Glacial Erosion: Processes, Rates & Landforms

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Over the last decade the Earth Science community interested in glacial erosion has expanded and diversified greatly

Climate/Topography Linkages (chicken-n-egg?):

a. Accelerated Quaternary uplift leads to climate change

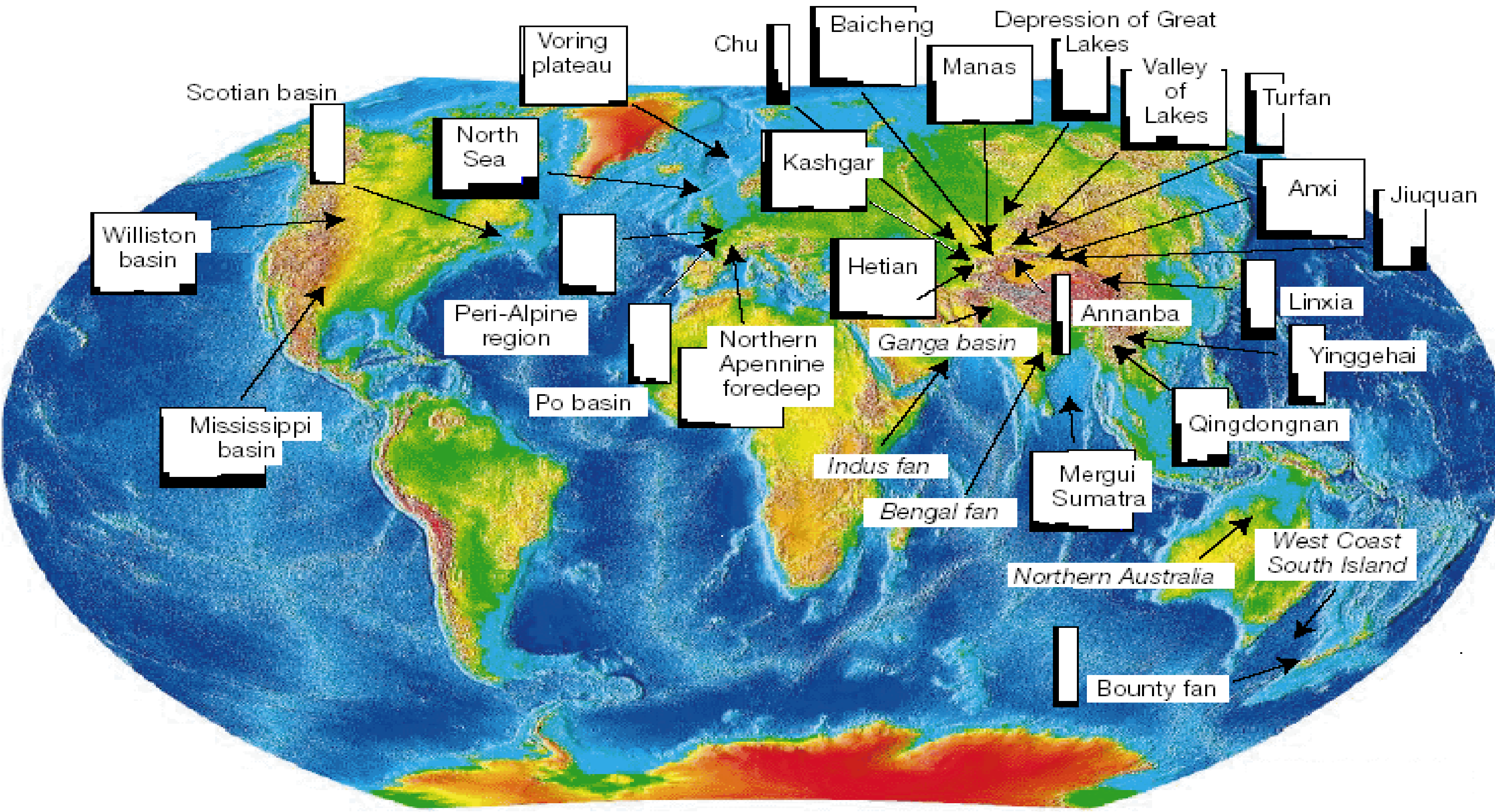
- elevation of Tibetan Plateau changes atmospheric circulation pattern
- uplift increases weathering rates and uptake of atmospheric CO_2. Resulting CO_2 draw down leads to glacial ages

b. Climate change leads "uplift"

Rapid erosion characteristic of Quaternary unloads regions of

high relief, resulting in accelerated isostatic rebound, and sediment delivery to oceans

Global sedimentation rates have increased over the last 2-4 Ma



Peizhen et al., 2001

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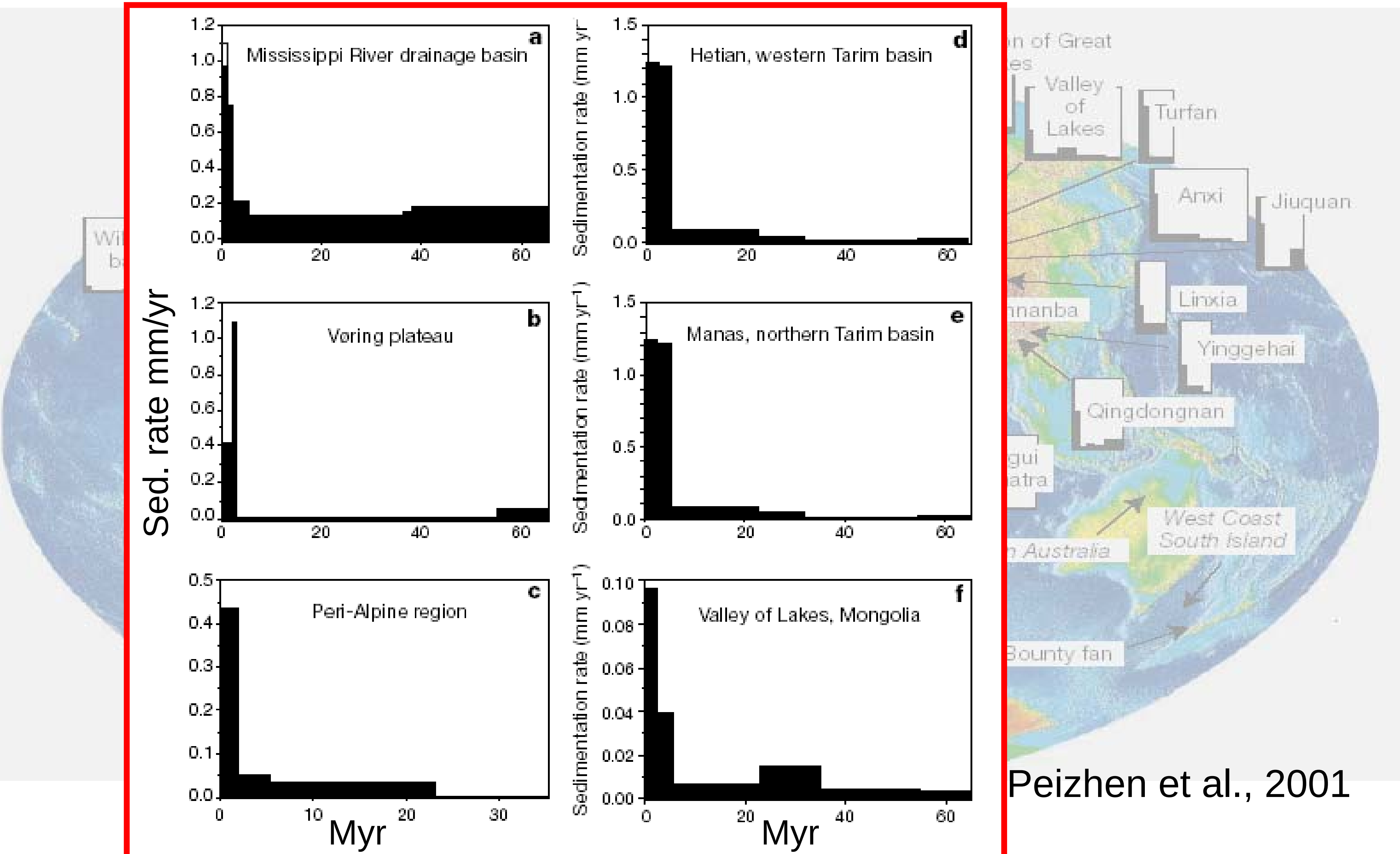


