Glacial Erosion II: Processes, Rates & Landforms

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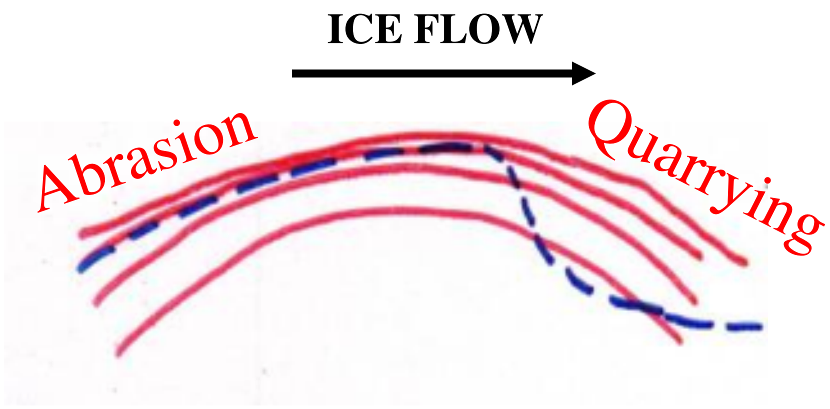
Continuing with glacial erosion…

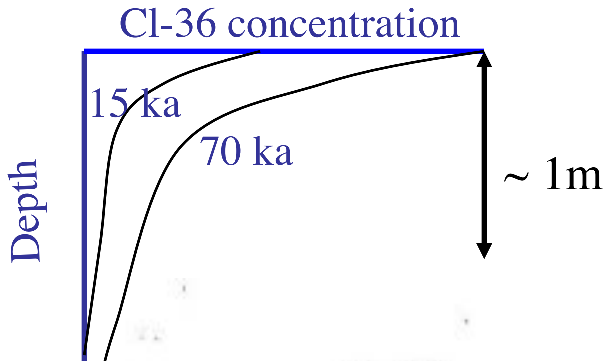
- Insights into quarrying, as well as chemical dimensions of glacial erosion
- Rates of erosion
- Checking aspects of theory
- Products of erosion from mm-scale striae, to glacial valleys, to beveled mountain ranges
- Sediments and their influence on ice masses

Relative importance of abrasion and quarrying



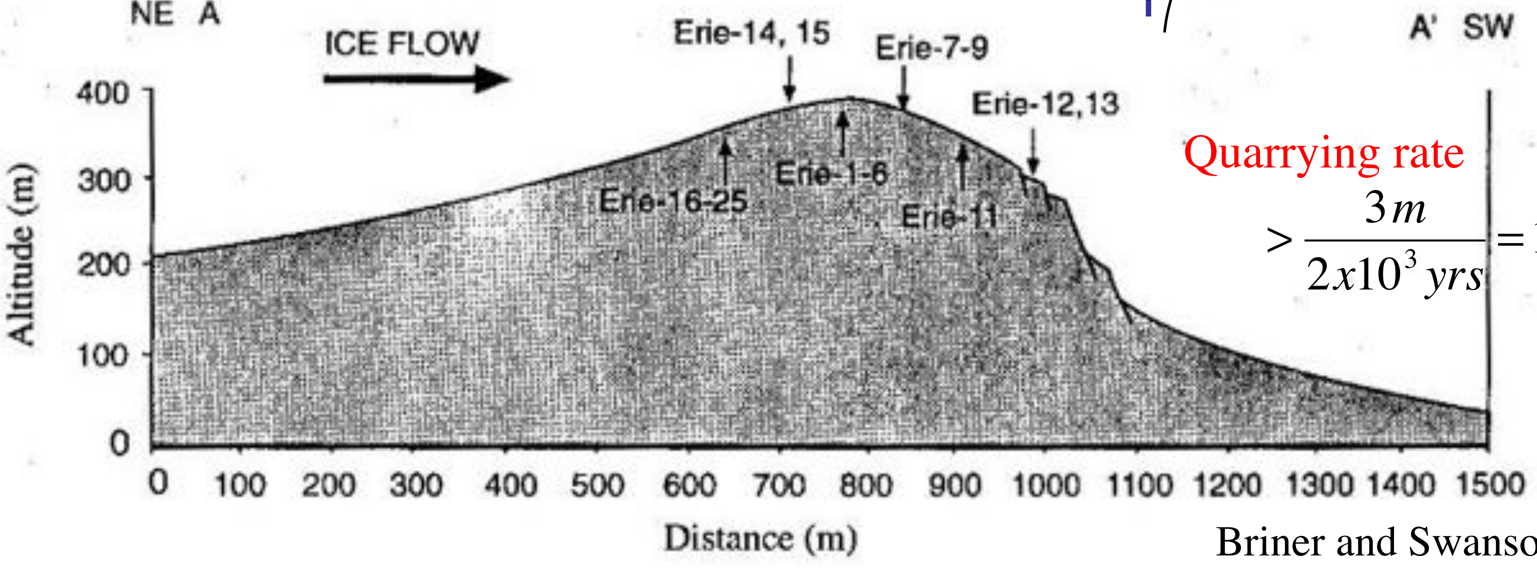
Asymmetry of exfoliating granite domes

R. Jahns (1943) recognized that more was missing from quarried side.



Abrasion rate

$$< \frac{0.3m}{2x10^3 yrs} = 0.15 \frac{mm}{yr}$$



Quarrying rate

$$> \frac{3m}{2x10^3 yrs} = 1.5 \frac{mm}{yr}$$

Briner and Swanson, 1998

Quarrying

Insights from Grinnell Glacier

2002
courtesy F. Ng

Work in subglacial cavities in early 1980s

Looking upglacier under 10-20m of ice at Grinnell Glacier

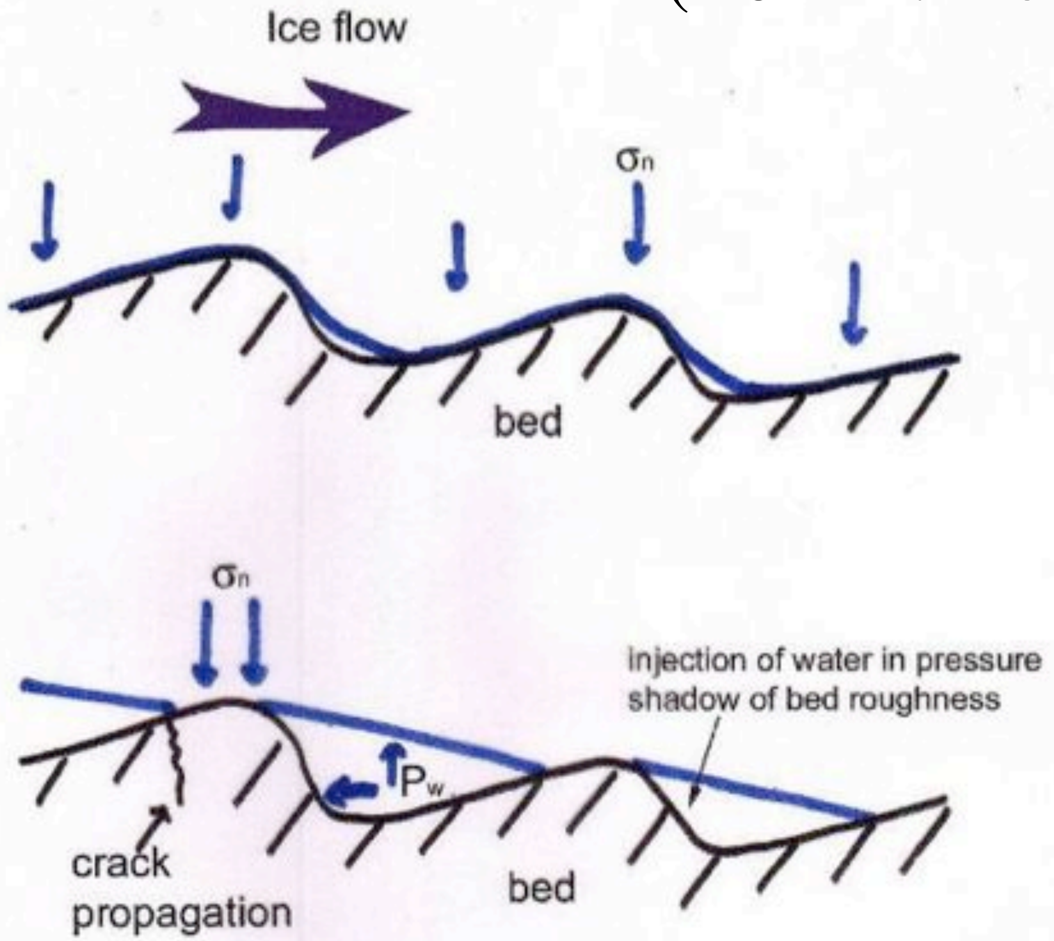
Measuring ice speed with circular saw cantilevered against ice roof under 10-20m of ice at Grinnell Glacier

Extensive cavities under 10-20m of ice at Grinnell Glacier

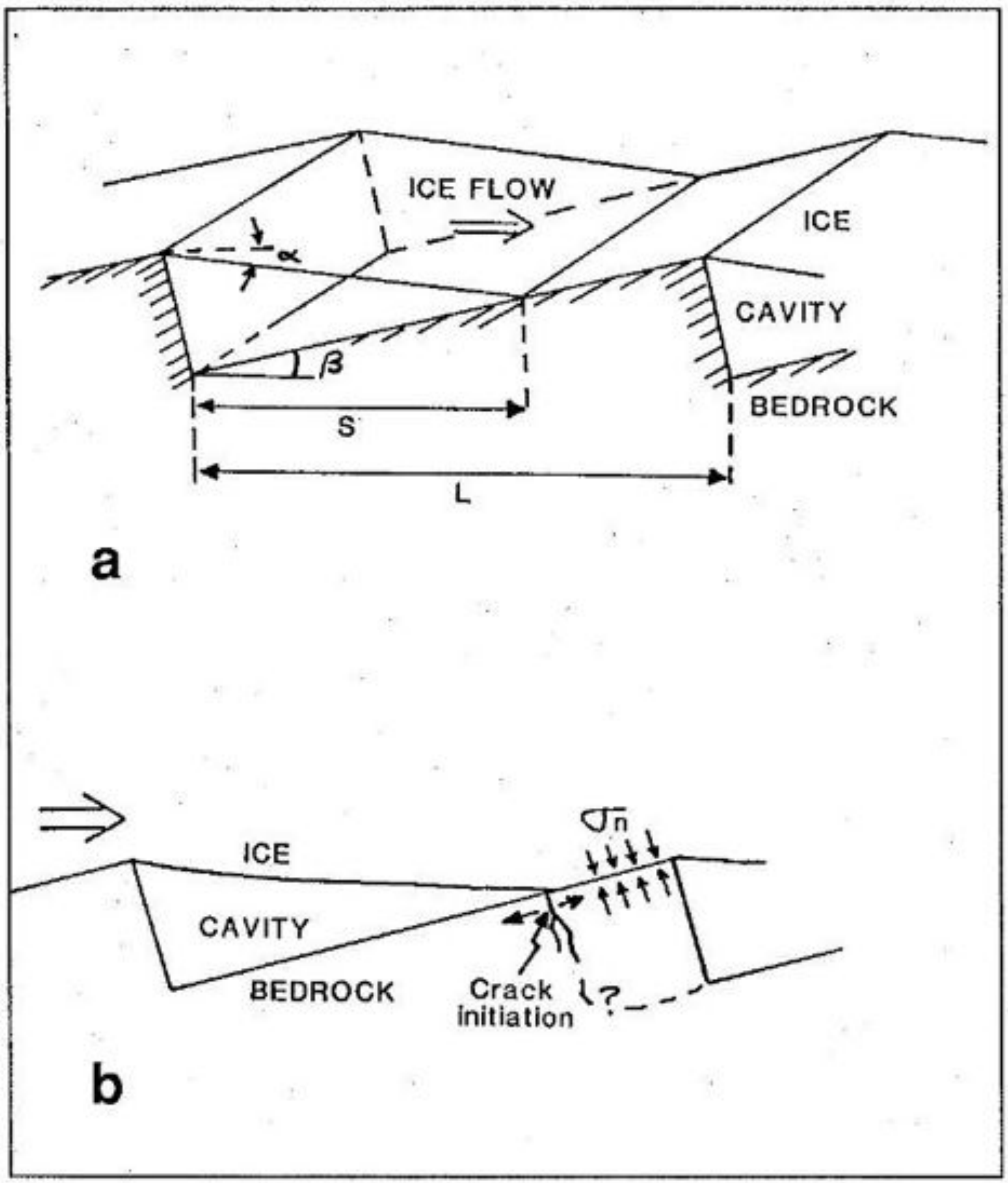
Pressure sensors under 10-20m of ice at Grinnell Glacier: before and after (note abrasion shadows)

Cavitation, stress concentration and quarrying

(from Y. Merrand)



Results in high water pressure, drowning of bed roughness, high rate of sliding, large deviatoric stress about roughness element and crack growth

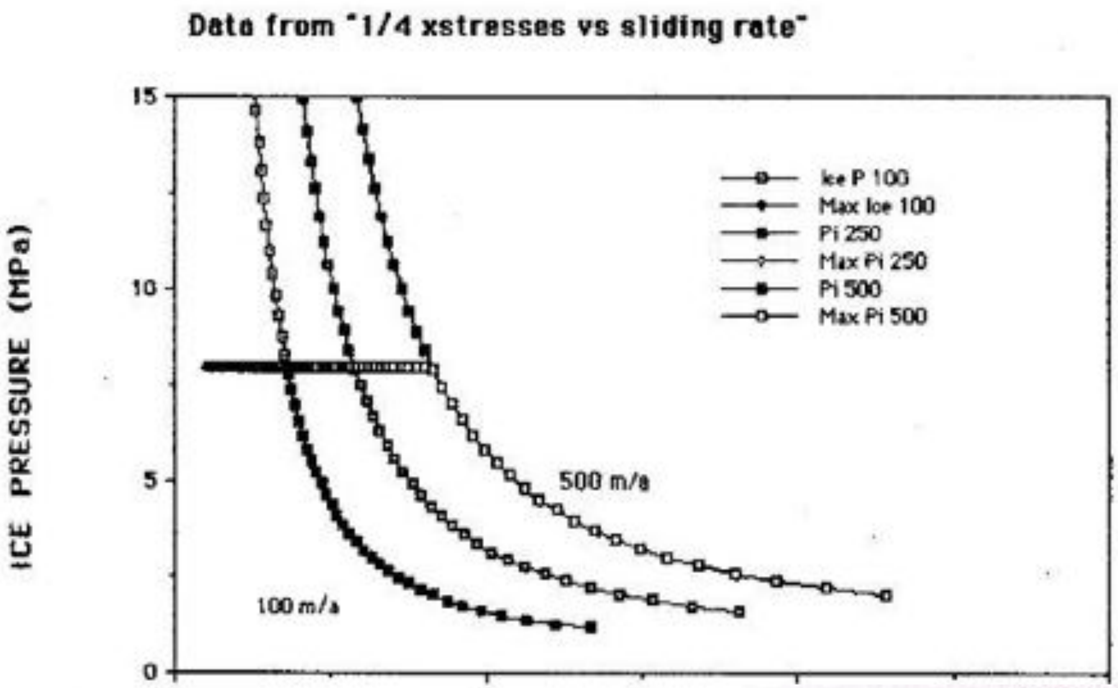


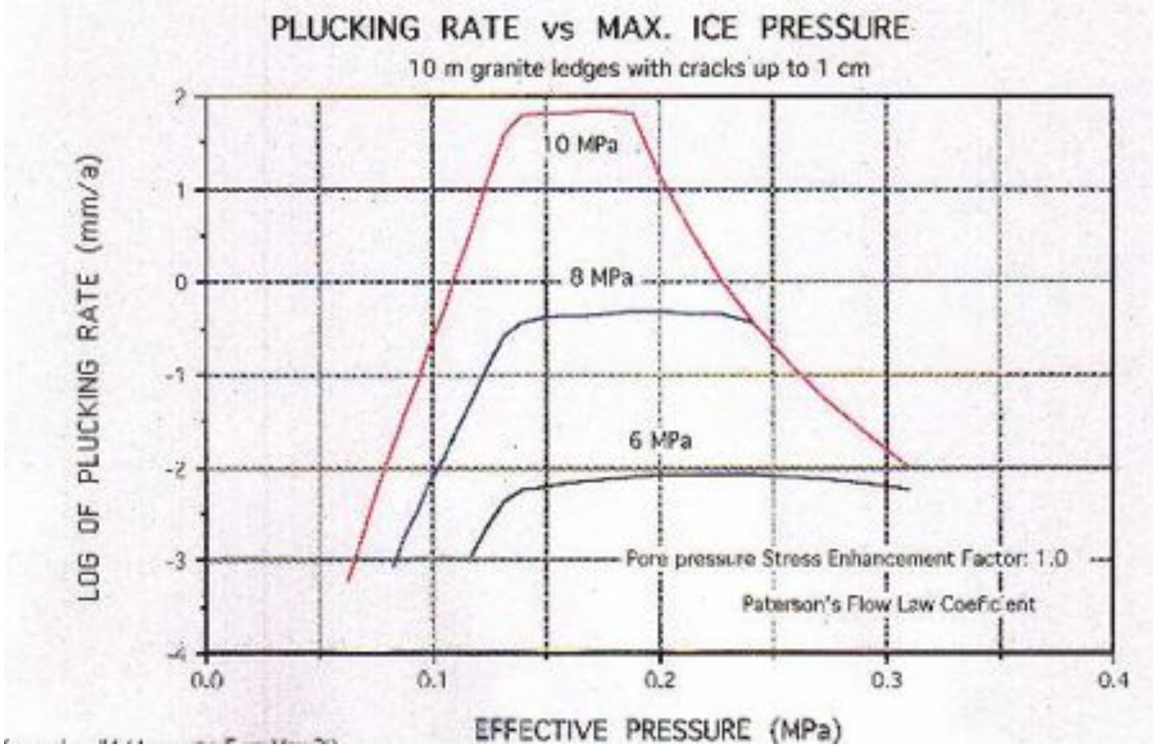
Idealization of glacier bed geometry in quarrying model (Hallet, 1996)

