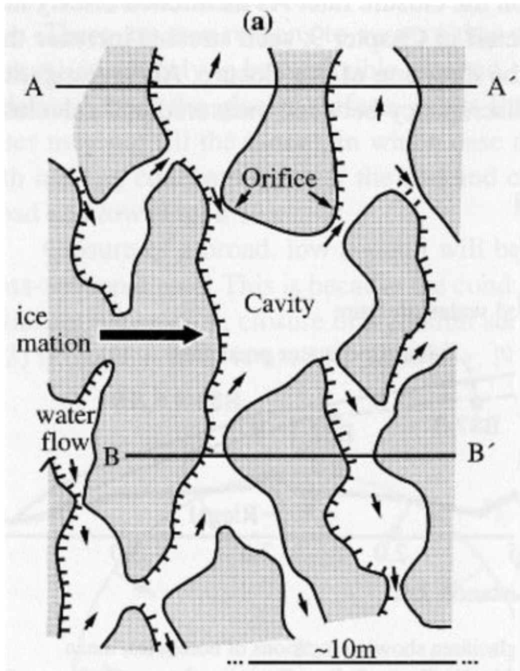


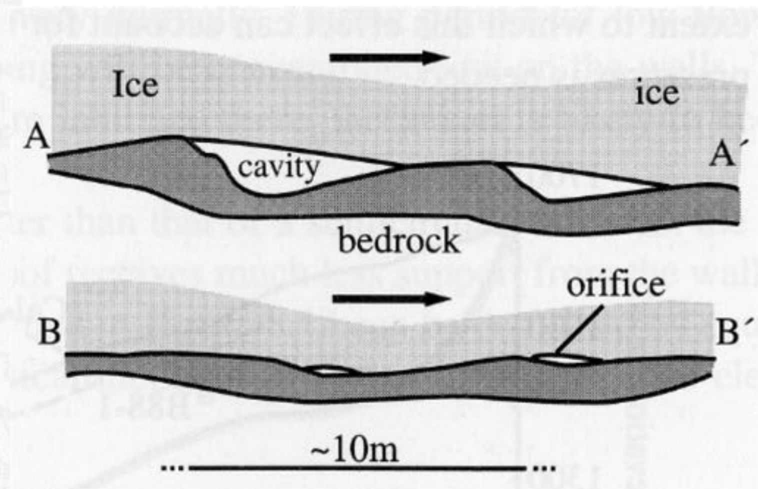
Brunton compass for scale

It did not survive when water flow stopped …

(Hooke, *Fundamentals of Glacier Mechanics*)

Linked Cavities



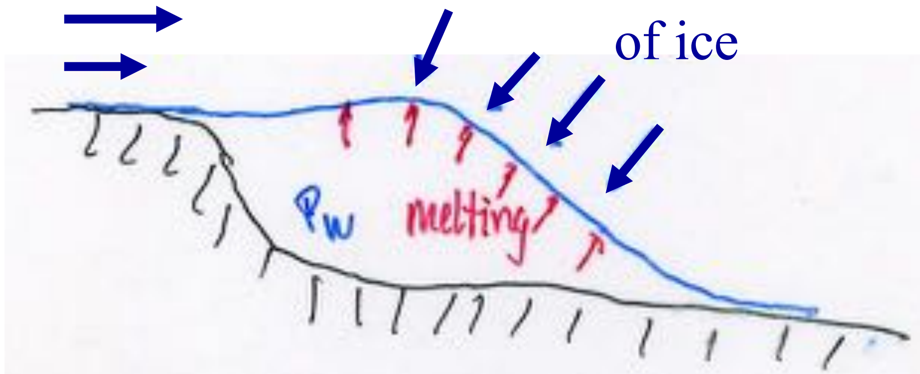


(Hooke, *Fundamentals of Glacier Mechanics*)

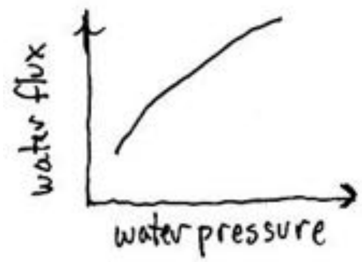
Water in Linked Cavities

Ice Flow
(sliding)

Inward flow
of ice



Higher water pressure
↔ higher water flux (transport)



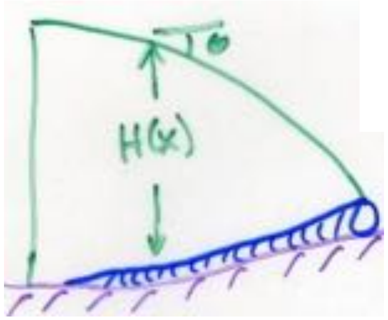
Questions, Questions, Questions …

1.Why do some glaciers speed up in late winter or early spring before there has been much melting?