Peizhen et al., 2001

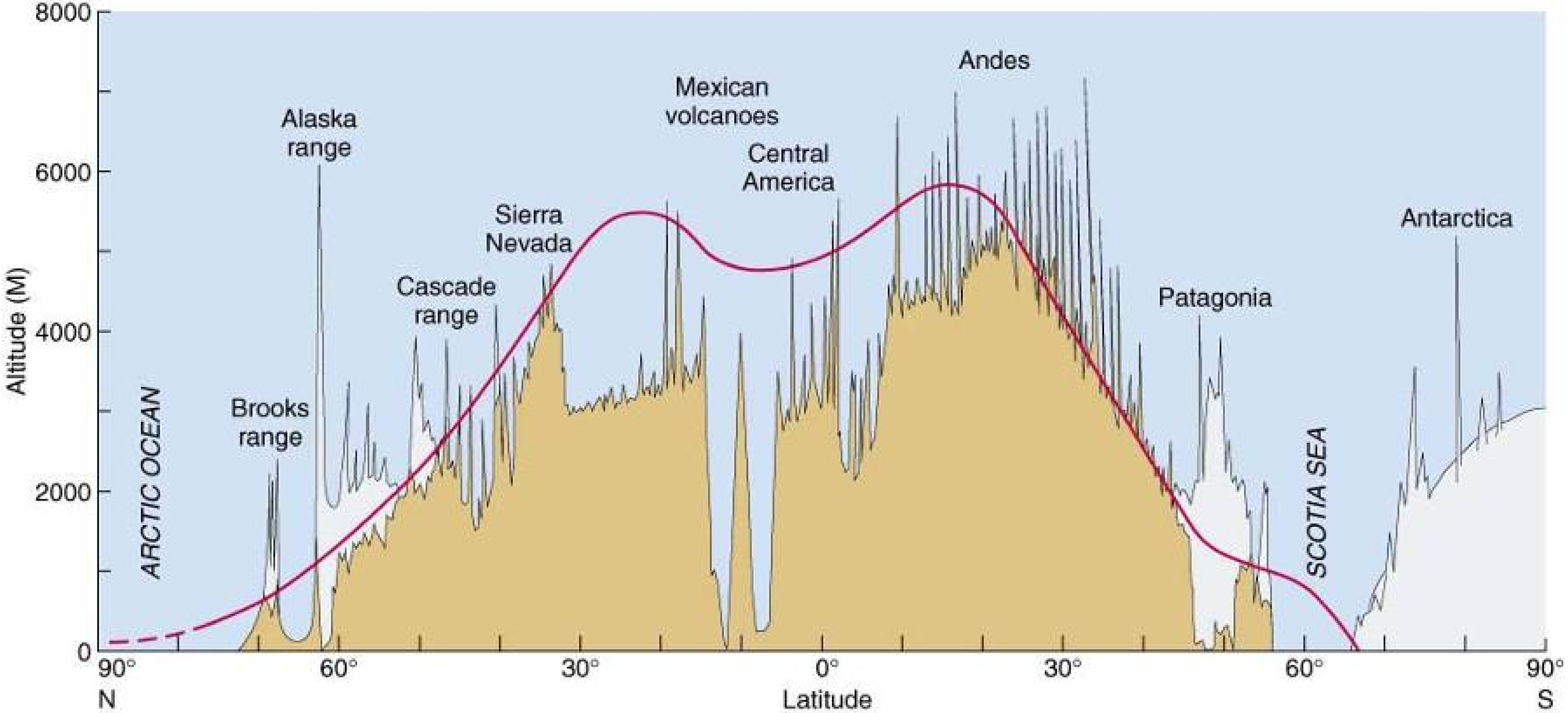
Other reasons to consider glacial erosion:

Erosion/Uplift Linkages in high mountain range in continental collision zones:

– erosion both affects and is affected by the spatial pattern of uplift, the lithologies exposed, even grade of metamorphic rocks, etc.

– snow buzz saw: glacial/periglacial processes fuel such rapid erosion that they tend to limit the height of high mountain ranges (e.g. Himalaya are high because of their low latitude