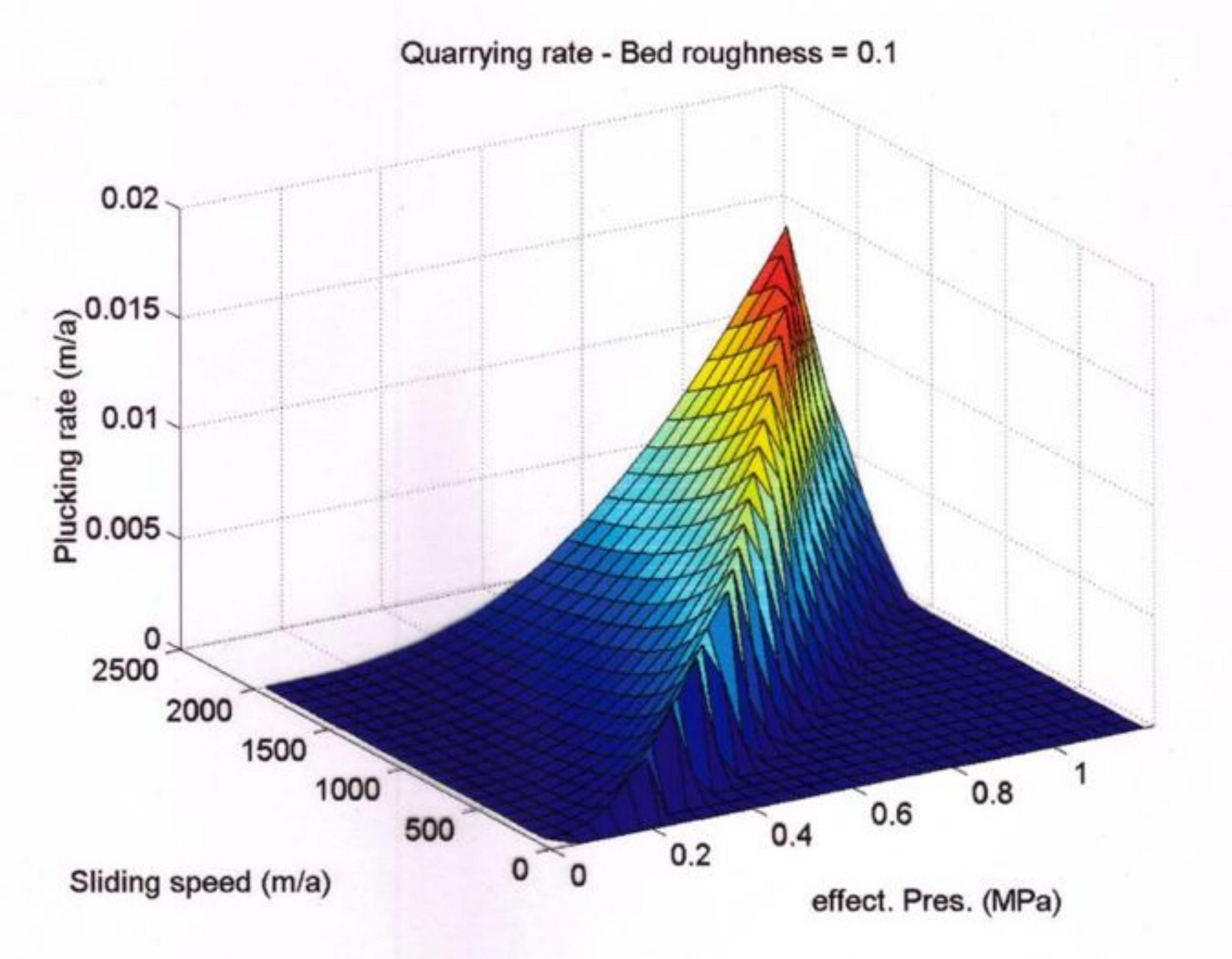
Quarrying model results

Left: ice pressure on ledge edges

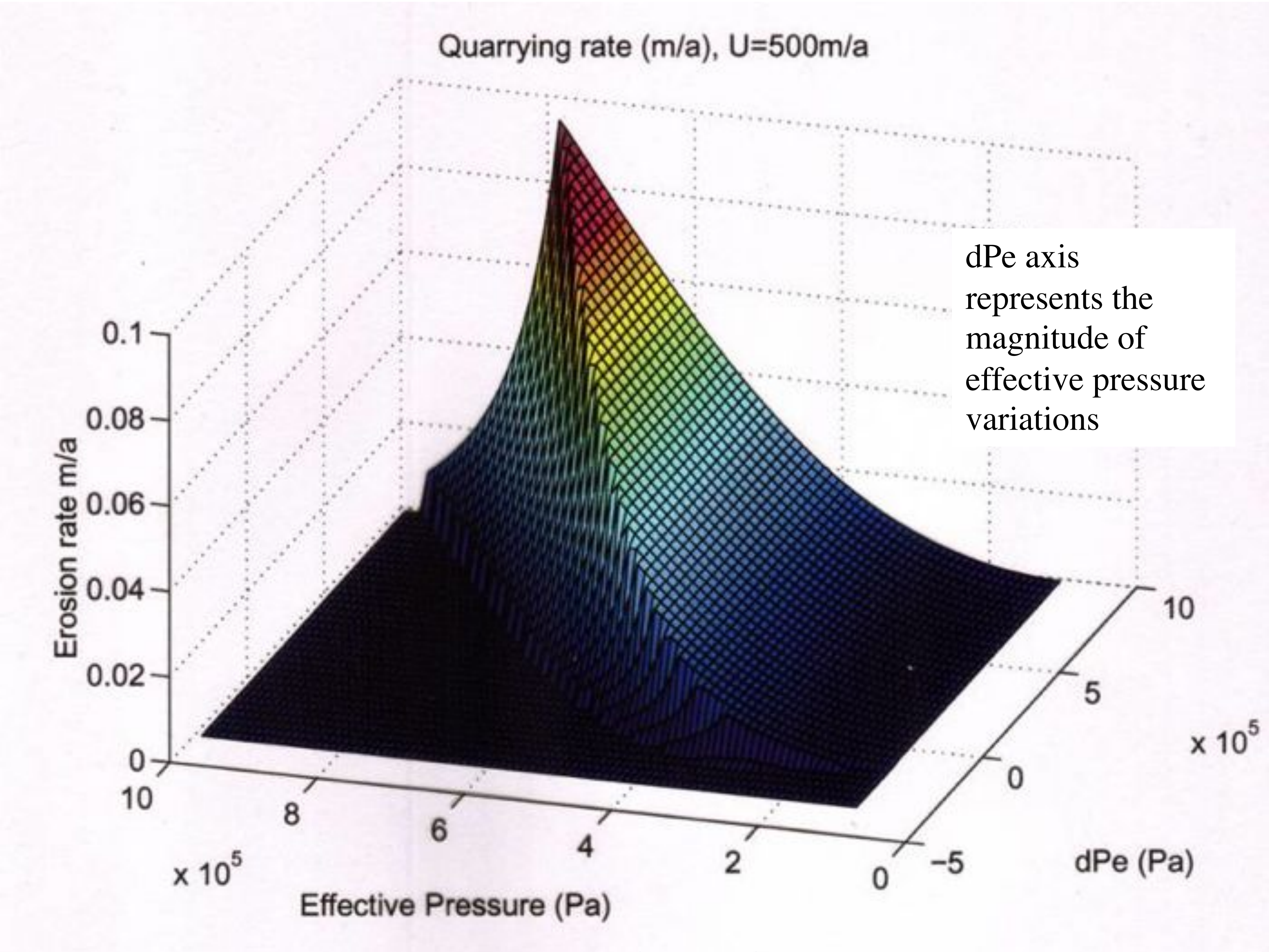
Below: calculated rate of quarrying (plucking)







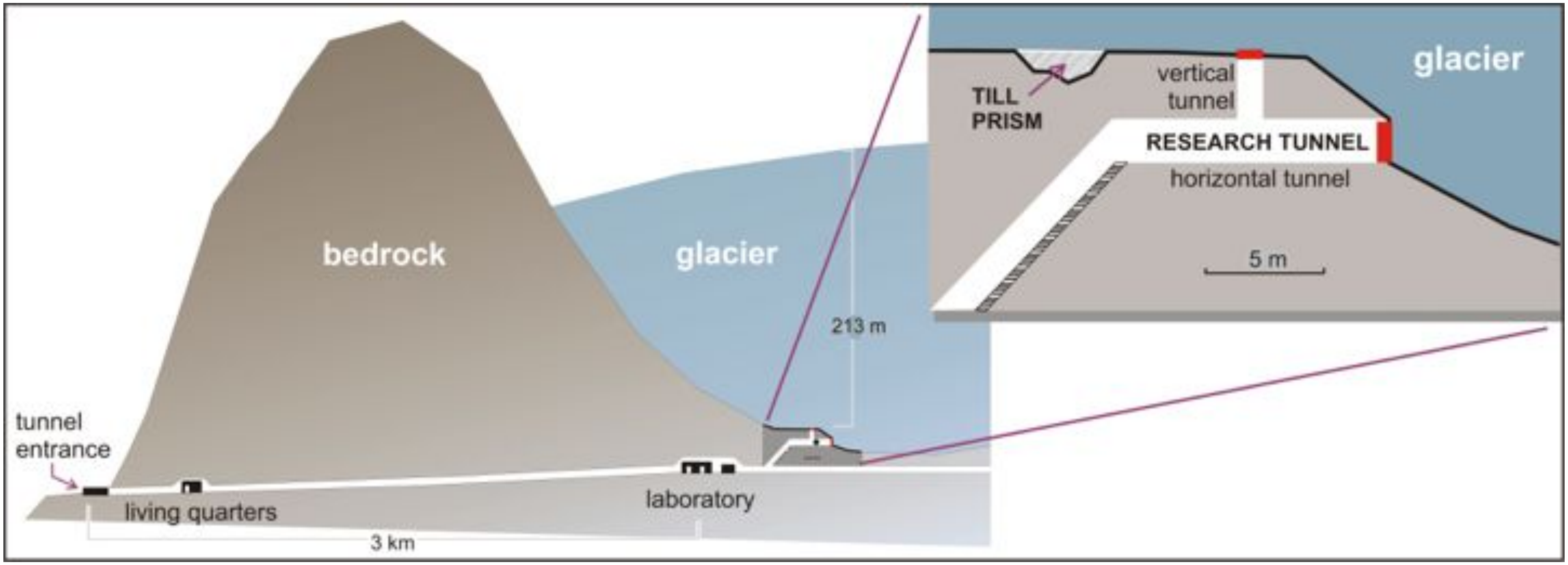
Quarrying model results from Yann Merrand



dPe axis represents the magnitude of effective pressure variations

Quarrying model results from Yann Merrand

Checking aspects of theory under glaciers



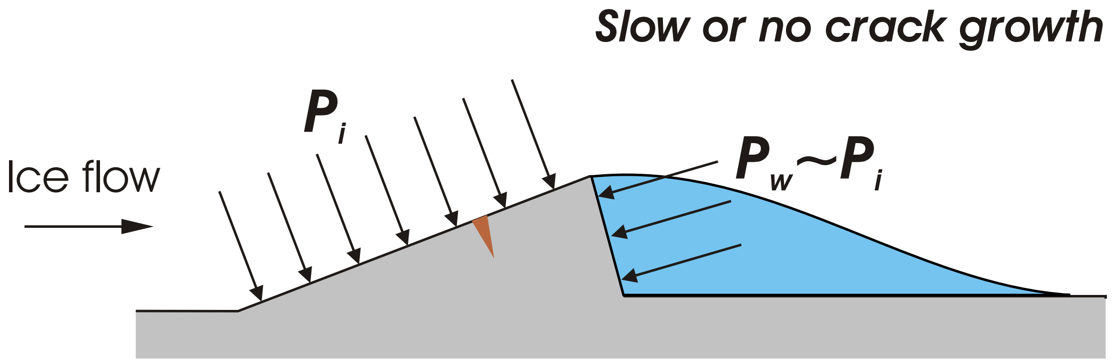
Under 210 m of ice at Engabreen, Norway

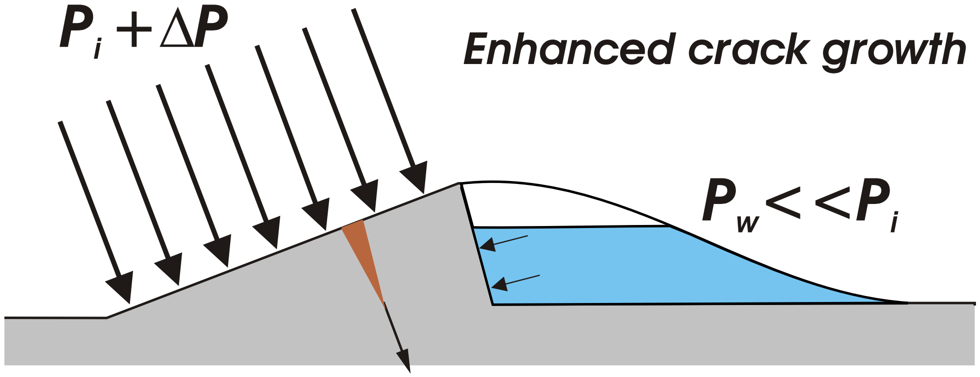
Sketch courtesy of Cohen and Iverson

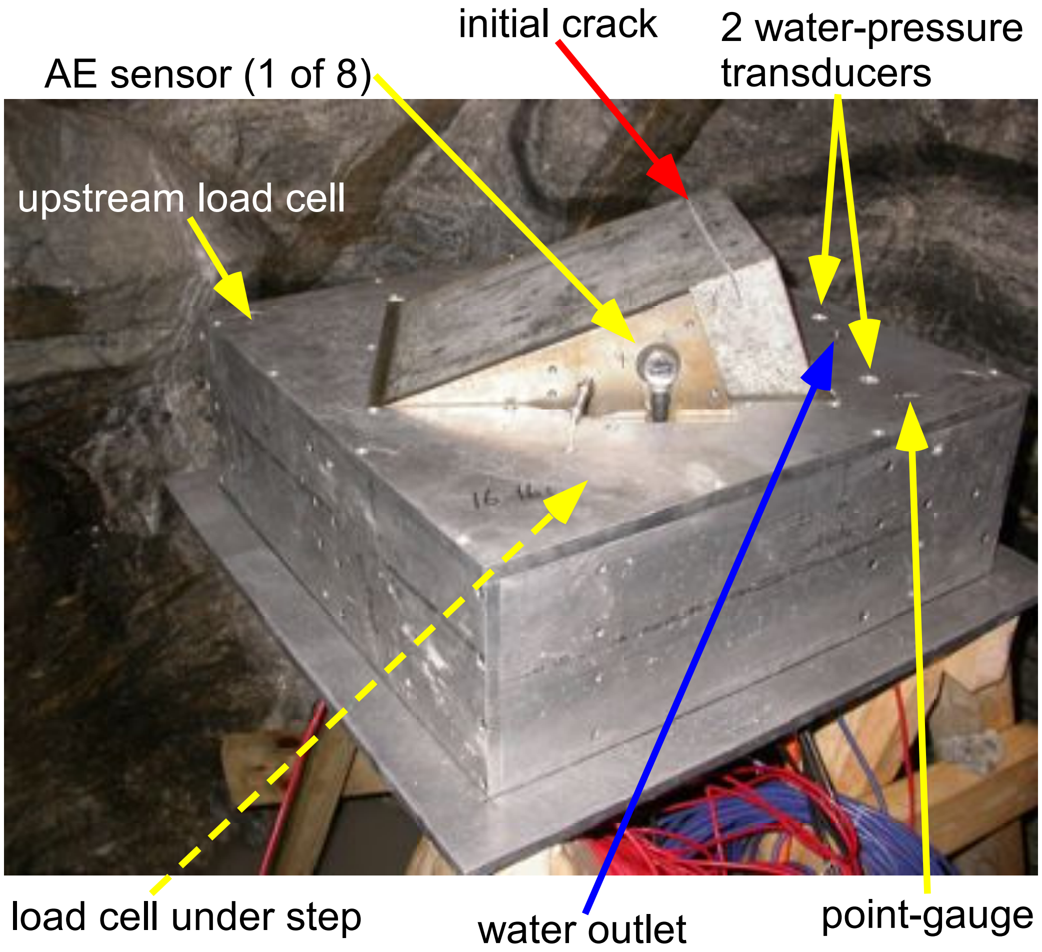
Field evidence for water pressure transients increasing rates of quarrying