•Why do they slow down in mid-summer when melting is at its peak?

2. Describe the pressure gradient in the conduit.

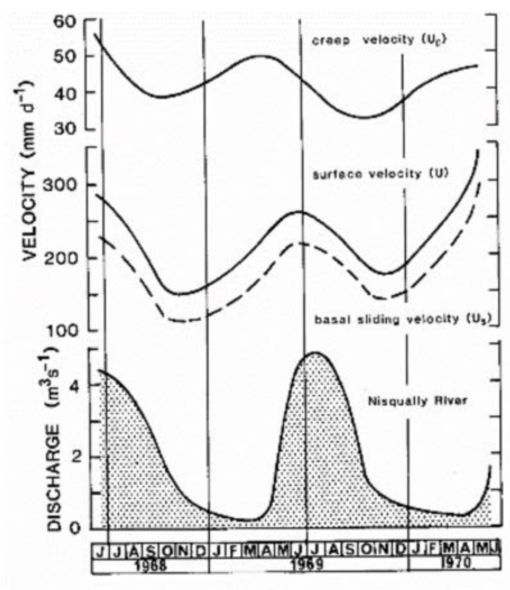
• Which way does the water flow?



3. Water is bubbling out of a crack in a glacier. The water is at the melting temperature.

• Some ice crystals are swept upwards by the flow. What has been happening to them on the way up?

Seasonal Water Cycle



Early winter: little meltwater, low water pressure

- Tunnels close, linked cavities survive

Late winter: seepage, basal melt

- water pressure rises slowly
- Sliding increases slowly

Spring: high meltwater flux enters cavities

- Water pressure rises
- Sliding increases slowly

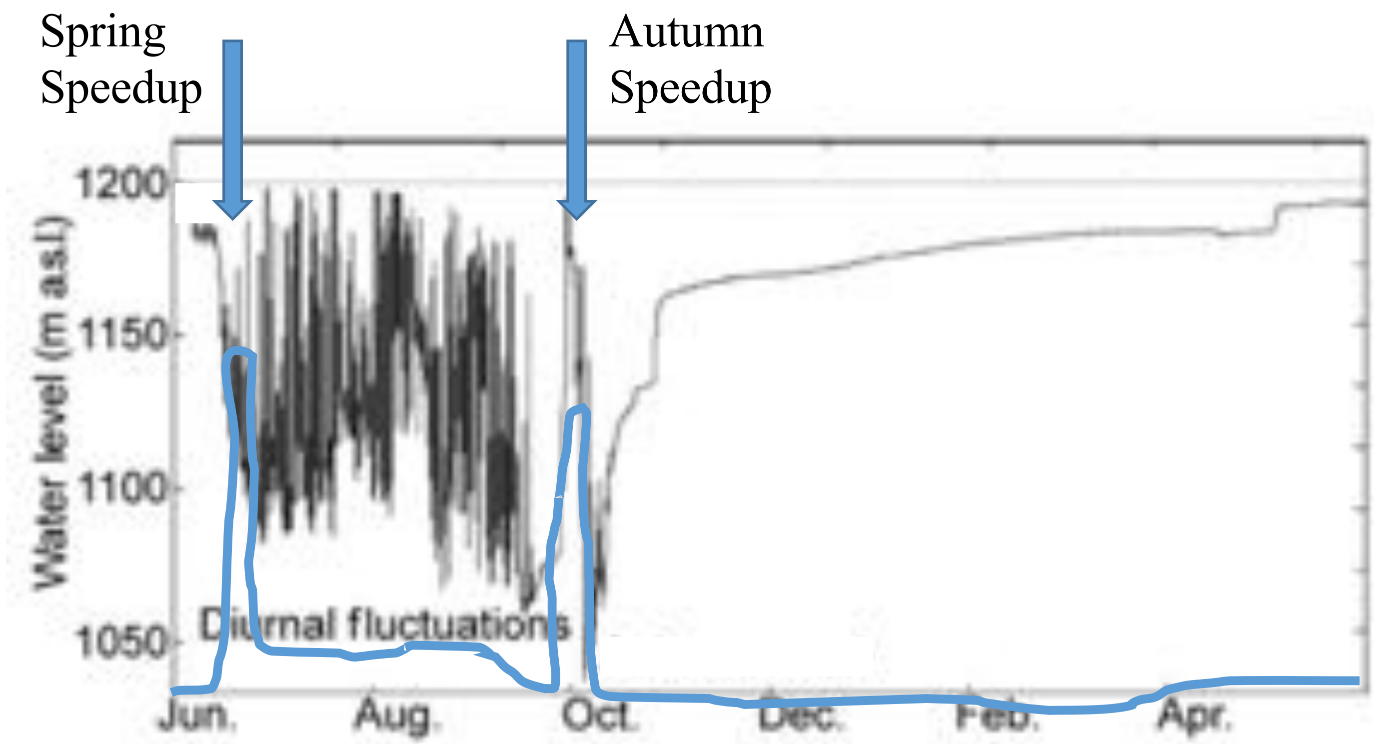
Early summer: too much water overloads cavities