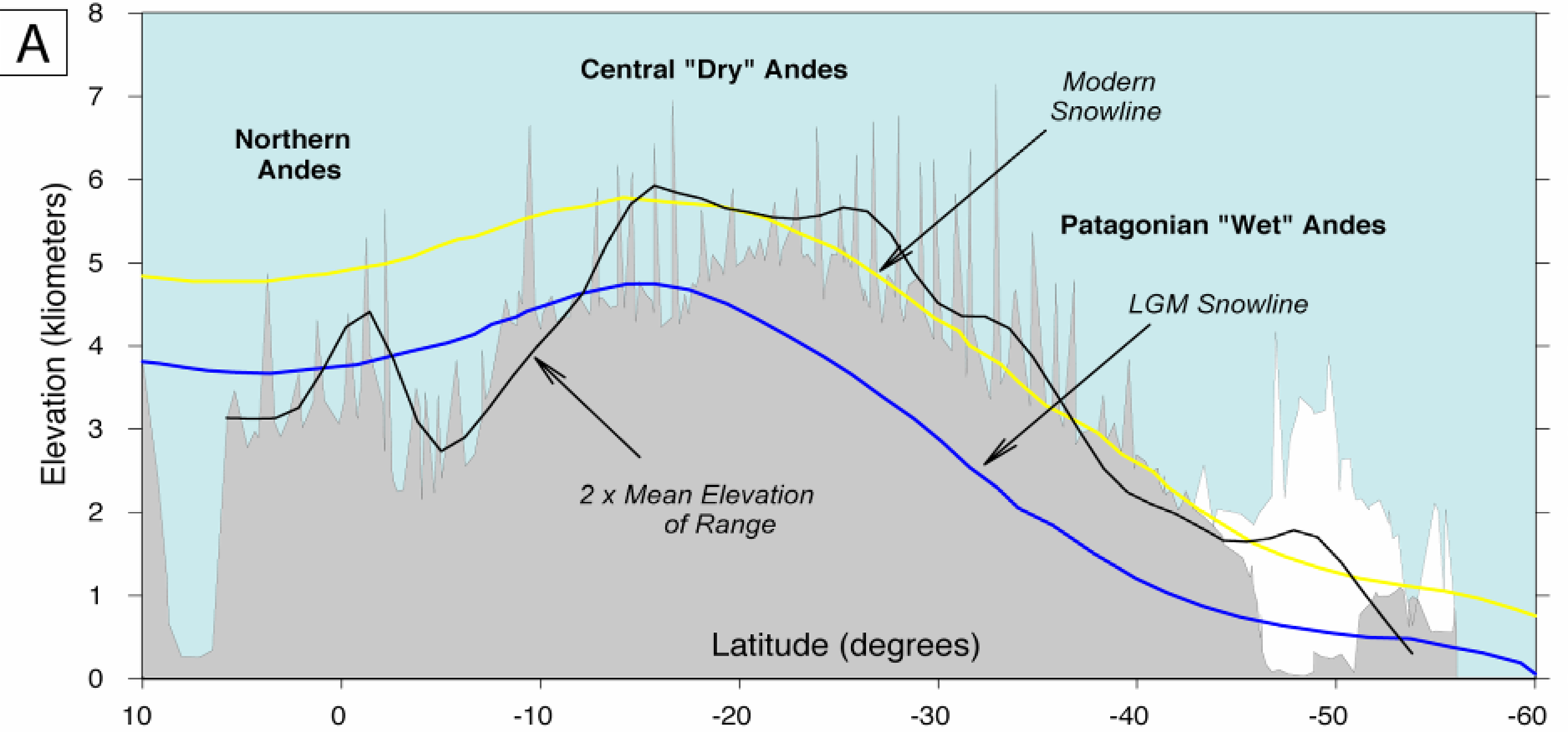
Glacial Buzz saw



S.C. Porter

Equilibrium Line Altitude “ELA”

Glacial Buzz saw



S.N. Thompson, 2004

From J. Tomkin

Glacial Buzz saw

From J. Tomkin

Additional reasons to consider glacial erosion

- Global Carbon Budget: glaciers/ice sheets affect rate of atmospheric CO_2 uptake by modulating rates *carbonate precipitation and organic carbon delivery to oceans*

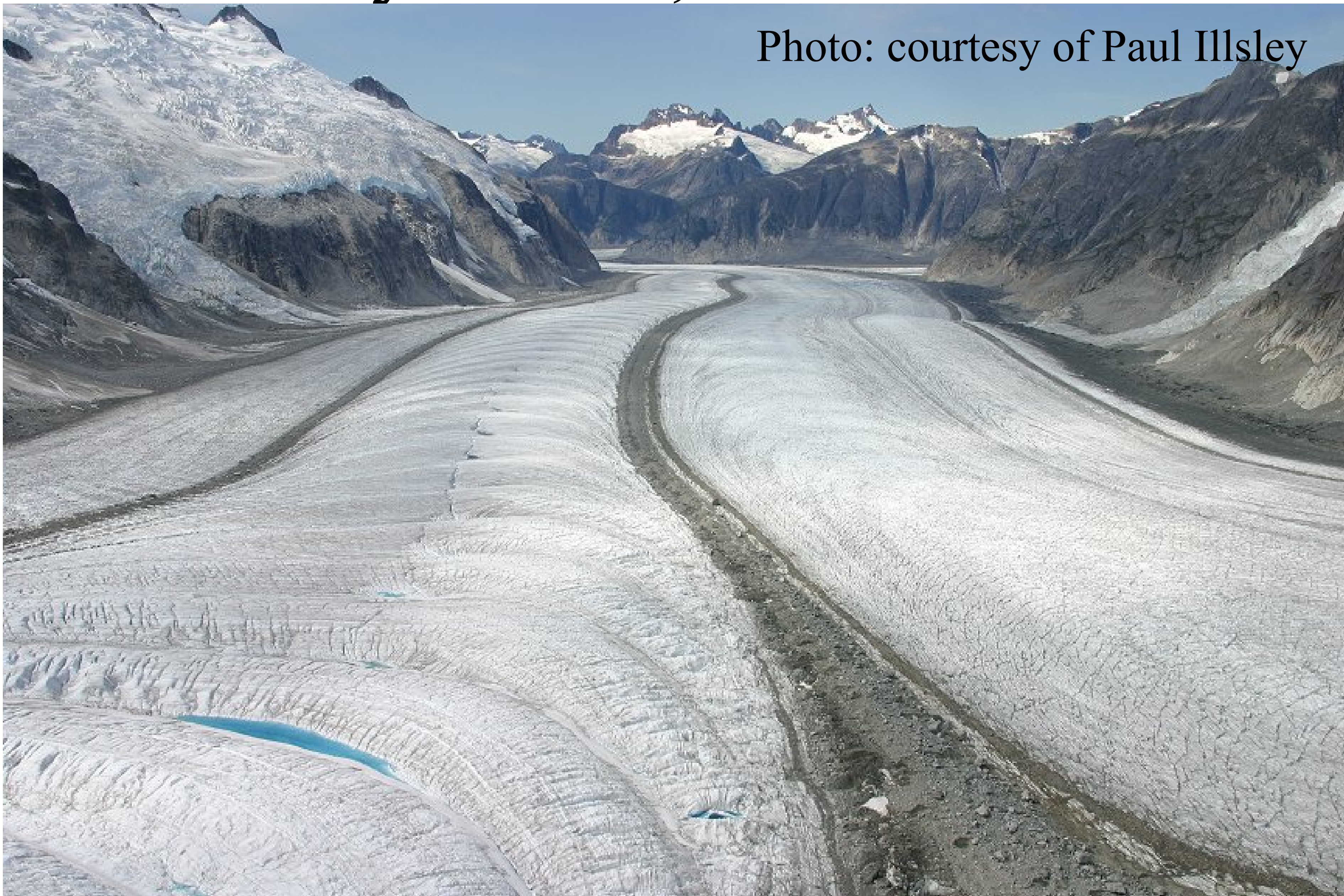
- Generation of soft beds &basal debris layers: perhaps critical for icesheet dynamics

- Carving the planet's fabulous alpine topography.