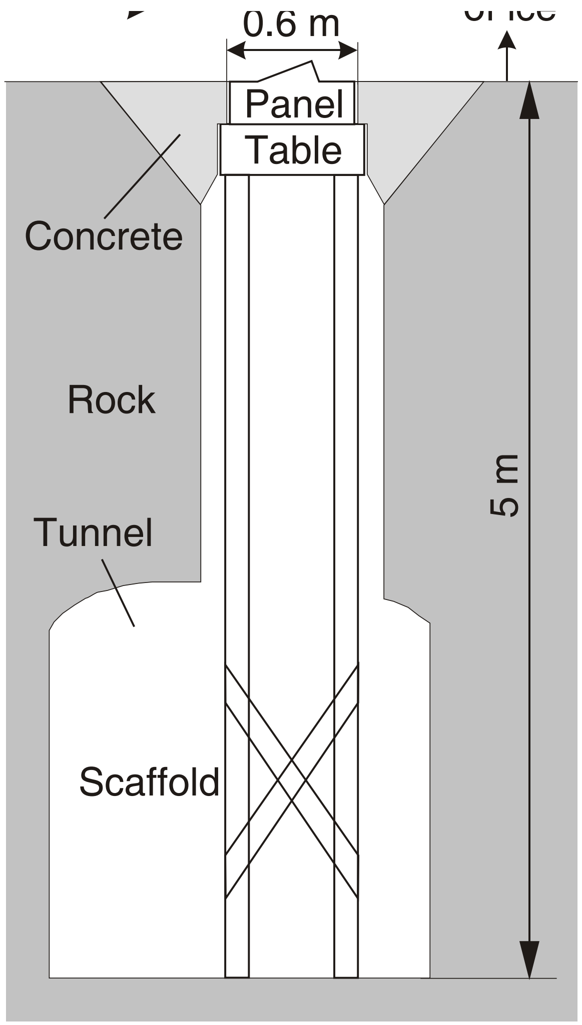
Cohen, D., T. S. Hooyer, N. R. Iverson, J. F. Thomason, and M. Jackson (2006), Role of transient water pressure in quarrying: A subglacial experiment using acoustic emissions, J. Geophys. Res., 111, F03006, doi:10.1029/2005JF000439.

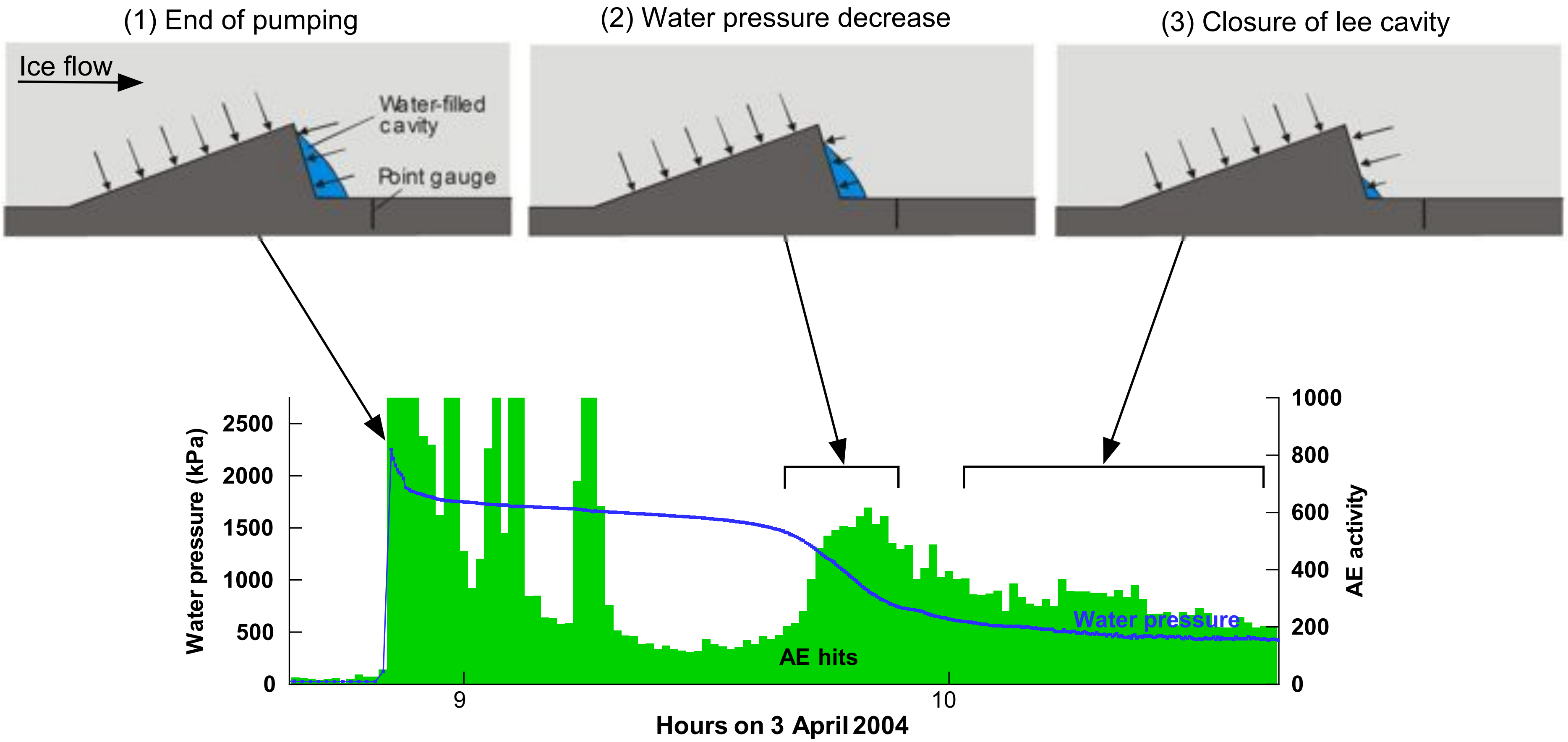
Hypothesis: decreasing water pressure promotes crack growth

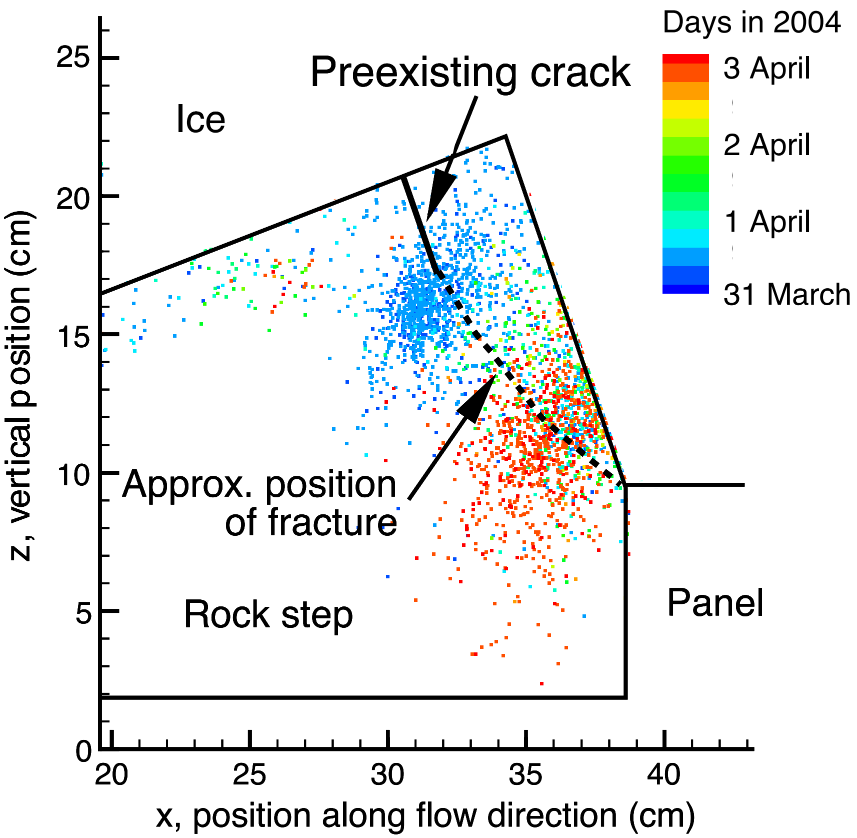


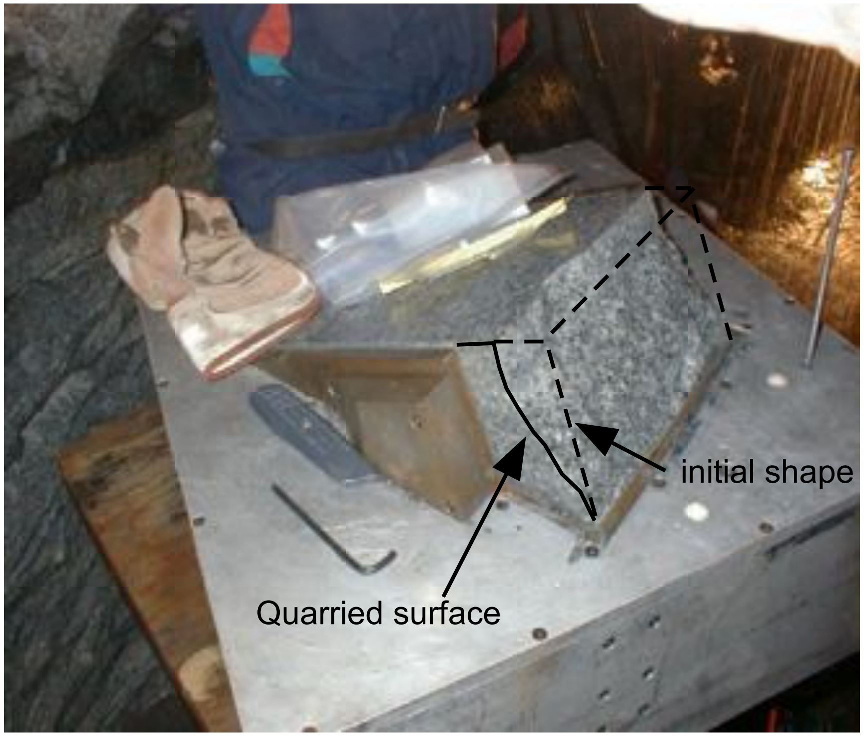



initial crack
AE sensor (1 of 8)
2 water-pressure transducers
upstream load cell
load cell under step
water outlet
point-gauge


0.6 m
Panel
Table
Concrete
Rock
Tunnel
Scaffold
5 m


(1) End of pumping
(2) Water pressure decrease
(3) Closure of lee cavity
Ice flow
Water-filled cavity
Point gauge
Water pressure (kPa)
2500
2000
1500
1000
500
0
AE activity
1000
800
600
400
200
0
9
10
Hours on 3 April 2004
AE hits
Water pressure


Days in 2004
3 April
2 April
1 April
31 March
Preexisting crack
Ice
Approx. position
of fracture
Rock step
Panel
z, vertical position (cm)
x, position along flow direction (cm)
0
5
10
15
20
25
20
25
30
35
40


initial shape
Quarried surface

Cohen and Iverson's Conclusions

- Pre-existing crack in bedrock step grew in response to water-pressure fluctuations
- Rates of crack growth measured using acoustic emissions were highest during periods of decreasing water pressure (increasing effective pressure)
- Water pressure transients may be associated with periods of high water pressure during which water cavities are largest and sliding speed is high. This may explain why rates of erosion have been observed to depend on sliding speed.
- Ultimately, rates of quarrying may depend on the magnitude and frequency of stress changes on the bed caused by water pressure fluctuations

Looking upglacier at striated bedrock, Tyndall Glacier.

Note sharp fractures and missing blocks

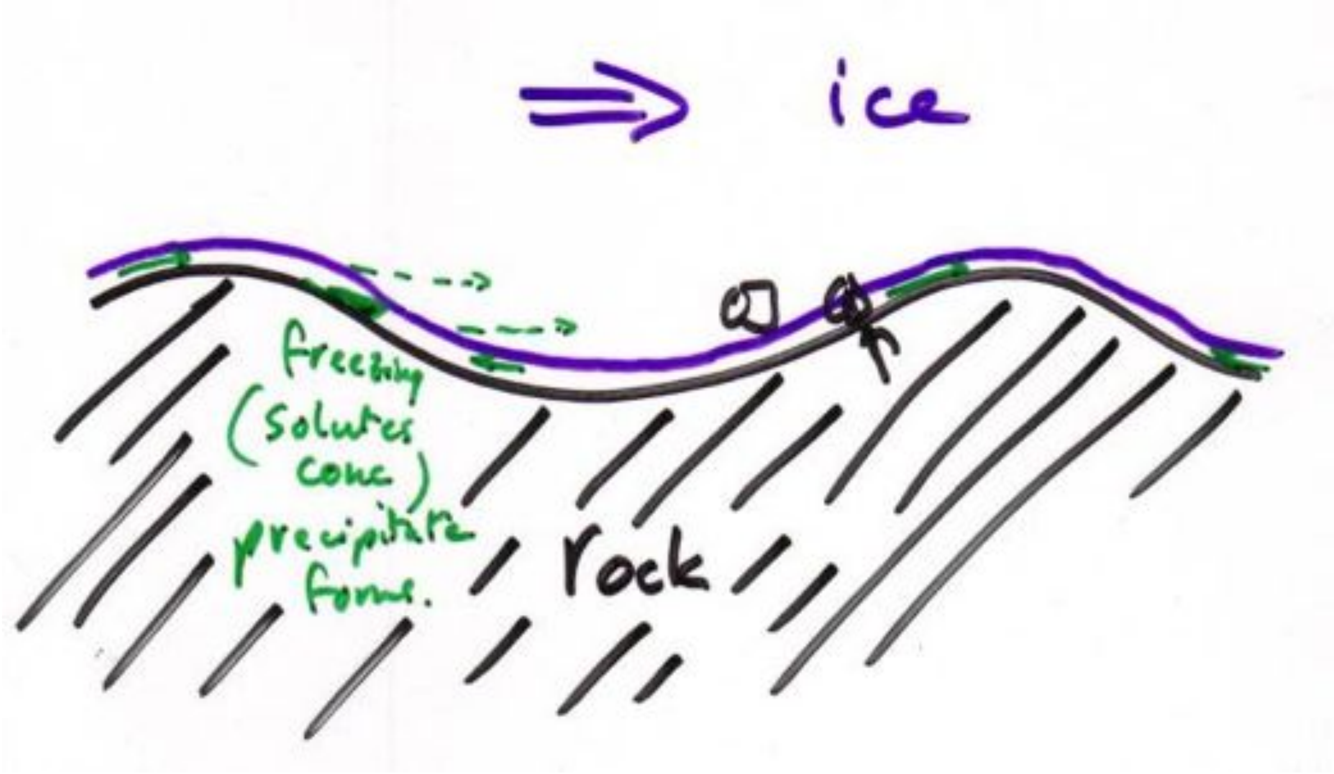
ttp://www.swisseduc.ch/glaciers/alps/rhonegletscher/gletscherschliffe_2007-en.html?id=0

Deeply striated stoss surface

http://www.swisseduc.ch/glaciers/alps/rhonegletscher/gletscherschliffe_2007-en.html?id=2

Sliding physics (regelation) & suglacial chemical processes

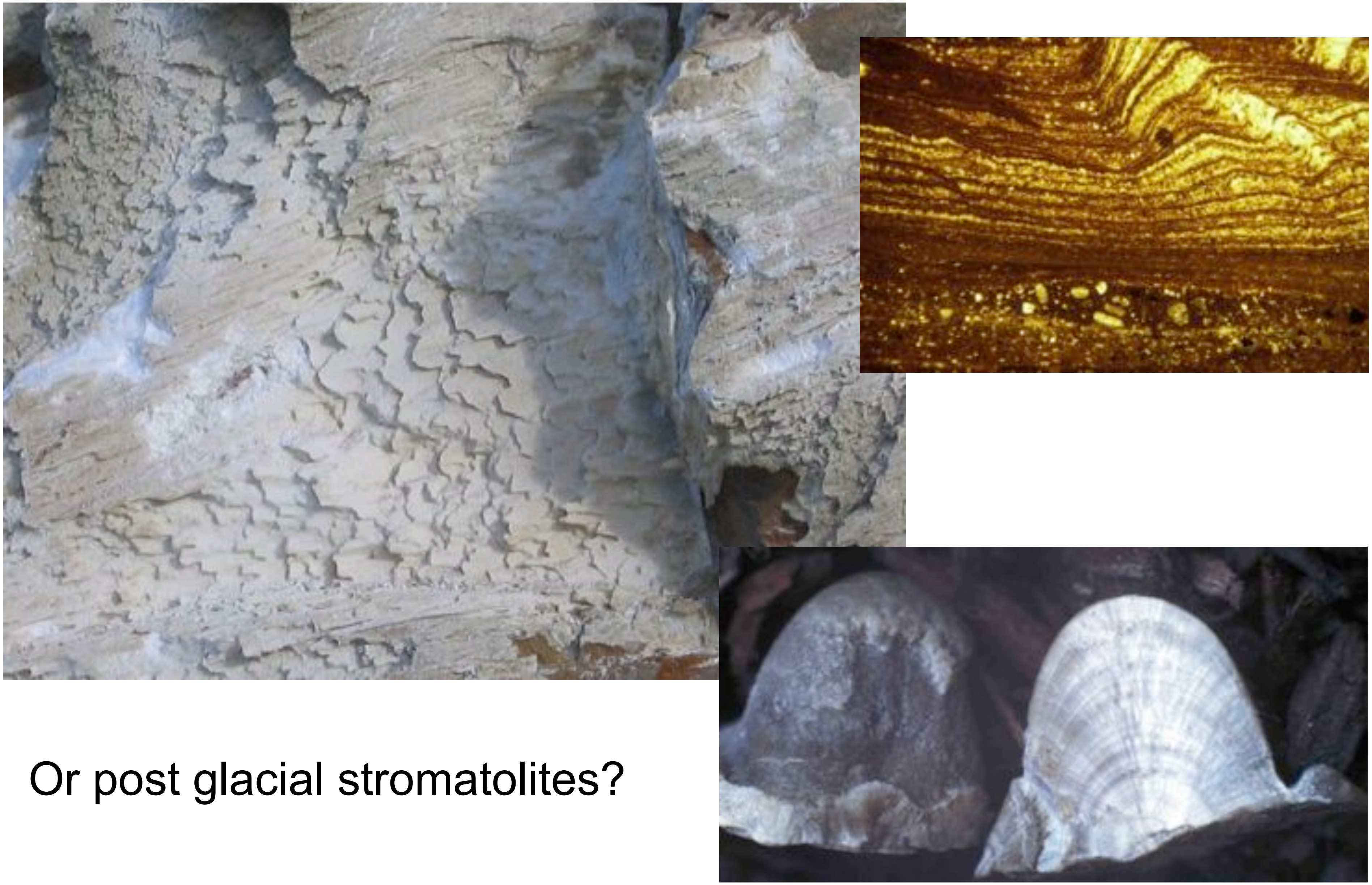
Sliding over small bumps is dominated by regelation, which involves melting/freezing, and water flow in thin basal film. Solutes that are rejected during the freezing process can exceed saturation, causing chemical precipitation.