- Surface rises
- Cavities join, tunnels start to form
- Sliding hits its peak

Mid-summer: water flows in low-pressure tunnels

- Basal water drains
- Sliding slows down

Seasonal Water Cycle

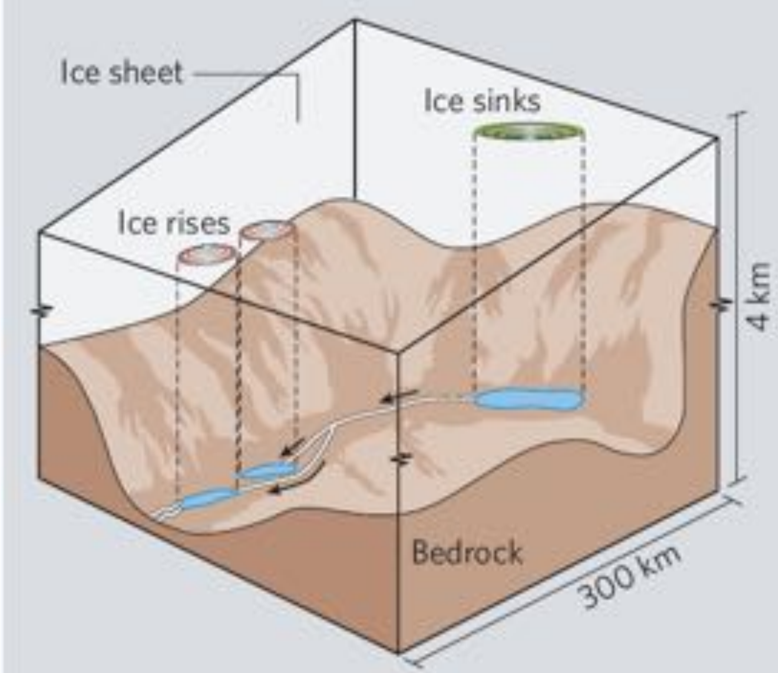


Water Pressure Variations on Bench Glacier, Alaska, 2002-2003 (Fudge et al, 2008)

Water moving in Antarctica

Recent work suggests large volumes of transient water can move under the ice.

- ~ 2 km^3 moved ~ 300 km beneath the ice sheet between 1996 and 1999.