Alpine character of high mountains: the legacy of glaciers.

Glacial cirques, tarns, arêtes, & horns in the Sierra Nevada, California

Gilkey Trench, Juneau Icefield



Glacial Topography:

U-shaped valleys, fjords, & hanging valleys

Mount Everest from space

Extreme relief due to glaciers slicing deeply into bedrock. Thick debris cover on lower portion of glaciers attests to active erosion.

Courtesy Space Imaging

∴ There is considerable incentive to better understand processes that control spatial patterns and temporal distribution of erosion rates.

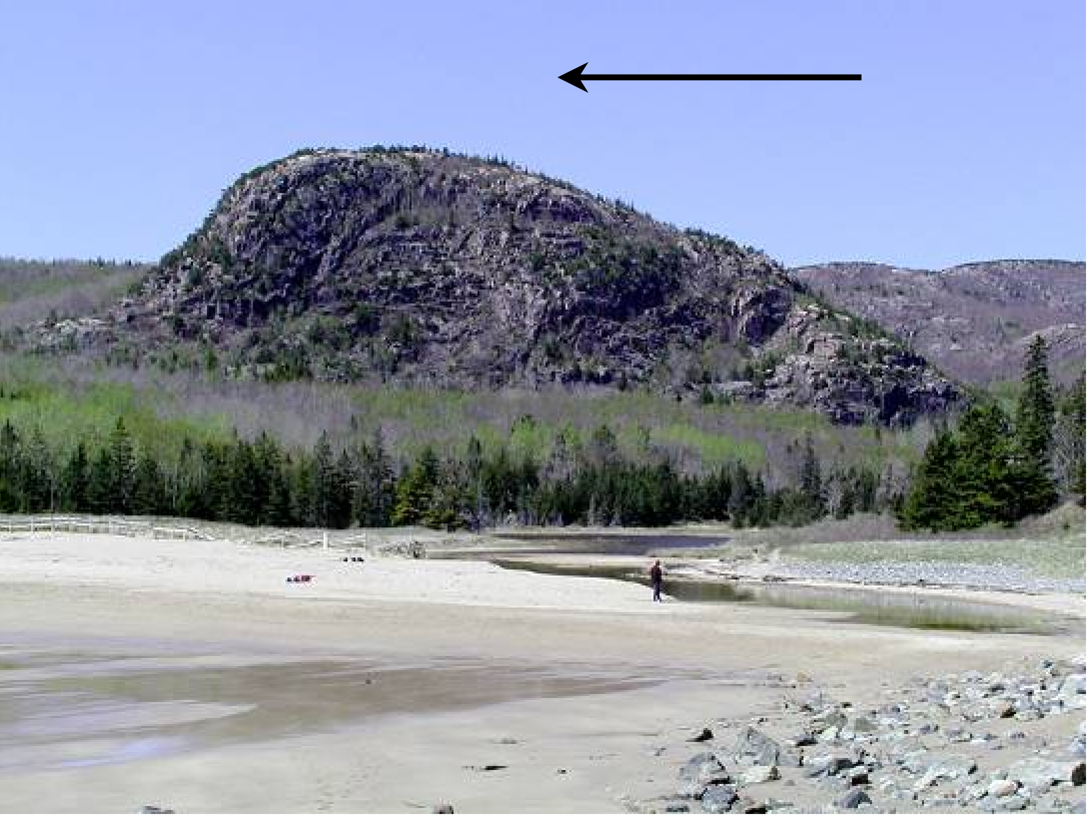
Our research at UW integrates:

- theoretical studies of erosion processes
- field research along the south coast of Alaska
  and Patagonia
- global compilation of sediment yields from
  glaciated and unglaciated basins