Calcium carbonate spicules point in ice flow direction, reflecting intimate regelation ice/rock contact, Tsanfleuron Glacier, Swiss Alps.

Subglacial carbonate precipitates

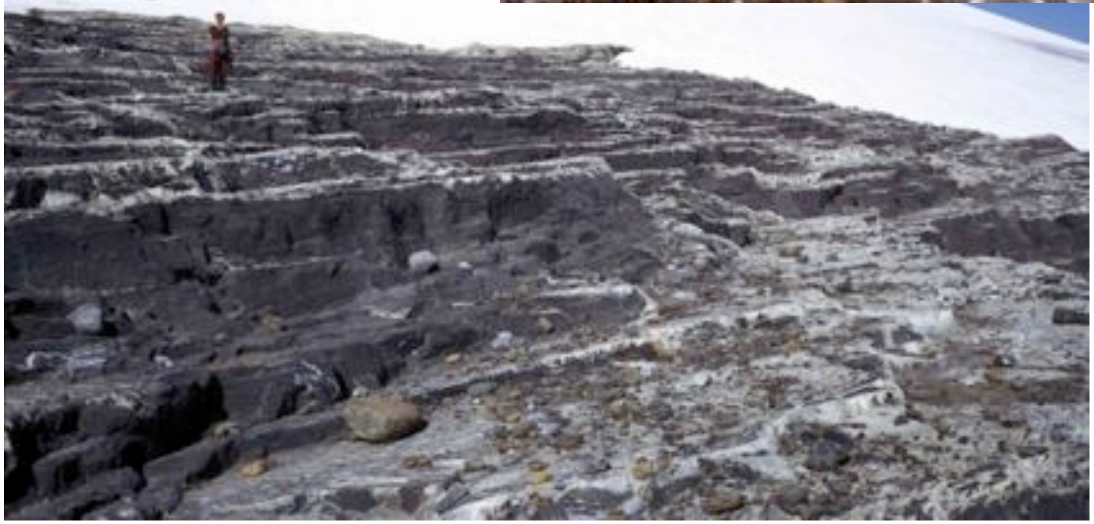
Tierra del Fuego, from J. Rebassa



Or post glacial stromatolites?

Proglacial area at Blackfoot Glacier, Montana, that was deglaciated decades ago, looking downglacier

Blackfoot (Montana) & Castleguard (Alberta) Glaciers



Former subglacial cavity systems criss-cross white domains, color coded with precipitates that reflect intimate contact between ice and rock.

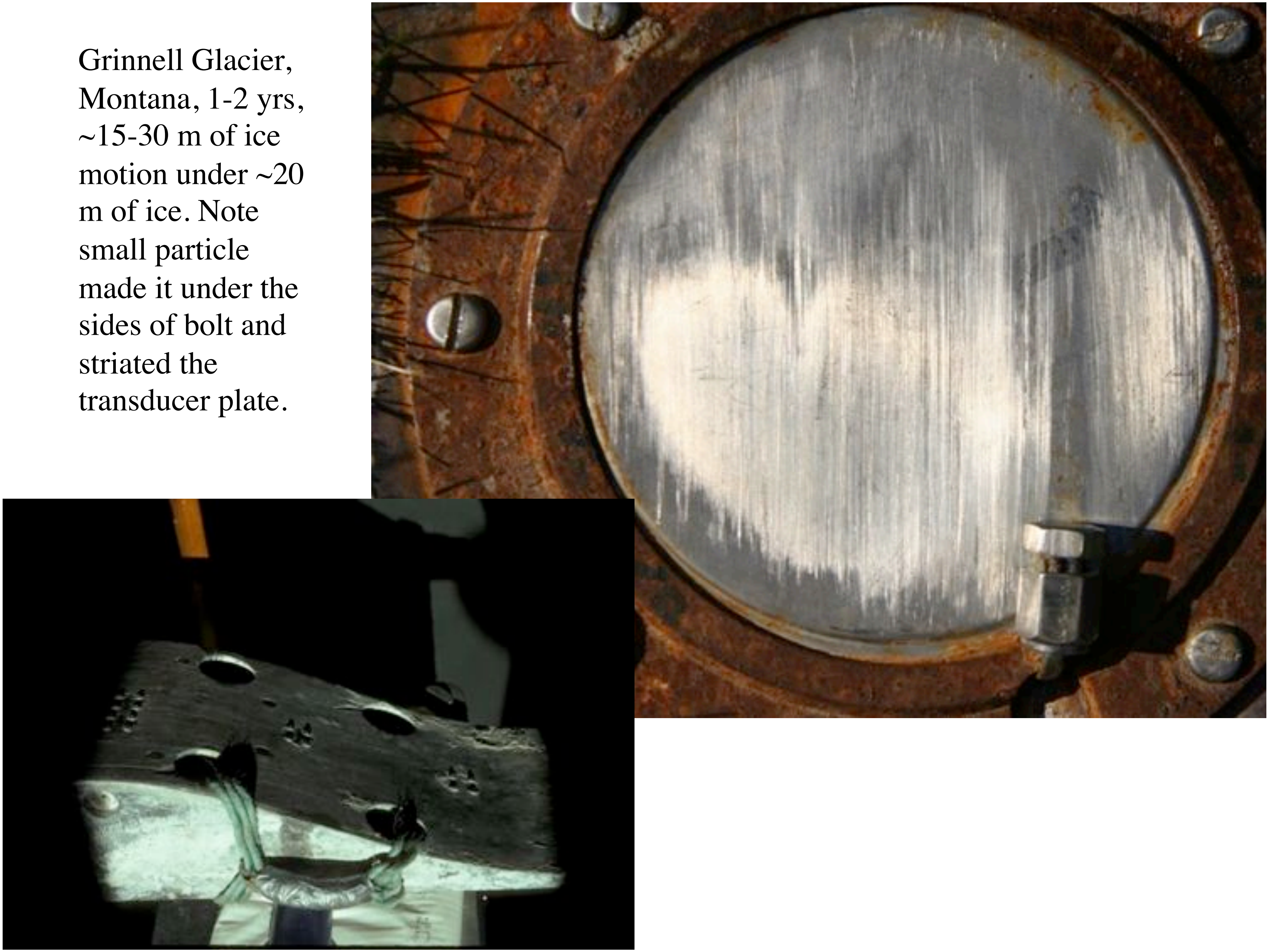
Looking under glaciers

Grinnell Glacier

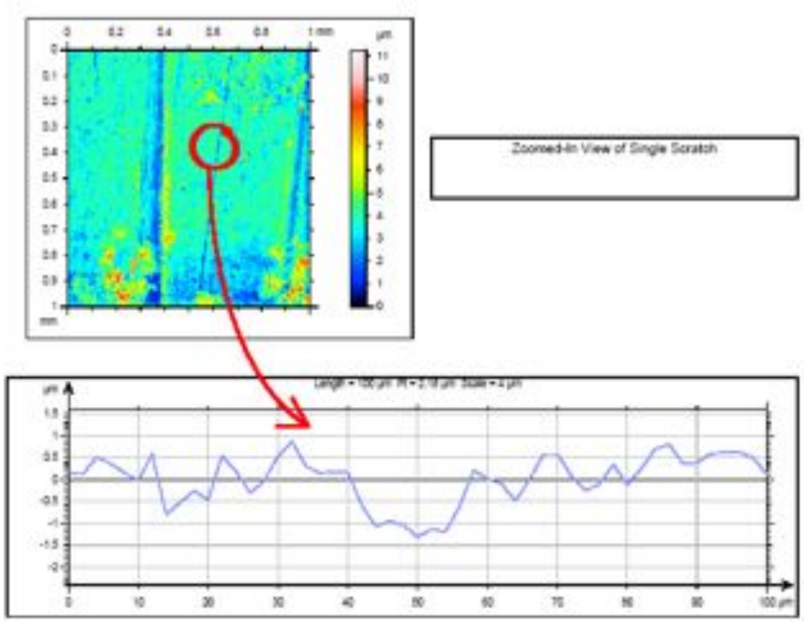
2002
courtesy F. Ng

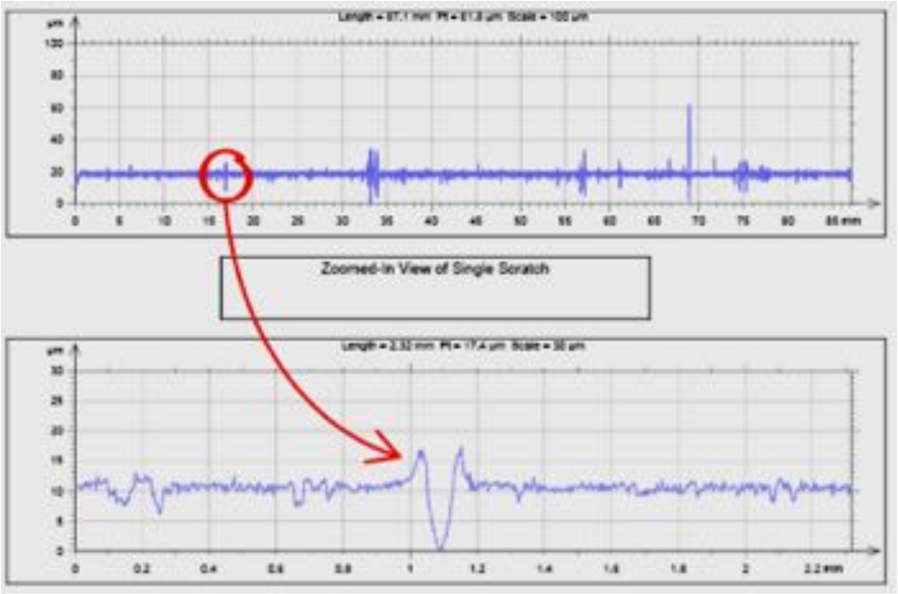
Work in subglacial cavities in early 1980s

Grinnell Glacier, Montana, 1-2 yrs, ~15-30 m of ice motion under ~20 m of ice. Note small particle made it under the sides of bolt and striated the transducer plate.