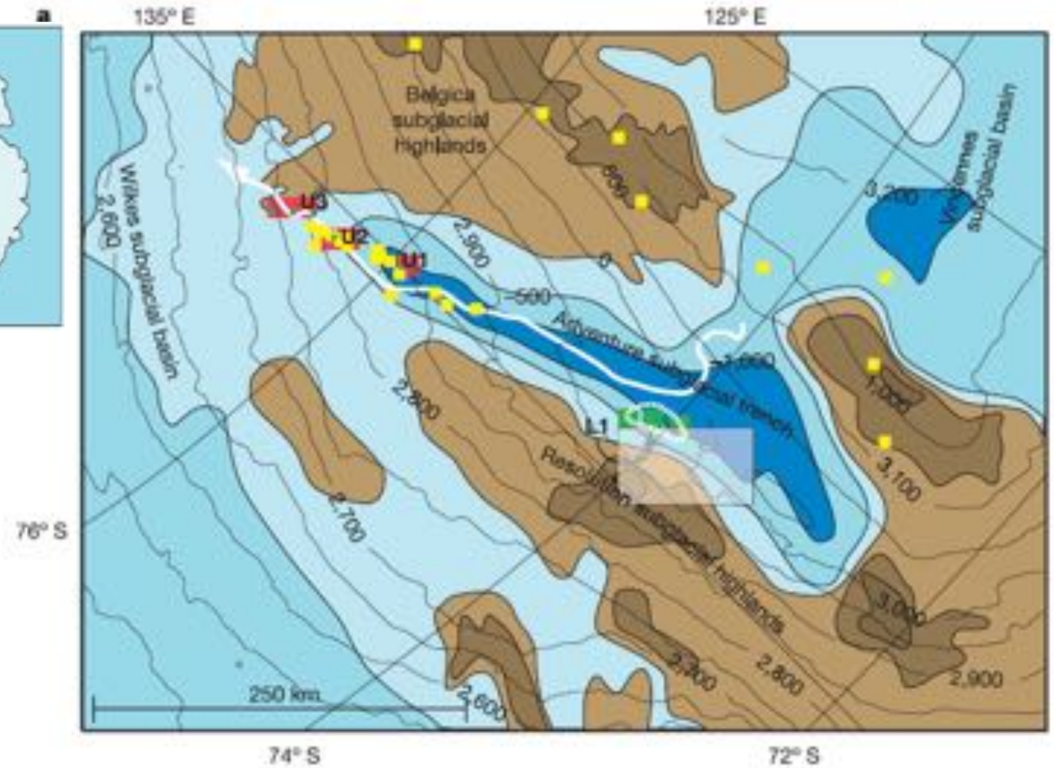


Satellite data showed ice sinking above one subglacial lake, while rising at two spots 290 km away.

The researchers conclude that water must have flowed from the first lake into two others downstream.

J. Giles 2006 *Nature* **440**, 977

Water moving in Antarctica



Large volumes of transient water can move under the ice, as detected by changes in surface height seen by satellite altimeters e.g. (ERS-1/ERS-2).

Wingham et al. (2006) *Nature* **440**, 1033.

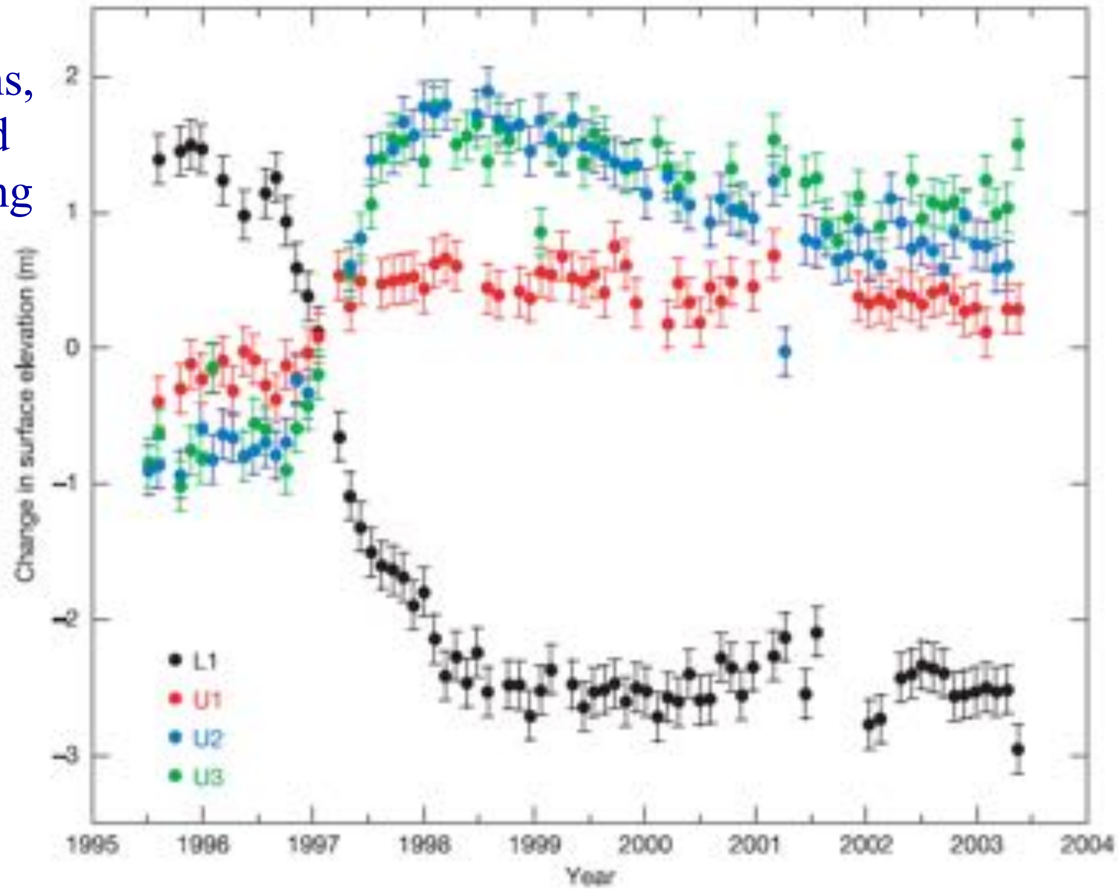
subglacial lakes - Yellow dots

- white dashes

L sites –lowering
U sites - rising

Surface Height Changes over Subglacial Lakes

As L1 drains, U1, U2, and U3 are filling up.