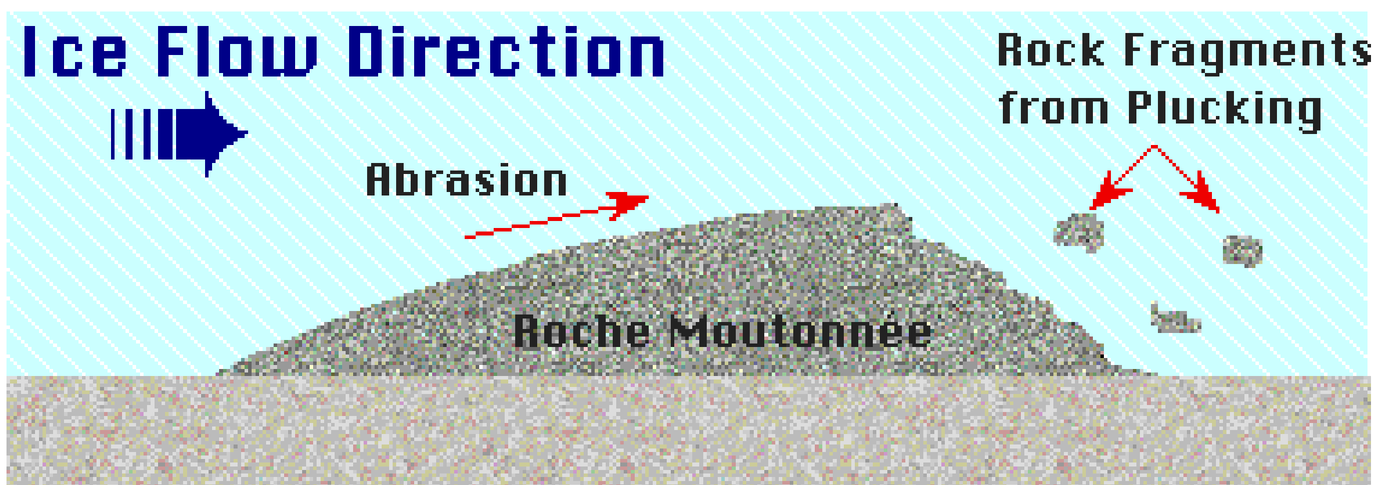
Erosion Processes - 1

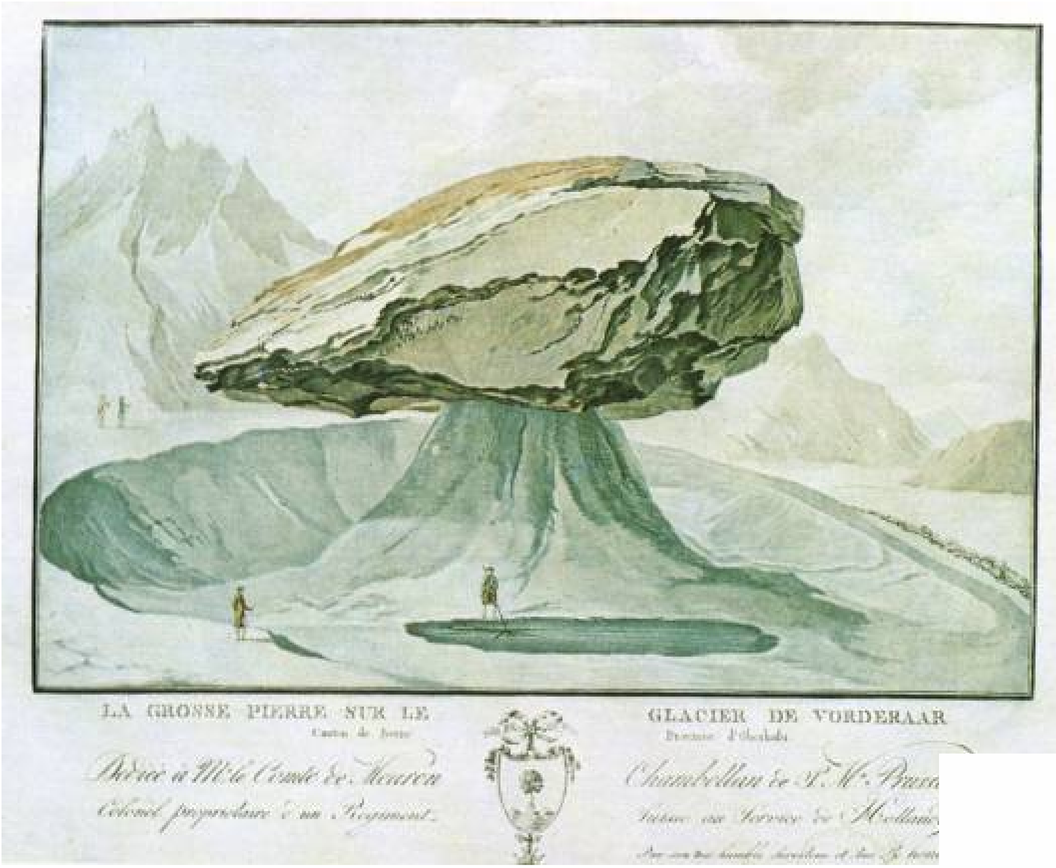
Quarrying - Plucking:

- **Evidence:** fractured bedrock, large glacial erratics
- **Diverse lines of evidence points to quarrying being dominant bedrock erosion processes**:
  - asymmetry of erosional forms
  - asymmetry of cosmogenic ages: old ages on abraded surfaces (quarrying rates > 10 times abrasion rates)
  - theoretical considerations, source of abraders and bed roughness elements



Roches Moutonnées





Glacial erratics are derived by plucking, as well as rock fall

Erosion Processes - 2

- Abrasion: dominant producer of fine sediments, but may account for < 10% of bedrock erosion.

- Subglacial fluvial activity: bulk (>90%) of sediment transport to glacier snout, but role in bedrock erosion is poorly known

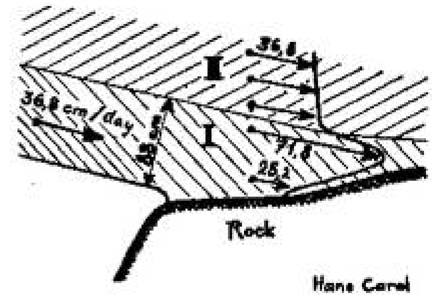
- Paraglacial processes: mass wasting (from frost-activated creep to massive landslides) and fluvial incision of proglacial sediments can be important but clearest examples are highly local.




Striations & Polish

Early observations related to abrasion: Junfräujoch, Swiss Alps

From Carol (1947, J. Glaciol.)