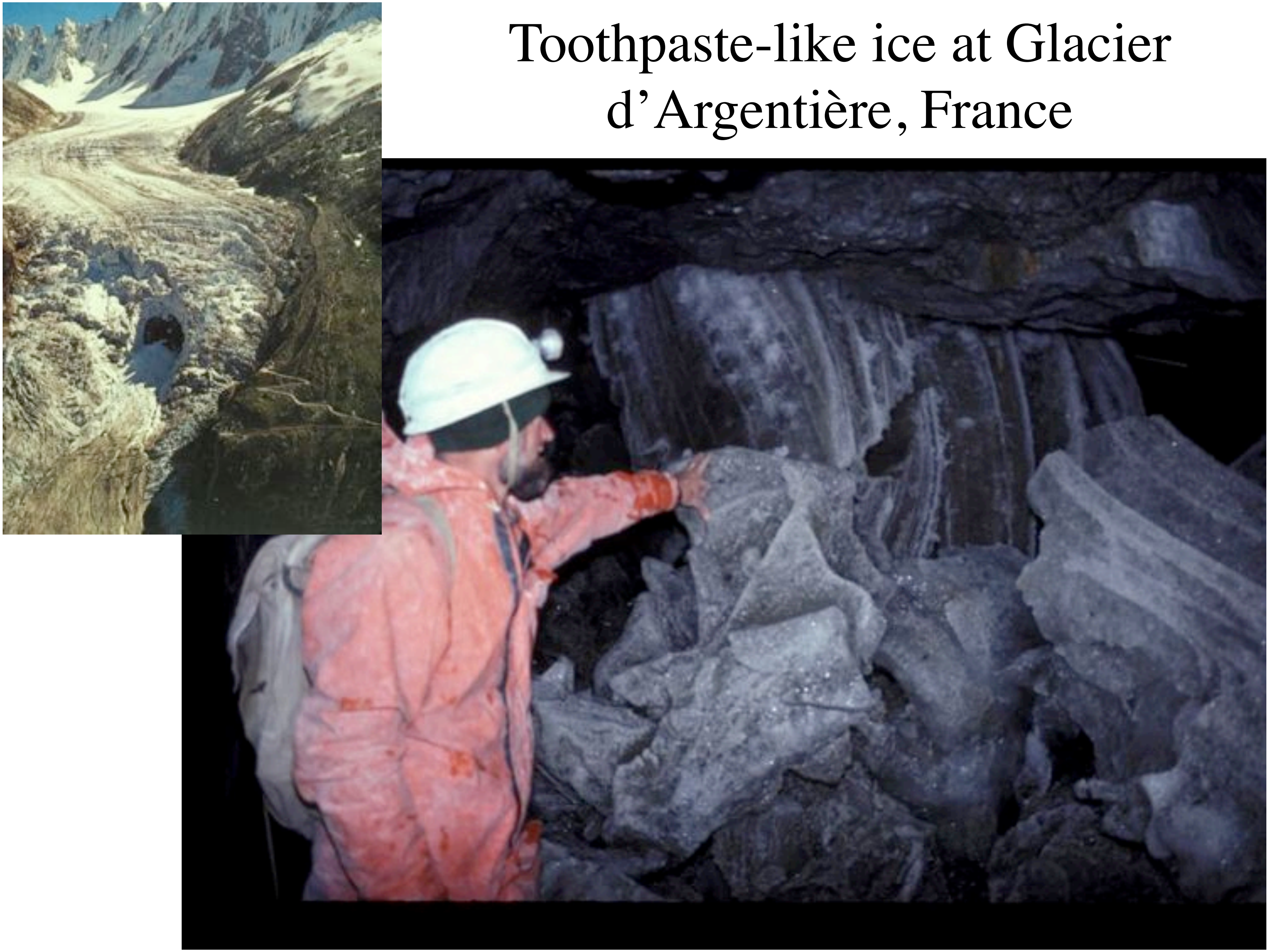


Laser profile of striation in stainless steel



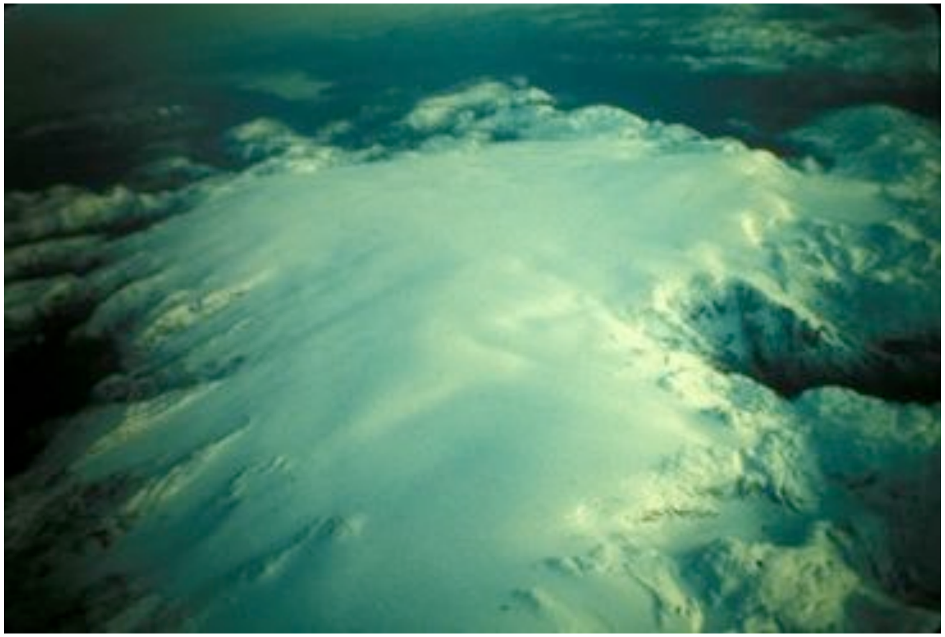


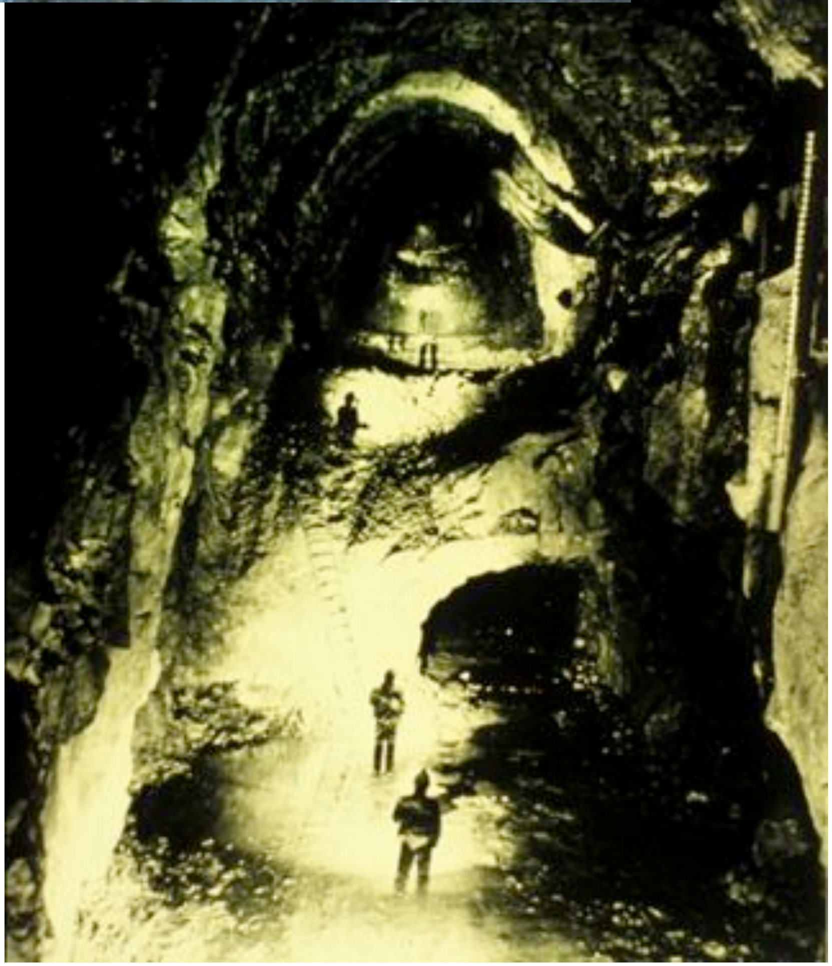
Toothpaste-like ice at Glacier d’Argentière, France



Big boulder in subglacial stream, Argentiere

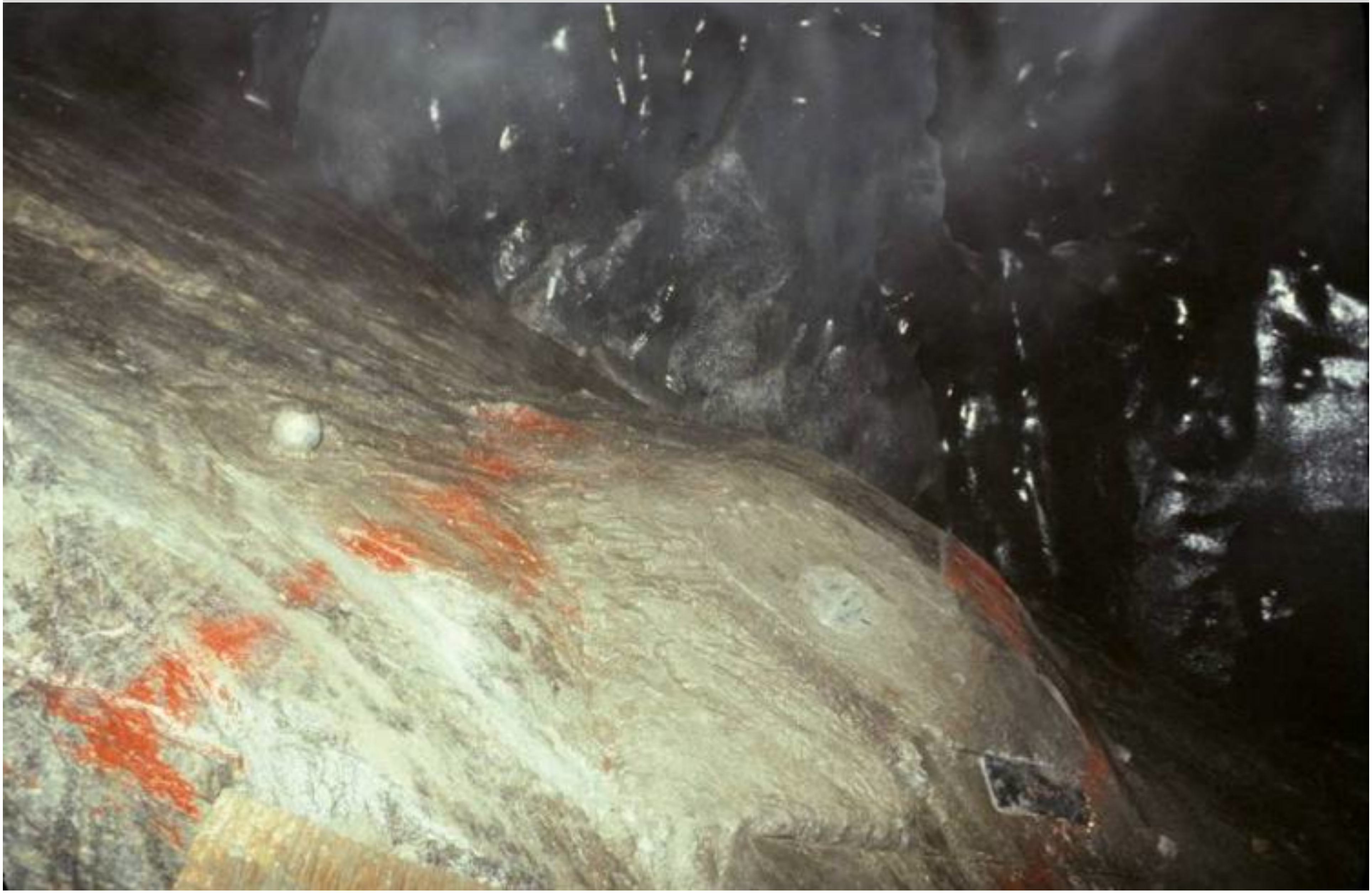
Bondhusbreen, S. Norway



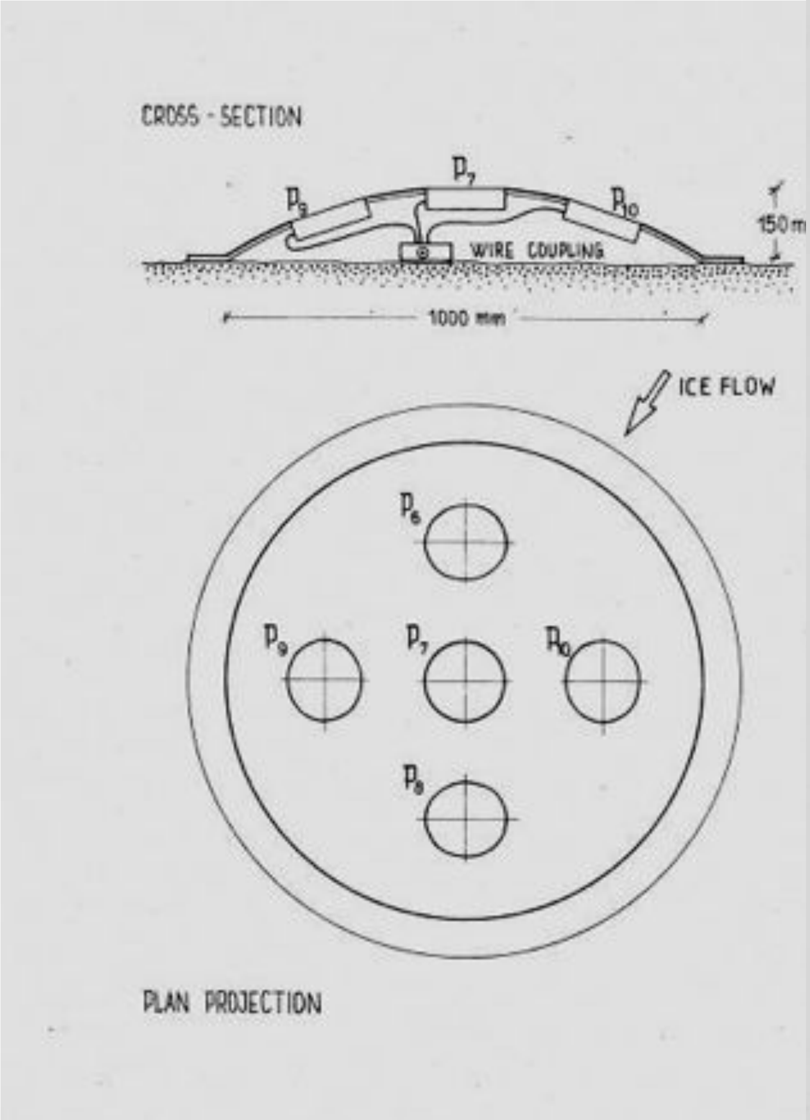


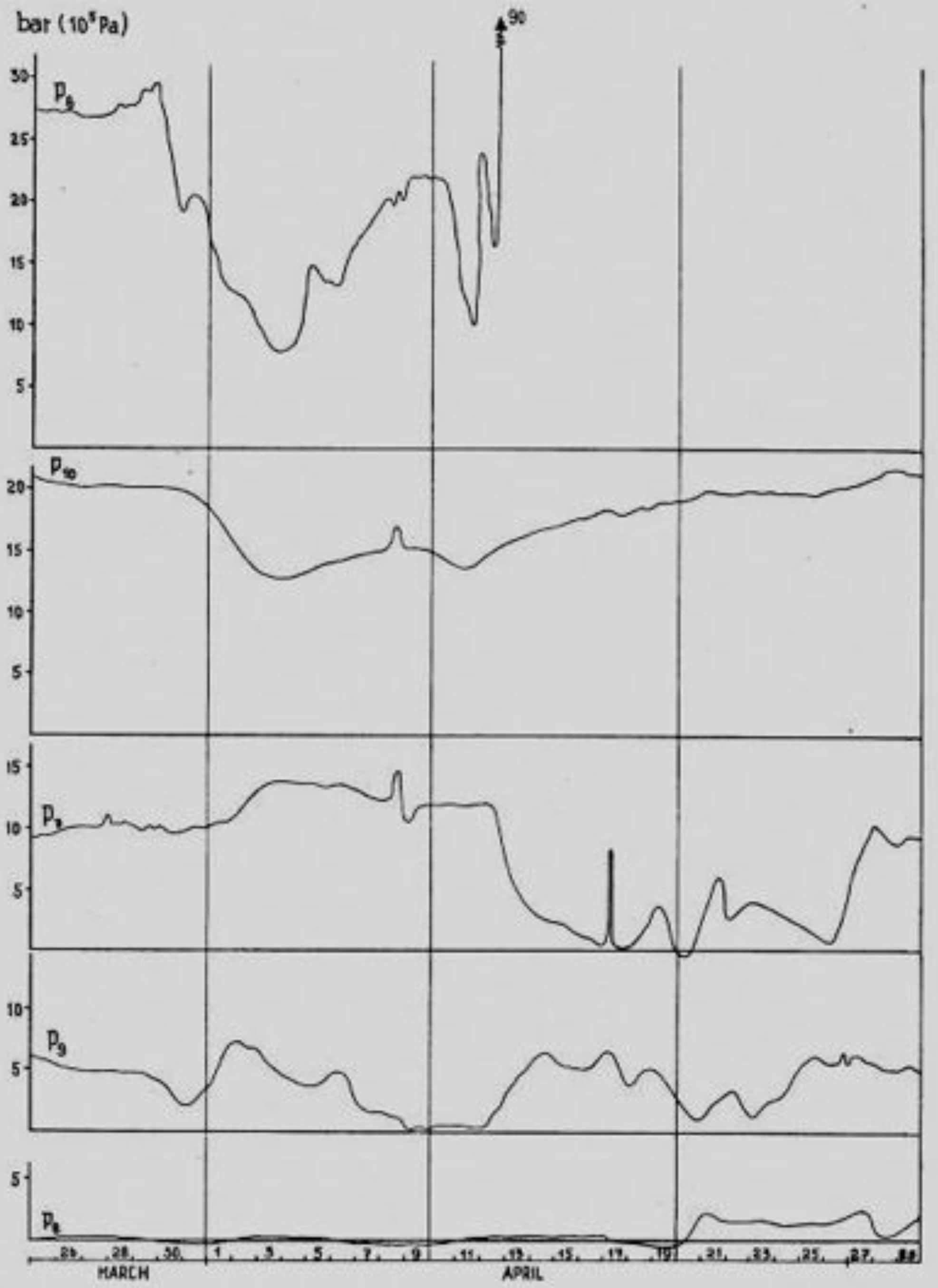
Subglacial sediment trap
emptied annually

500 ft-thick, clean ice sliding over bare bedrock, Bondhusbreen

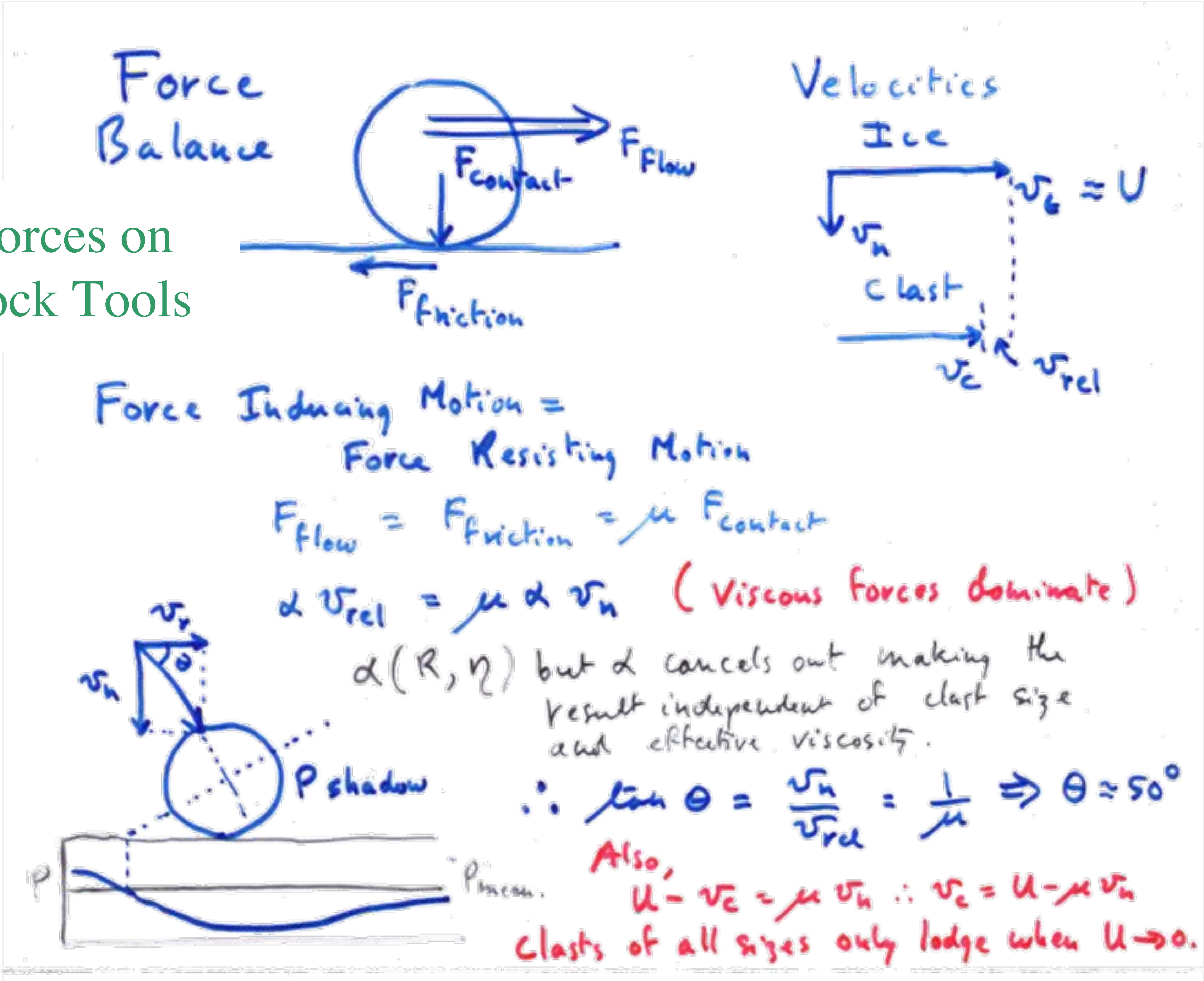


Ice sliding over bed bump under 150-200m of ice at Bondhusbreen, Norway





Forces on Rock Tools



Force Inducing Motion = Force Resisting Motion

$$F_{flow} = F_{friction} = \mu F_{contact}$$

$$\alpha v_{rel} = \mu \alpha v_n$$ (Viscous forces dominate)

$\alpha(R, \eta)$ but α cancels out making the result independent of clast size and effective viscosity.