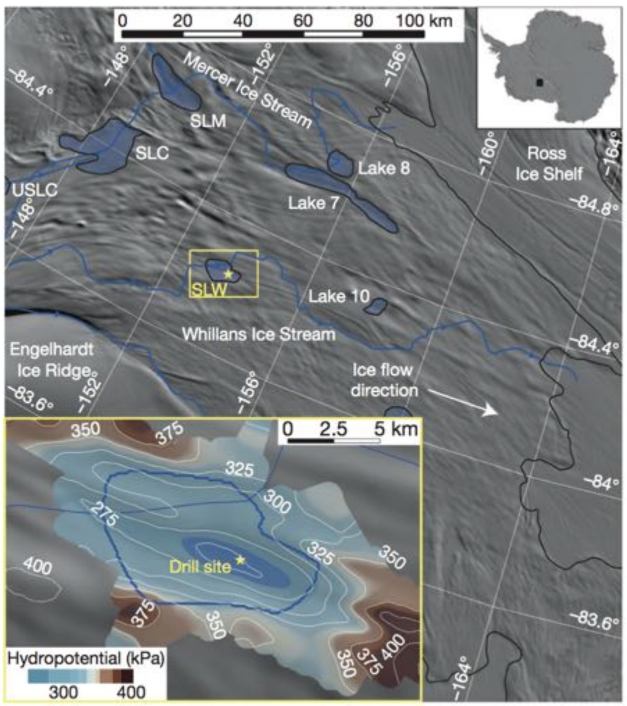


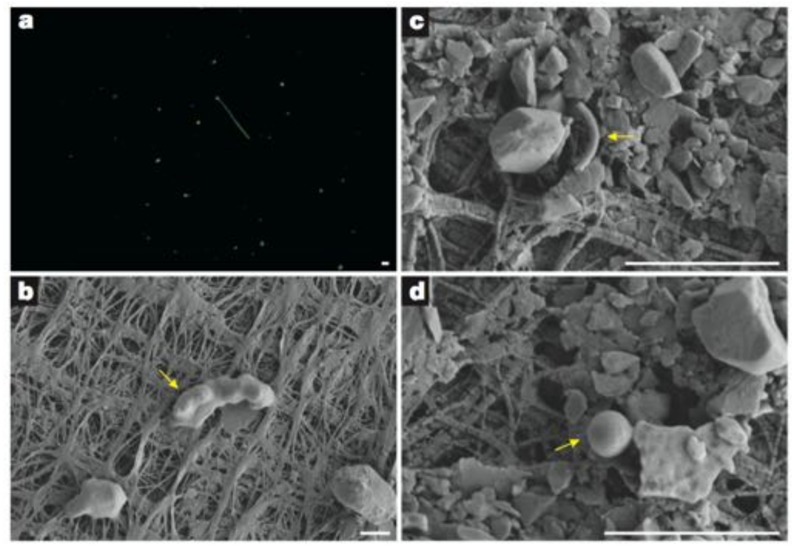
Wingham et al. (2006) *Nature* **440**, 1033.

Subglacial Lakes: Like Beneath the Ice

A microbial ecosystem beneath the West Antarctic ice sheet

Brent C. Christner[1], John C. Priscu[2], Amanda M. Achberger[1], Carlo Barbante[3], Sasha P. Carter[4], Knut Christianson[5]†, Alexander B. Michaud[2], Jill A. Mikucki[6], Andrew C. Mitchell[7], Mark L. Skidmore[8], Trista J. Vick-Majors[2] & the WISSARD Science Team‡





Christner et al. (2014), *Nature* **512**, 310.
Christianson et al. (2012), *EPSL* ***331-332***, 237.
Horgan et al. (2012), *EPSL* ***331-332***, 201.

Sliding Summary

- Negligible sliding if base is cold
- Sliding is typically comparable to internal deformation in temperate valley glaciers

  but

- Sliding can be up to 500-1000 m a^{-1} over slippery beds of large glaciers (e.g. West Antarctic Ice Streams)

Sliding depends on water

- Lubrication
- Regelation
- Bed separation (high water pressure)

Water can flow

- Through distributed linked cavities (high-pressure system)
- Through tunnels (low-pressure system)
- Through subglacial sediments

Sliding can change rapidly with changing bed conditions