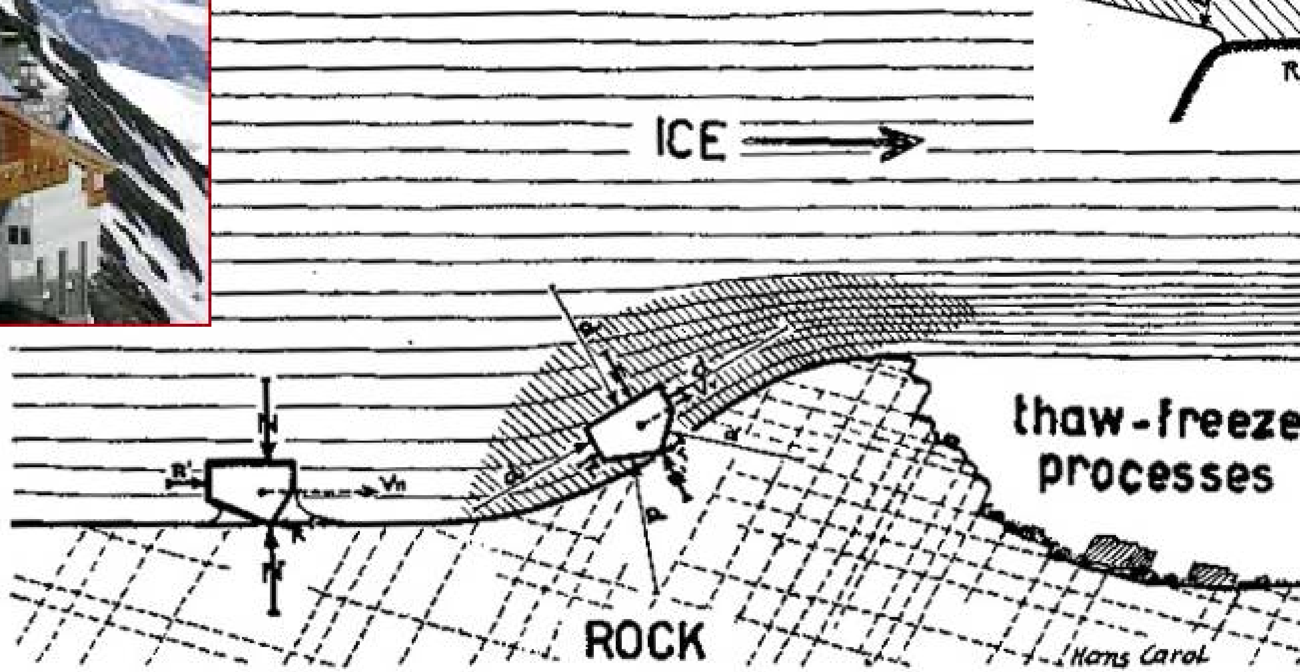
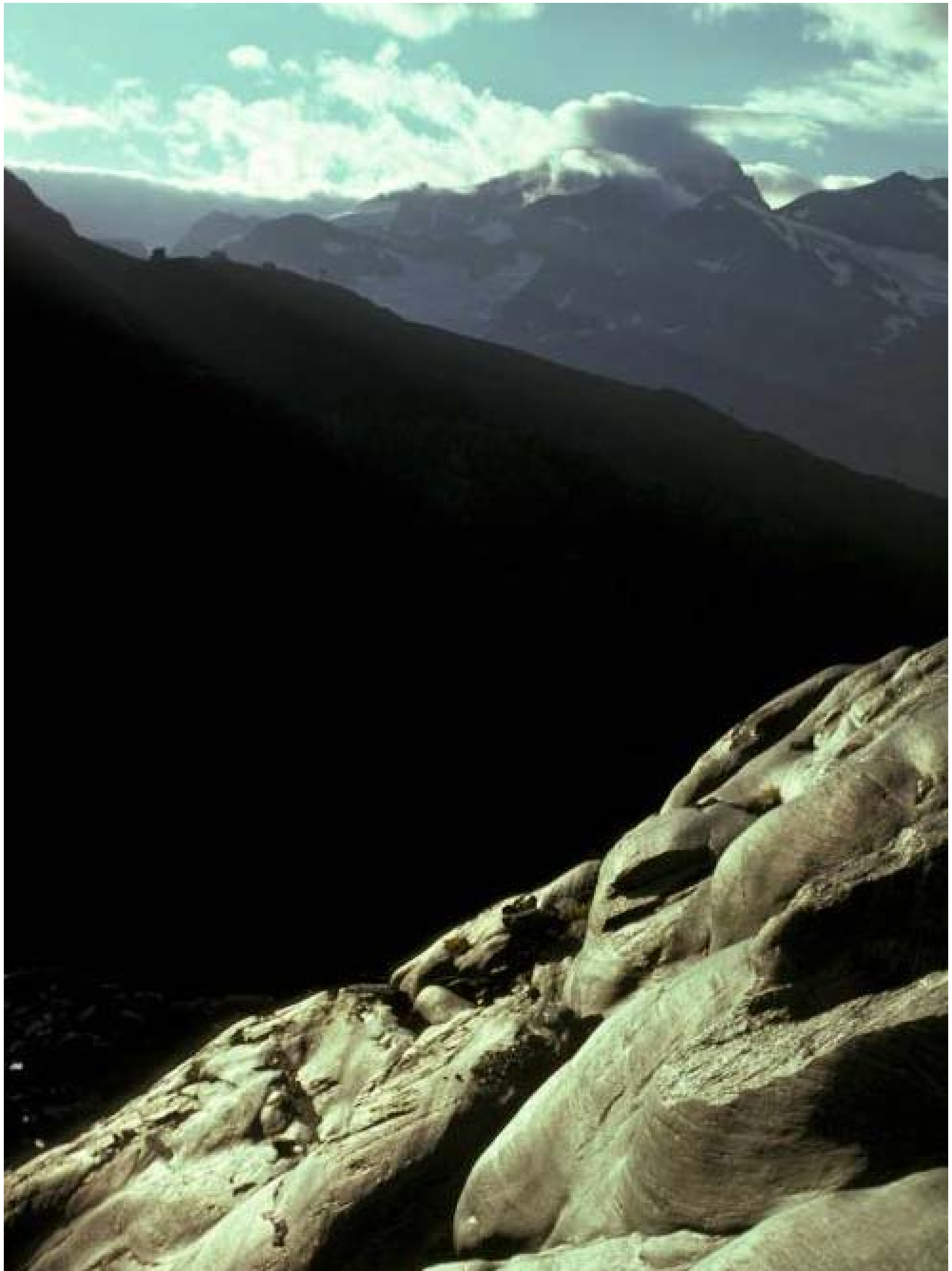


Fig. 7. Diagrammatic representation of a roche moutonnée forming under a living glacier. The hatching indicates the area of semi-fluid conditions

N pressure of superincumbent ice upon eroding stone
R, frictional resistance
Vn, normal speed of ice-flow
dd, hydrostatic pressure
n, reduced pressure upon stone
r, reduced frictional resistance



Smooth, striated bedrock forms produced by abrasion dominate the view looking down valley. Relatively rough and fractured bedrock surfaces produced by quarrying would dominate the view looking up-valley.

Near Zermatt, Switzerland

Subglacial rivers erode ice, rock and sediment

Subglacial Fluvial Erosion & Sediment Transport

Factors Controlling Rates of Glacial Erosion

Erosion rate, E, increases with sliding velocity, U ($E \sim 10^{-4}$ U), and ice flux. This flux is, in long-term, dictated by snow input, hence erosion would tend to increase with amount of snow, S ($E \sim 10^{-3}$ S)

Quarrying rates are high for glaciers that:

- move rapidly (sliding ≥ 100 m/yr)
- nearly float (Pe ~ Pi/100, Pe & Pi are effective and ice pressures);
- small Pe ~ 0.2 to 1 Mpa (few bars). Large water pressure fluctuations help.

Such glaciers tend to be large.

Overall Erosion Rate also depend on

Basal temperature (Negligible if ice is frozen to the bed; that is when surface is cold and ice is thin)

Glacial extent

Bedrock characteristics (lithology, structure, micro- & macro-cracks)

Tectonic setting (fractures, pervasive damage, strain rate)

Weathering is NOT required for glaciers to erode. In S. Alaska rates are high and the area has been under ice for >5 Myr.

A closer look at erosion mechanisms

- Abrasion
- Plucking, quarrying
- Subglacial fluvial erosion
- Chemical denudation

Abrasion: factors affecting rate

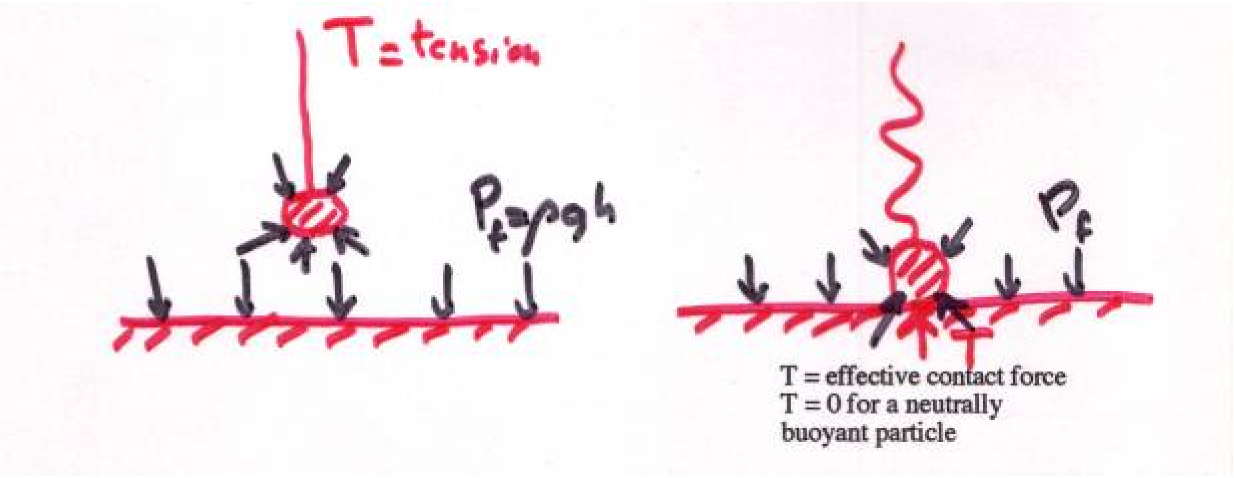
- # cutting tools: rock fragment concentration
- fragment velocity

Combine to give flux of fragments.