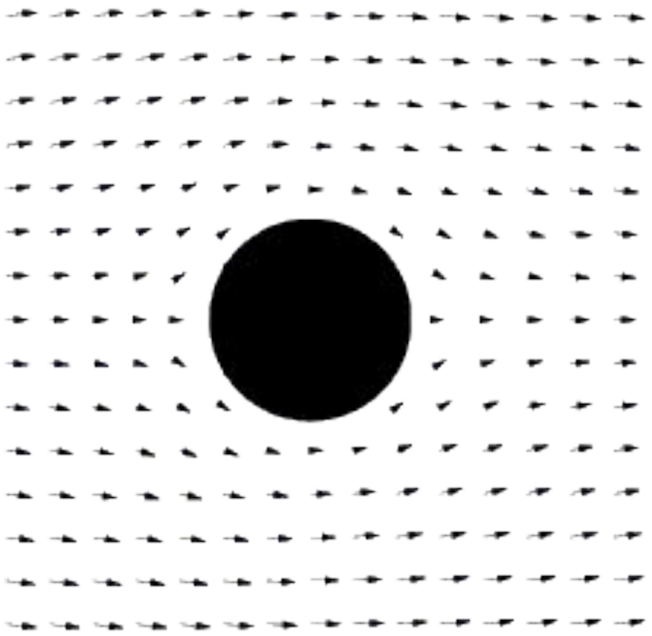
$$\therefore \tan\theta = \frac{v_n}{v_{rel}} = \frac{1}{\mu} \Rightarrow \theta \approx 50^\circ$$

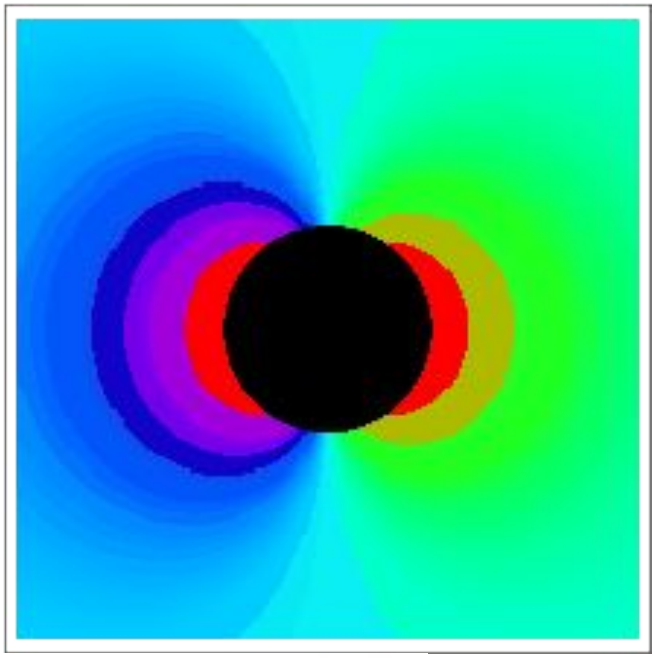
Also,

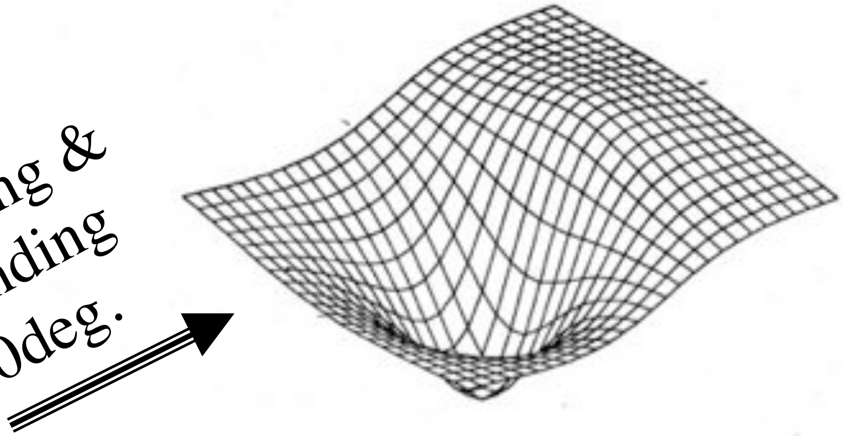
$$U - v_c = \mu v_n \therefore v_c = U - \mu v_n$$

Clasts of all sizes only lodge when $U \to 0$.

Pressure field around boulder


Fluid Velocity


Pressure


Ice sliding &
Descending
at ~50deg.

Checking aspects of the abrasion model

Journal of Glaciology

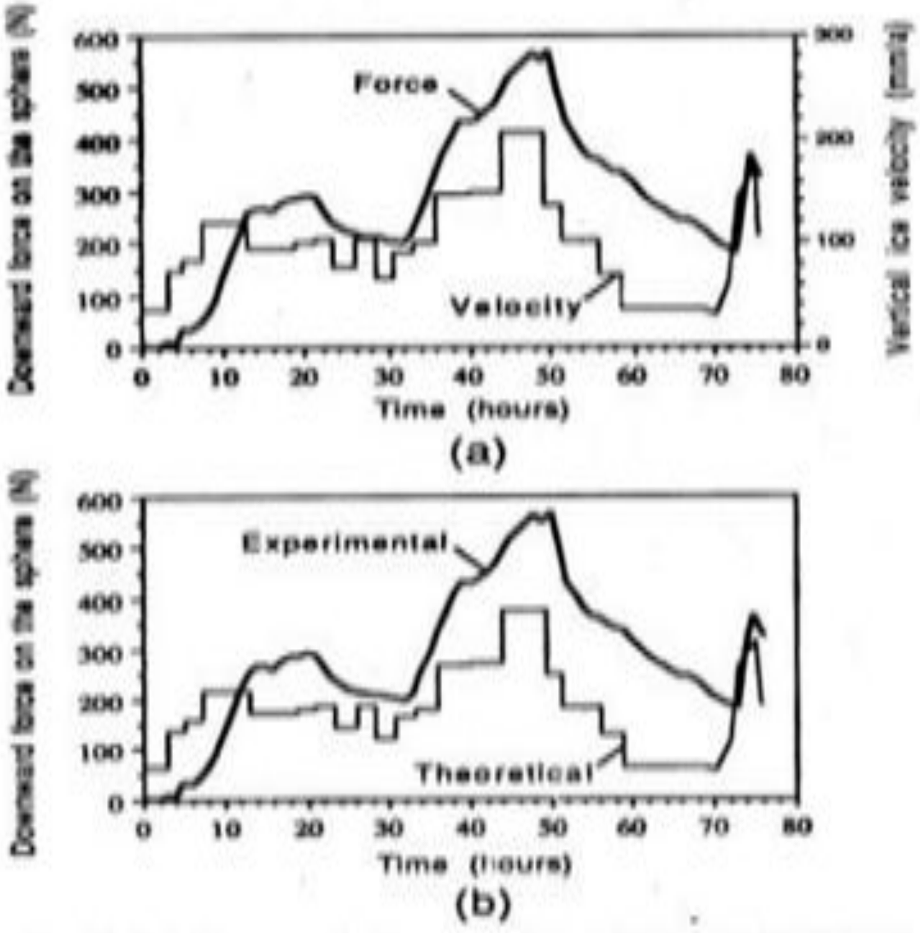
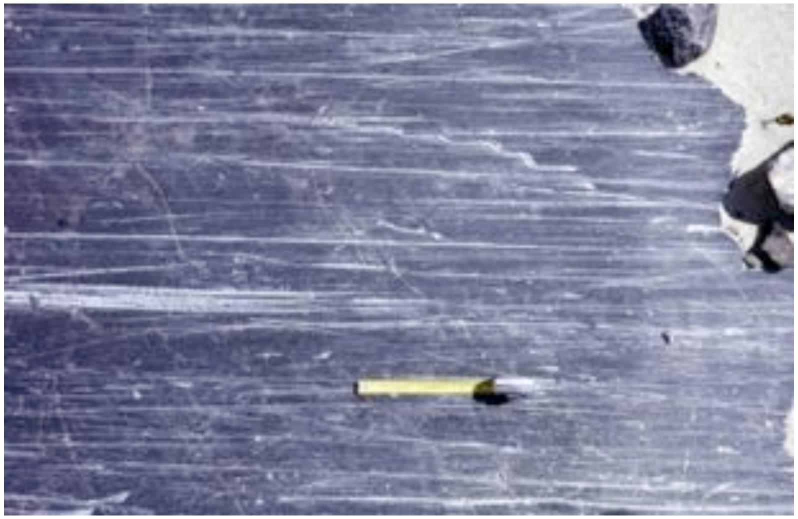


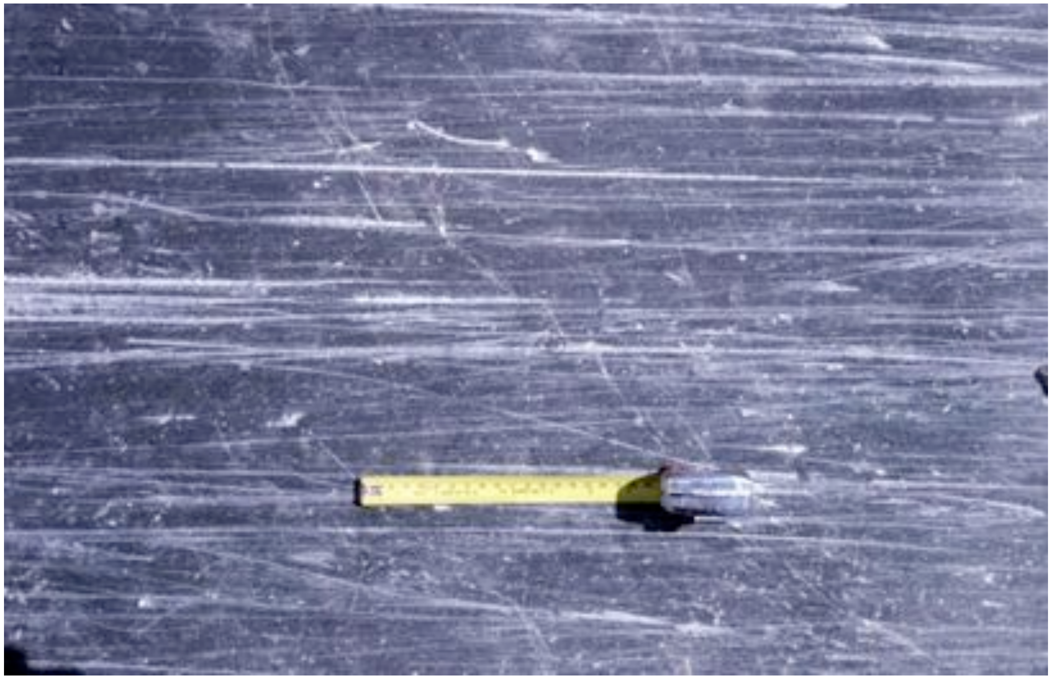
Fig. 8. (a) Downward force on the sphere and downward vertical ice velocity during experiment S1. (b) Downward force on the sphere and the theoretical drag force that was calculated with the vertical ice velocity using $\eta = 0.1$ MPa a.

From N. Iverson

Left: Heavily abraded (lighter color) stoss surface; erratic, scattered scratches on lee side suggest cavity collapse

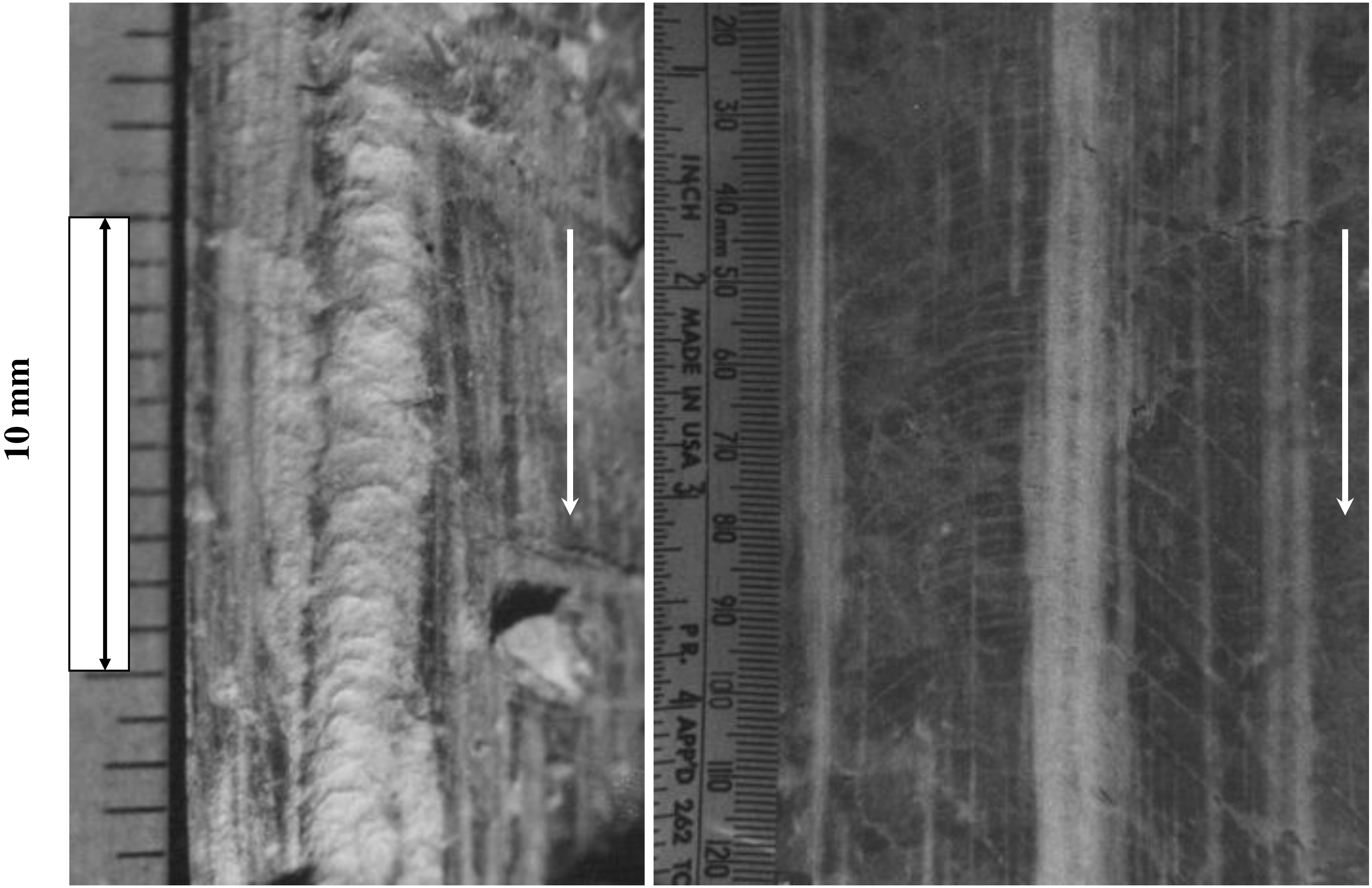
Below: striae are parallel, consistent with scattered rocks entrained in linear ice motion; exceptional jog (lower left) suggest rock moving past one another



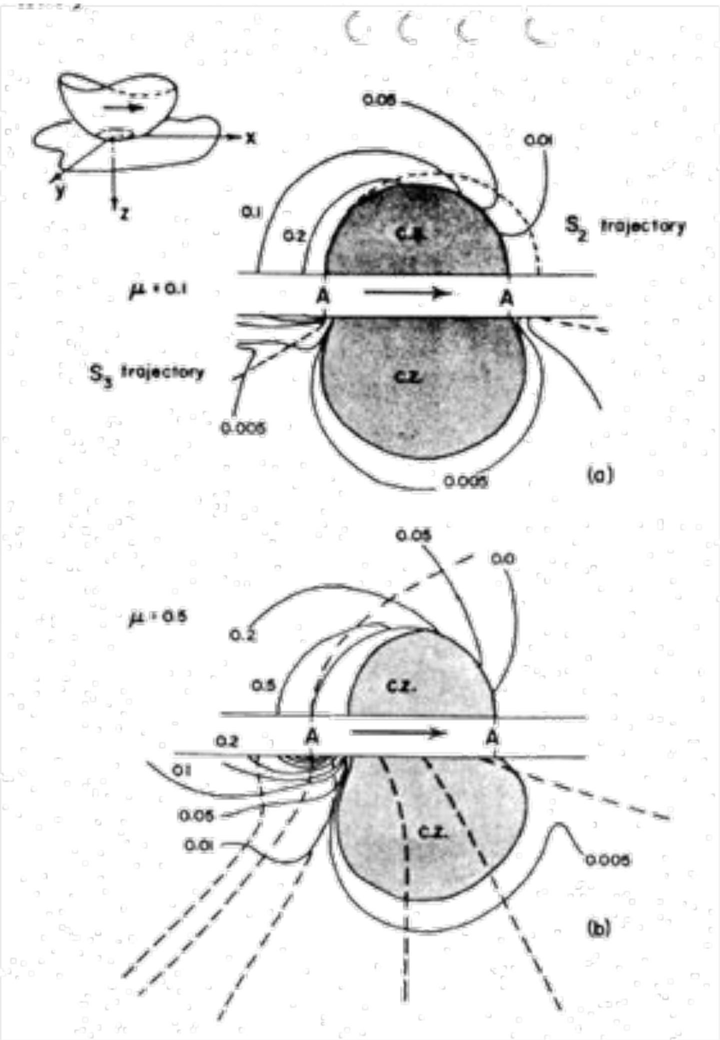


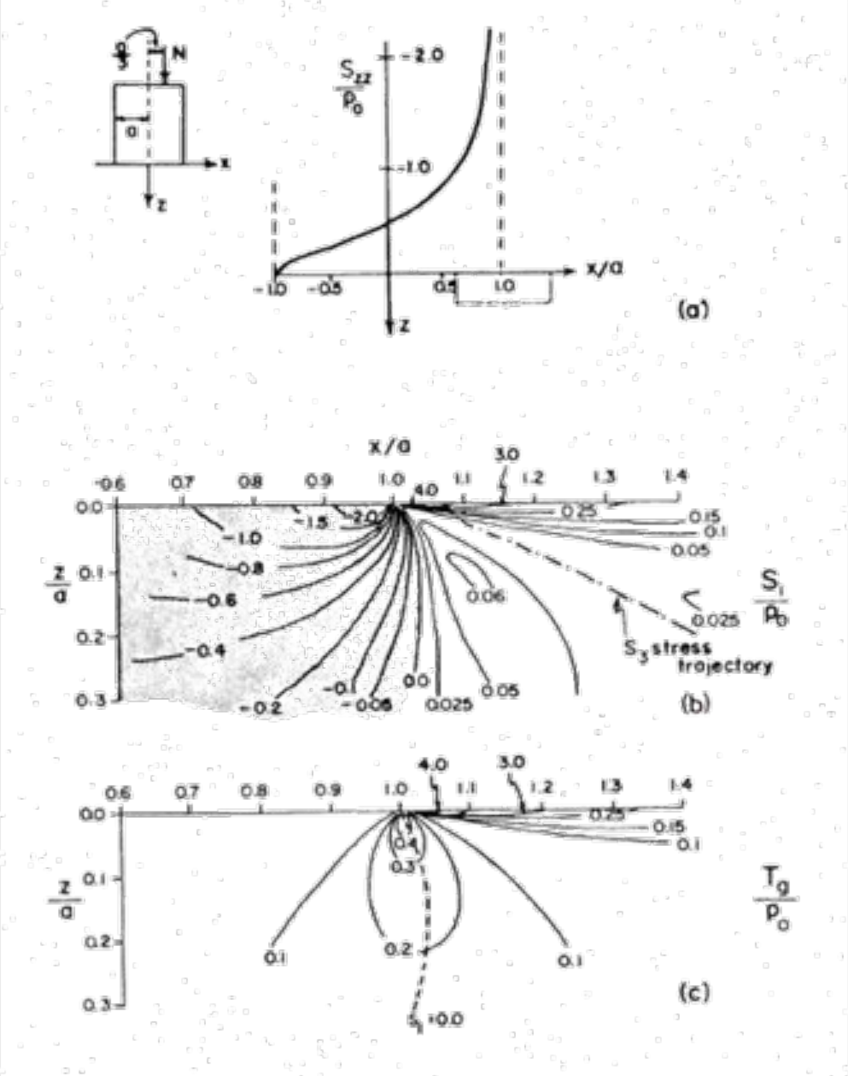
Ice is surprisingly fluid…and yet it can press rock fragment with sufficient force to scratch the rock

Products of erosion from mm-scale striations to glacial valleys ~100 km long



Chatter marks, arcuate cracks & lunate fractures: Sliding indentors





Rotating blocks

From B. Johnson dissertation, 1975

Chatter marks, arcuate cracks & lunate fractures

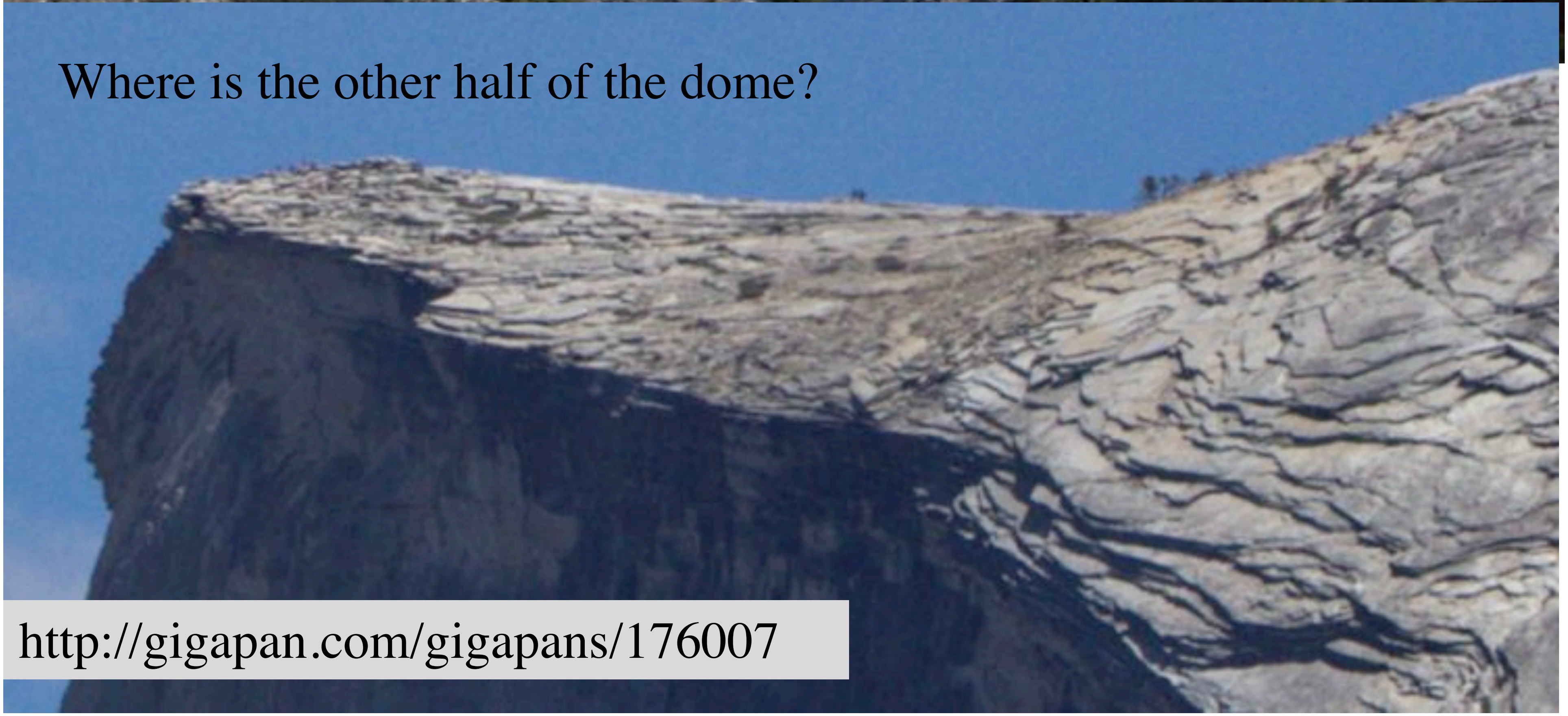
Lunate Fractures

Remaining challenges

What does this research on quarrying tell about erosion of real bedrock terrain (rock masses with pervassive joints and fractures)?

How can we validate and test erosion models?

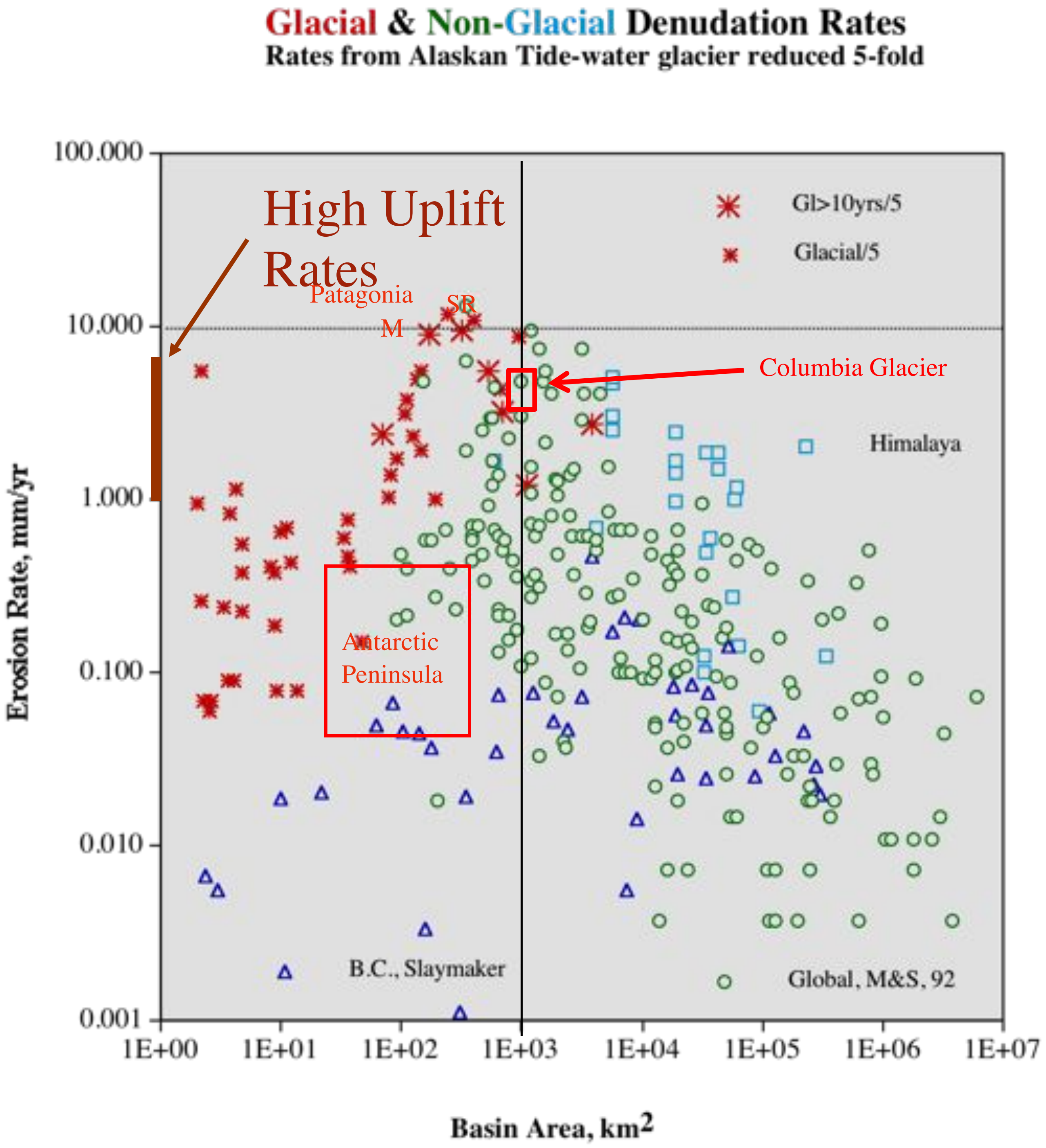
How about the rates of erosion?



Where is the other half of the dome?