- lithology and shape of fragments
- shape of the bed (including erosion shadows)
- effective contact force

Factors affecting contact force

- Ice pressure



Factors affecting contact force

- Ice pressure

  but fluid pressure does not affect contact force in water or other viscous fluids

Factors affecting contact force

- Ice pressure: not important, nor is glacier thickness (controversial, common misconception)
- Gravity

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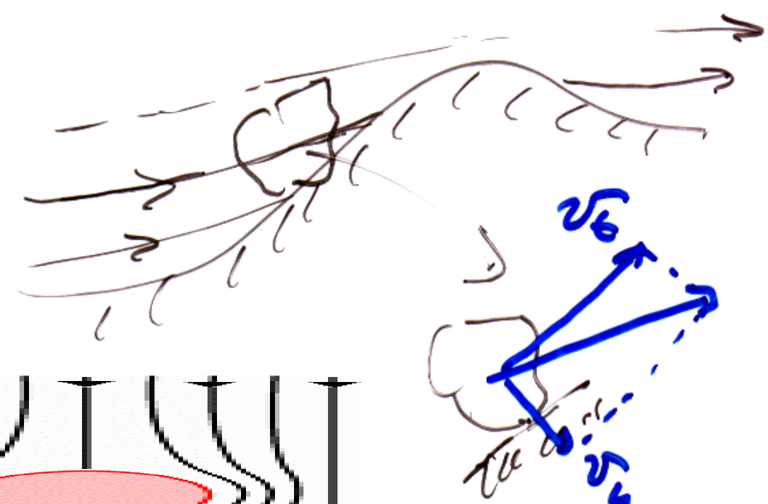
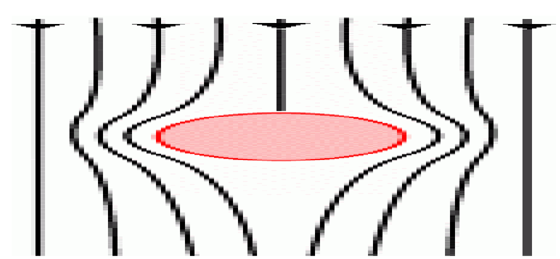
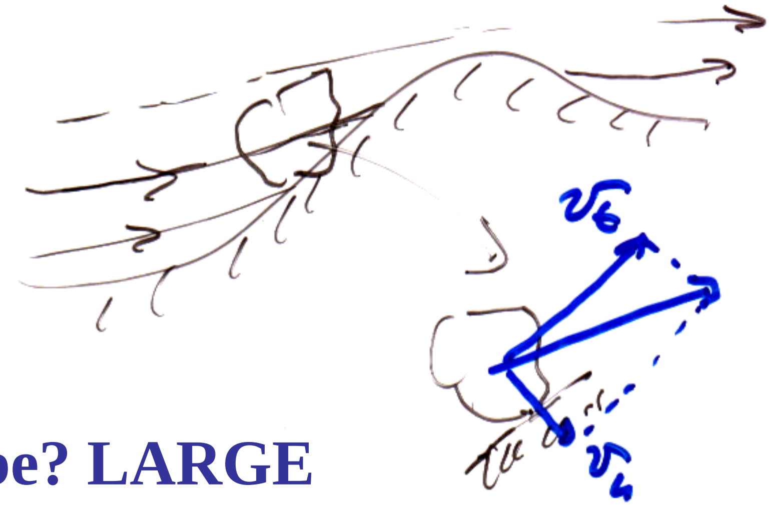
- Gravity: not important - vertical bedrock surfaces are often striated, as are overhangs
- Viscous forces



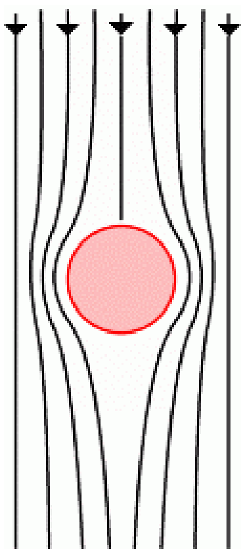


Viscous force: a rough estimate

Stokes Law: $F = 6\pi\eta R v_{rel}$



where η is viscosity, *R* the sphere radius and v_{rel} the relative velocity.



How large can this force be? LARGE

Take the viscosity of ice to be 1 bar-yr ($3x10^{12}$ Pa-s), the radius of the rock to be 0.5 m, and the normal velocity v_n to be a small fraction of the sliding velocity , say 1% of 100 m/yr. The contact force would be:

6π x 1 bar-yr x 0.5 m x 1m/yr = 10^6 N = 100 tons.

Note: its weight is 800 kg or 0.8 tons

Complications: melting, not infinite, not linear….

Simple linear model (1)

- The simplest equation describing abrasion rate:

$$\text{Å} = \alpha F_c \, v_p \, C \quad \text{where}$$

α is a constant (hardness of rock and shape of point), C is the particle concentration (number/area). Note that v_p (particle velocity) and F_c (contact force) both scale with sliding velocity.

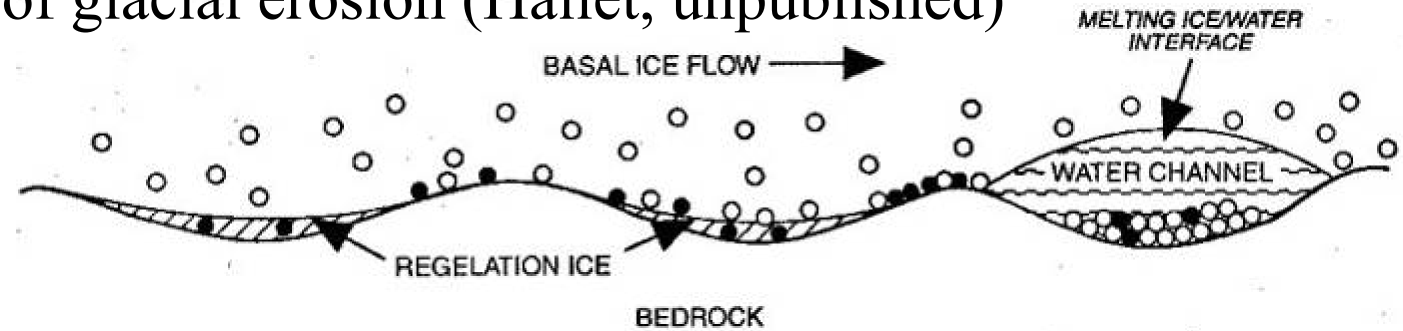
Simple linear model (2)