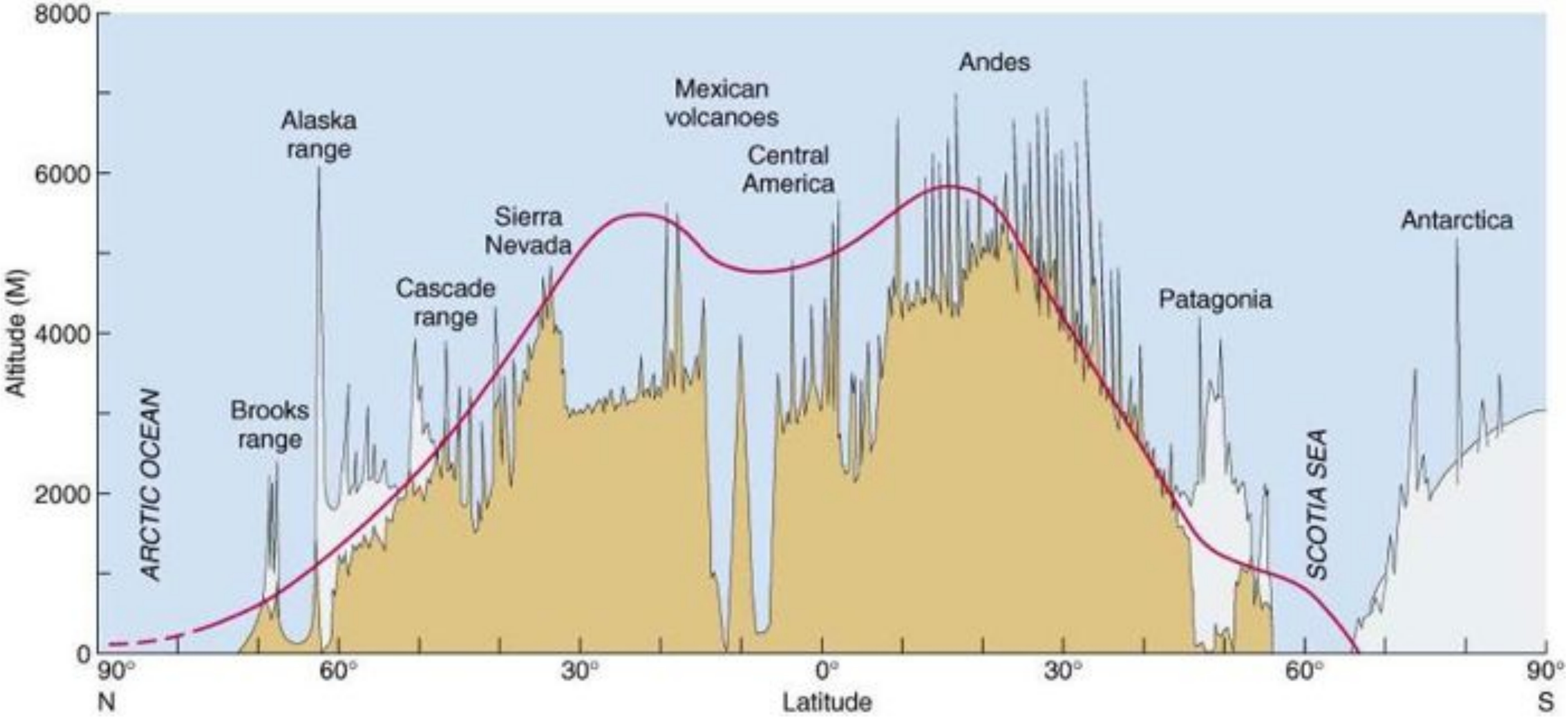
http://gigapan.com/gigapans/176007

Global erosion **rates**



High Uplift Rates

Glacial Buzz saw



S.C. Porter

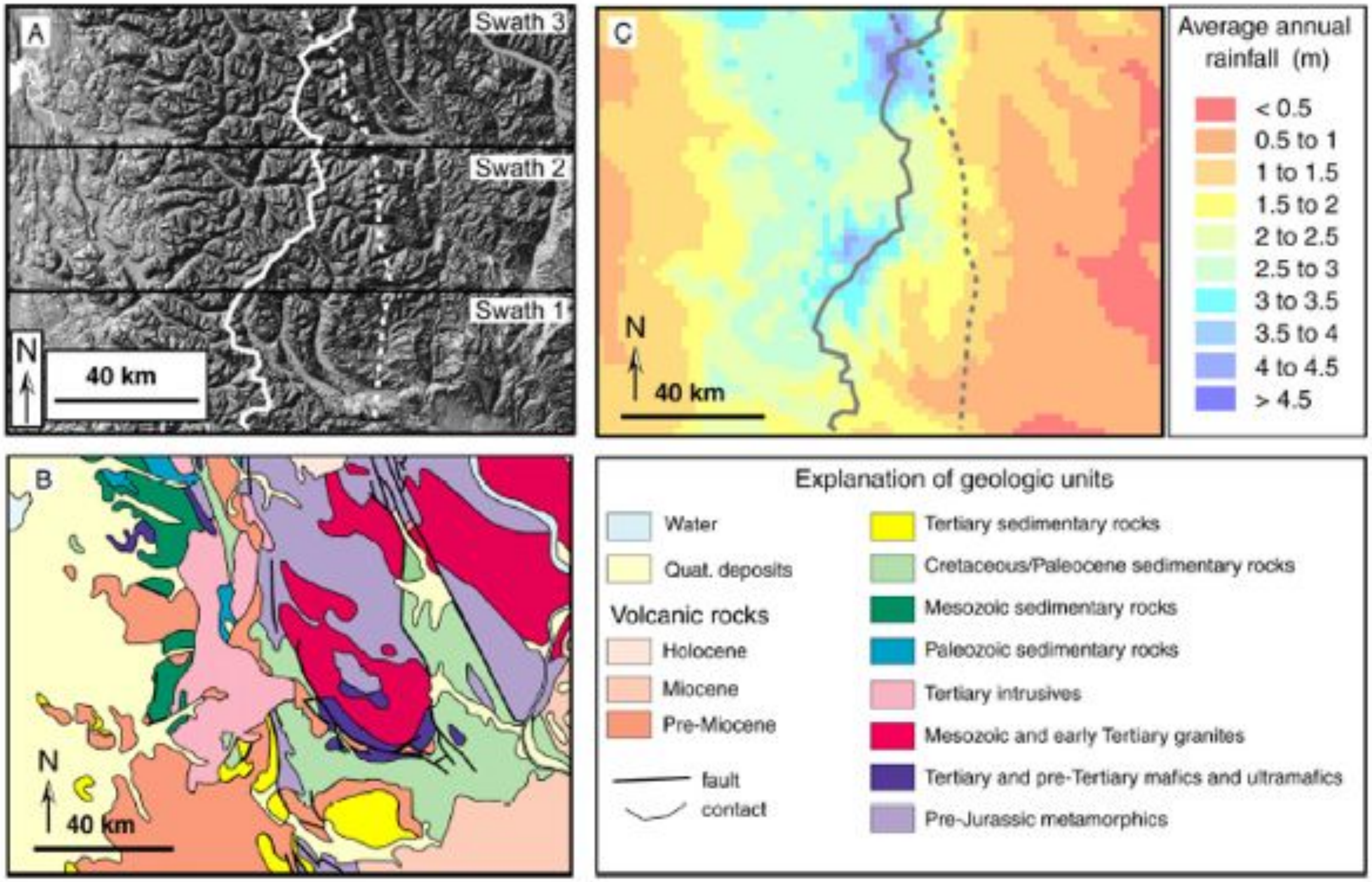
Equilibrium Line Altitude “ELA” ———

Glacial Buzzsaw history

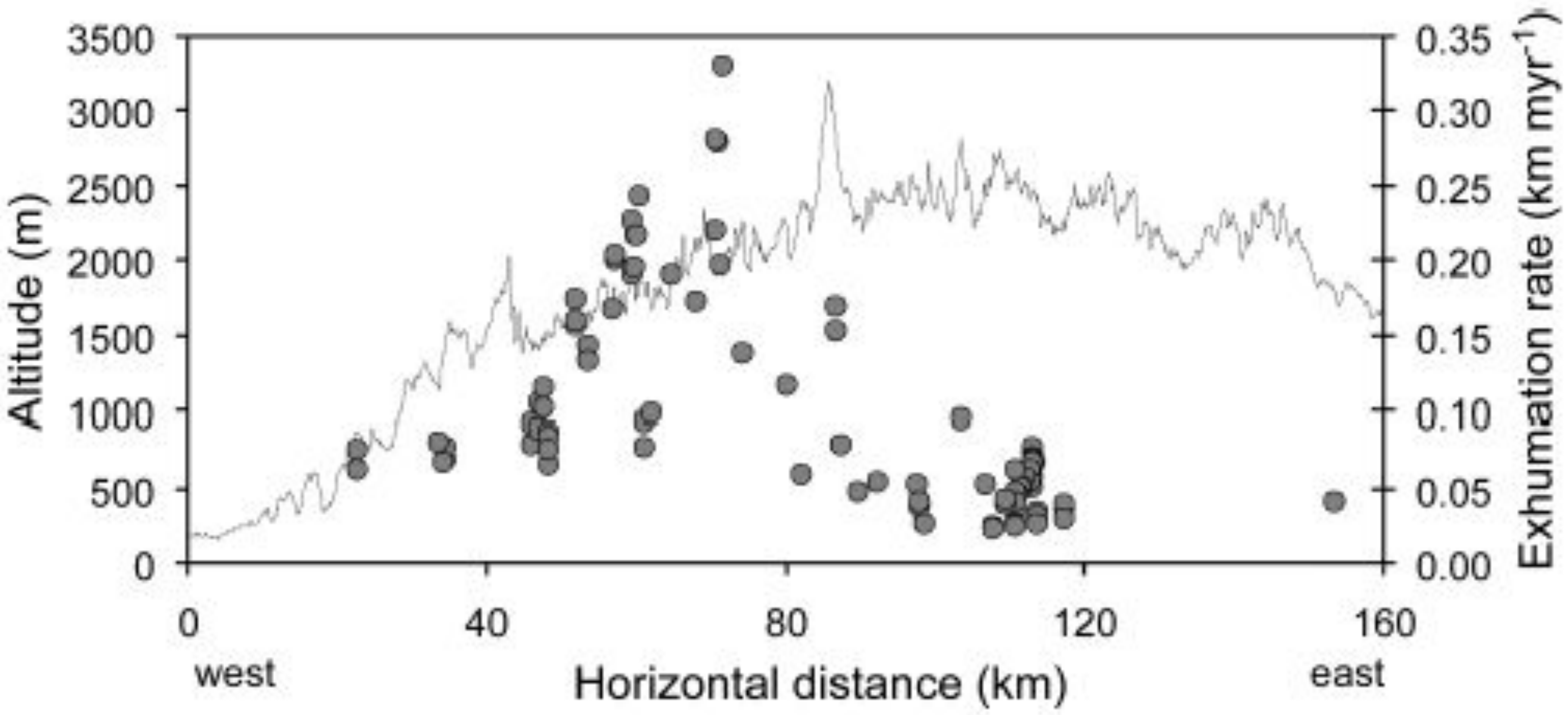
- Steve Porter's diagram (~1980s) used by M. Raymo
- Brozovic et al. (1997) *Himalayas are high because they are in tropics*
- Mitchel & Montgomery (2006) Cascades
- Egholm et al. (2009) Global compilation & modeling

What controls peak elevations in Cascades?

Note great diversity of rock type, and amounts of precipitation

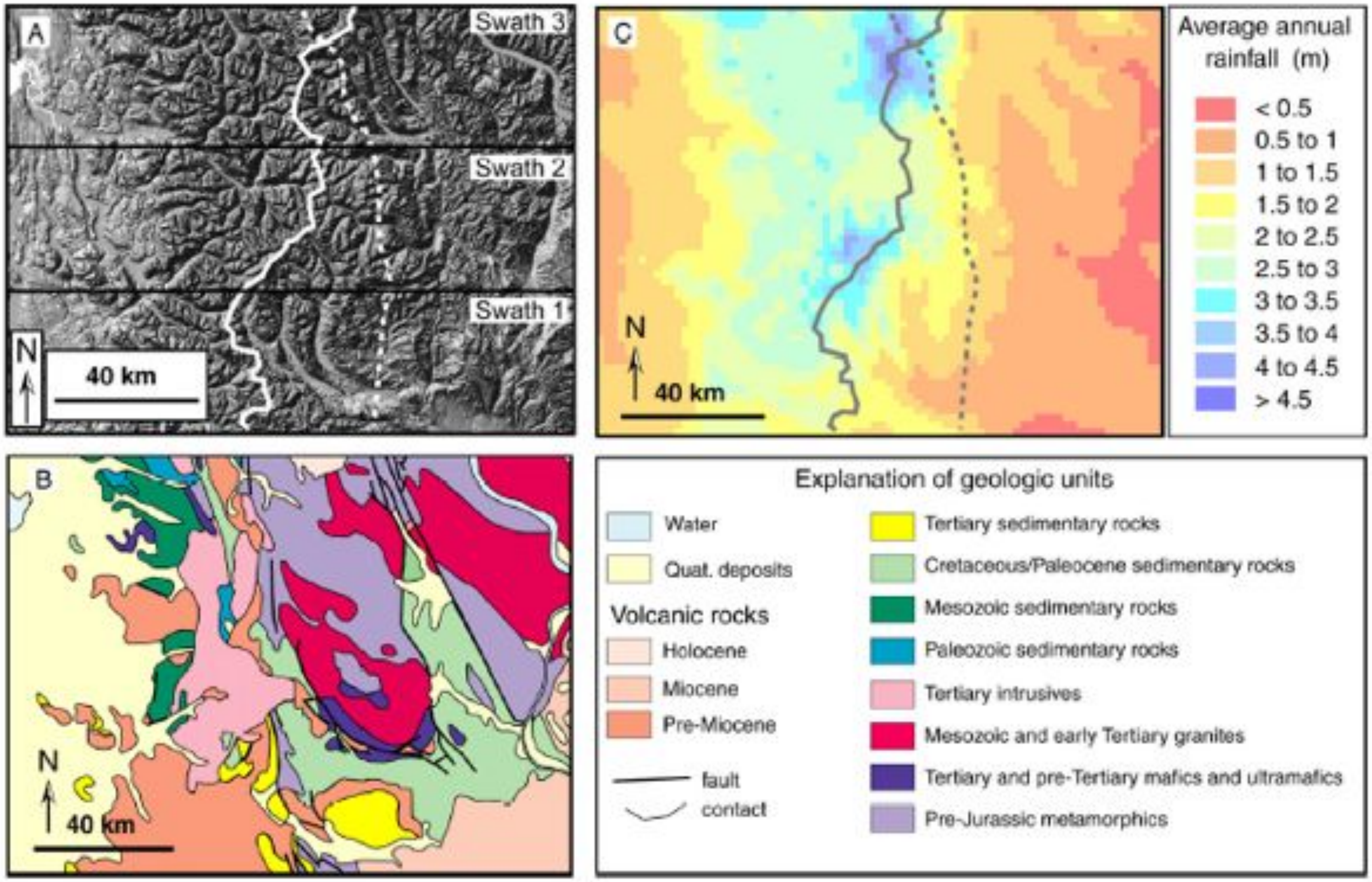


Cascades: well defined cross-range variation in rates of exhumation/uplift

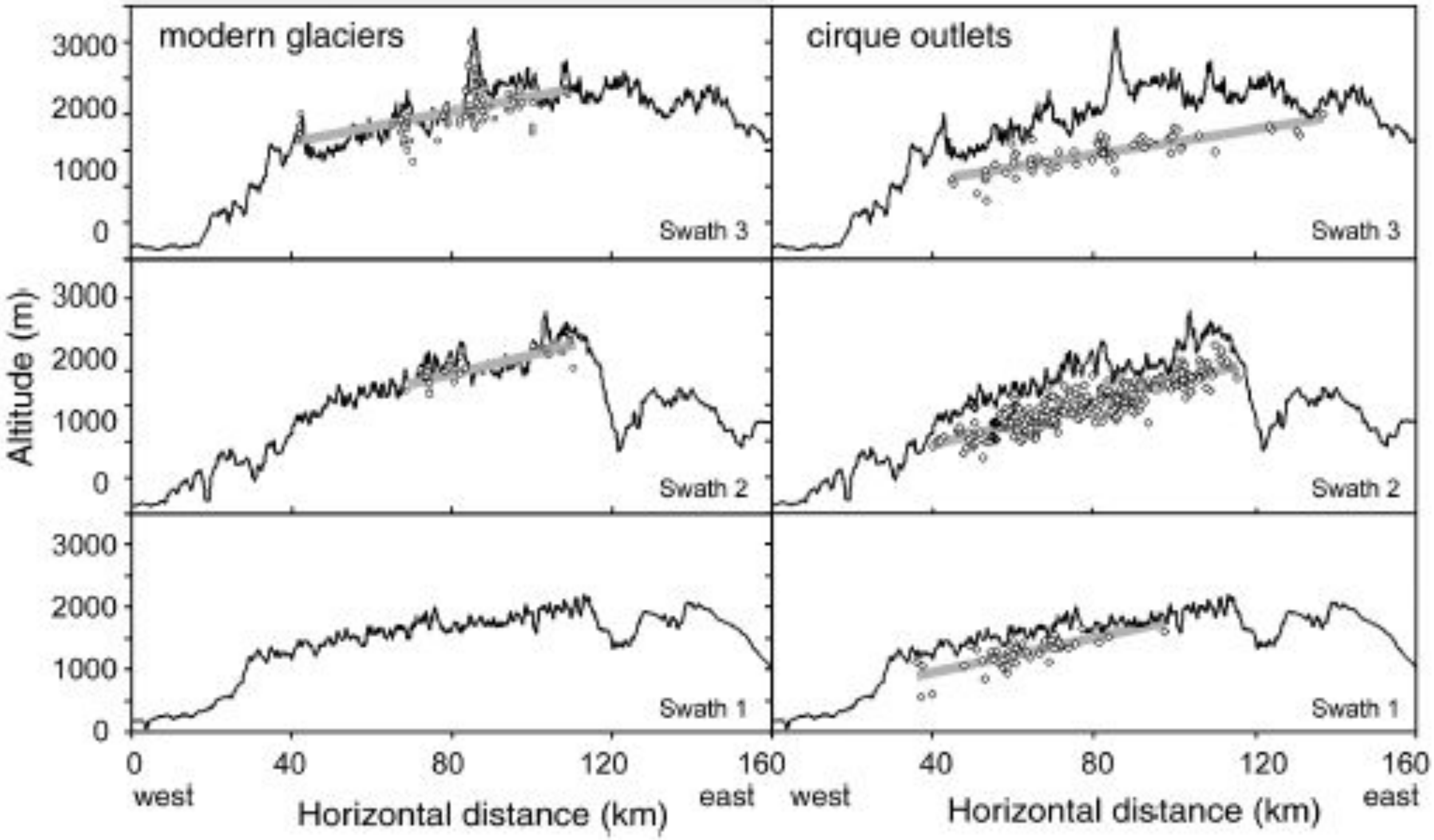


In a steady state, rock uplift rates must equal exhumation rates

What controls peak elevations in Cascades? Surprisingly it is NOT the rock type, amounts of precipitation, or rate of exhumation/uplift.

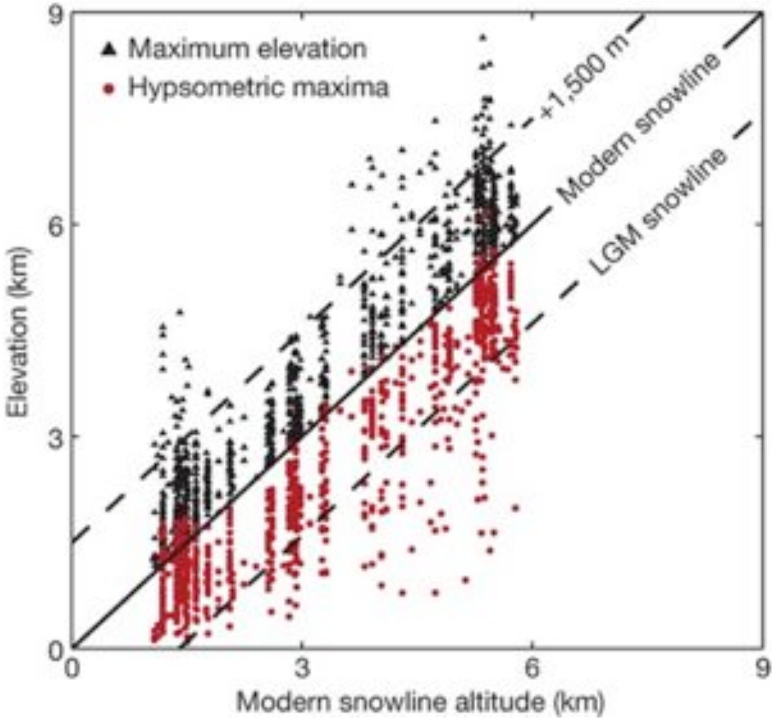


Peak elevation in the Cascades closely parallel the “snow line” suggesting that they are curtailed by the Glacial Buzzsaw



Sara Mitchel’s doctoral research

Maximum elevations and hypsometric maxima elevations correlate with local snowline altitudes.



DL Egholm *et al. Nature* **460**, 884-887 (2009) doi:10.1038/nature08263

Near Polar Regions: Alpine topography at sea level, Lofotan Islands, Norway

Near the Equator, the World's Highest Mountains, Mt Everest in center