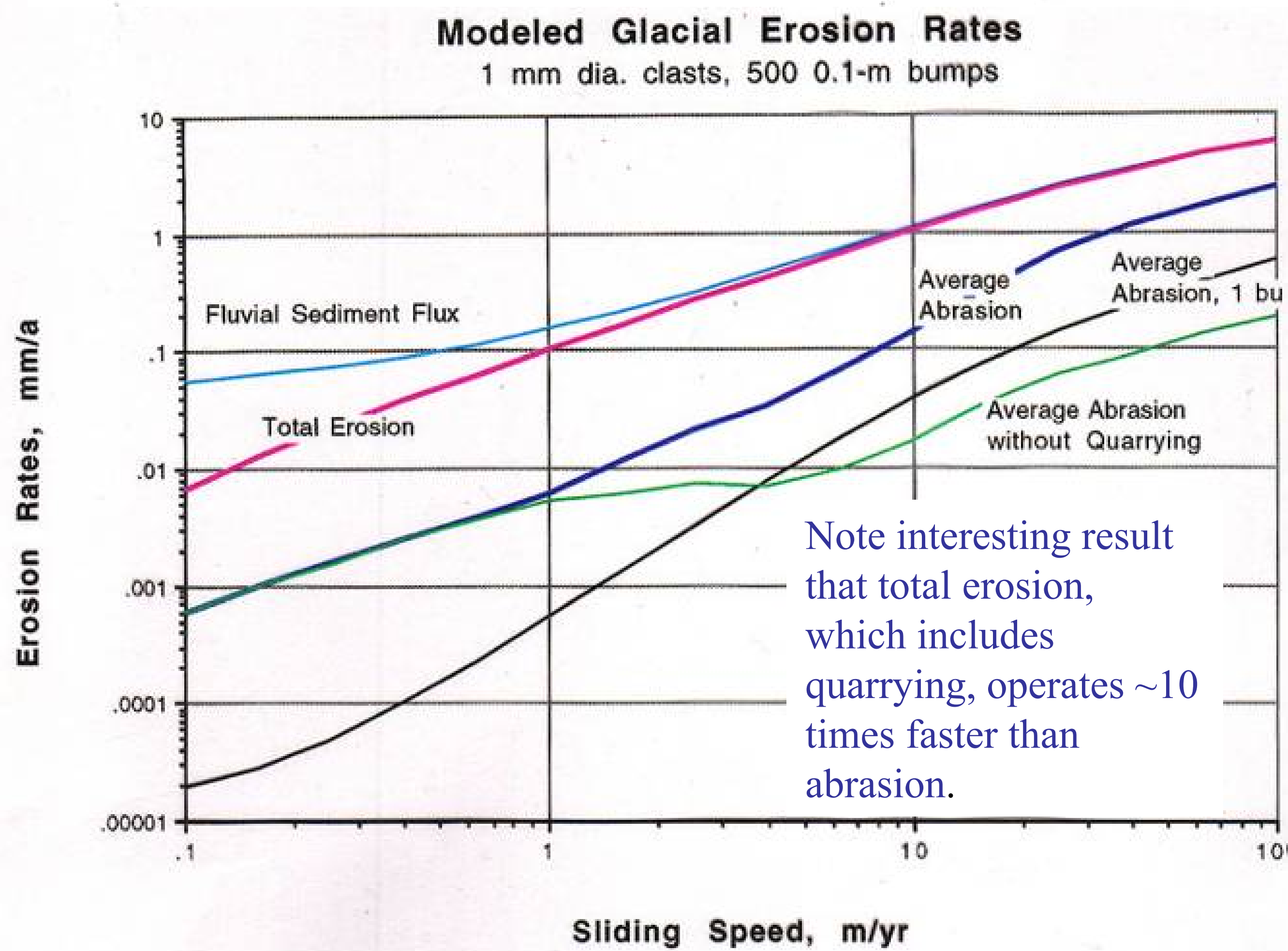
- note: $\mu F_c v_p$ - Work done by one particle per unit time in frictional motion over the bed (μ: coefficient of friction)

$\therefore$ $(\mu F_c v_p)$ C = Work done (energy dissipated) per unit time per unit area on friction/abrasion.

- Thus, the rate of glacial abrasion ($\AA = \alpha F_c v_p C$) is proportional to the rate at which work is being done on rock/rock friction.

A model of glacial erosion (Hallet, unpublished)





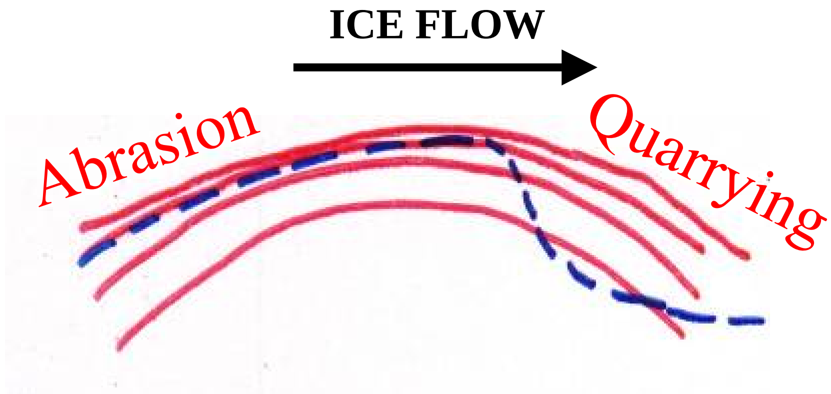
Note interesting result that total erosion, which includes quarrying, operates ~10 times faster than abrasion.

Abrasion is slow

Striations: more than one set of striations can coexist. Distinct directions may reflect changes in configuration of ice sheet typically over 100s or 1000s of years.

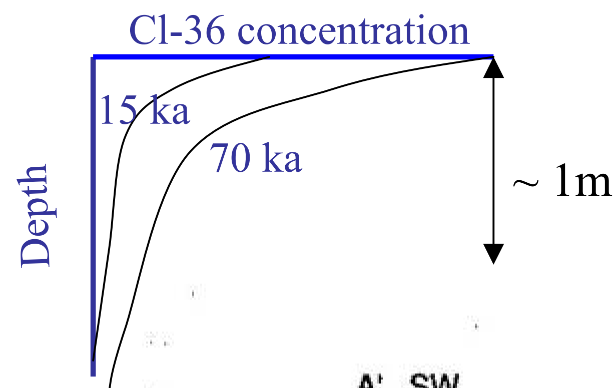
They suggest that abrasion is very slow, since earlier striations are not removed. Abrasion is limited to mms in 10^2-10^3 yrs.

Relative importance of abrasion and quarrying



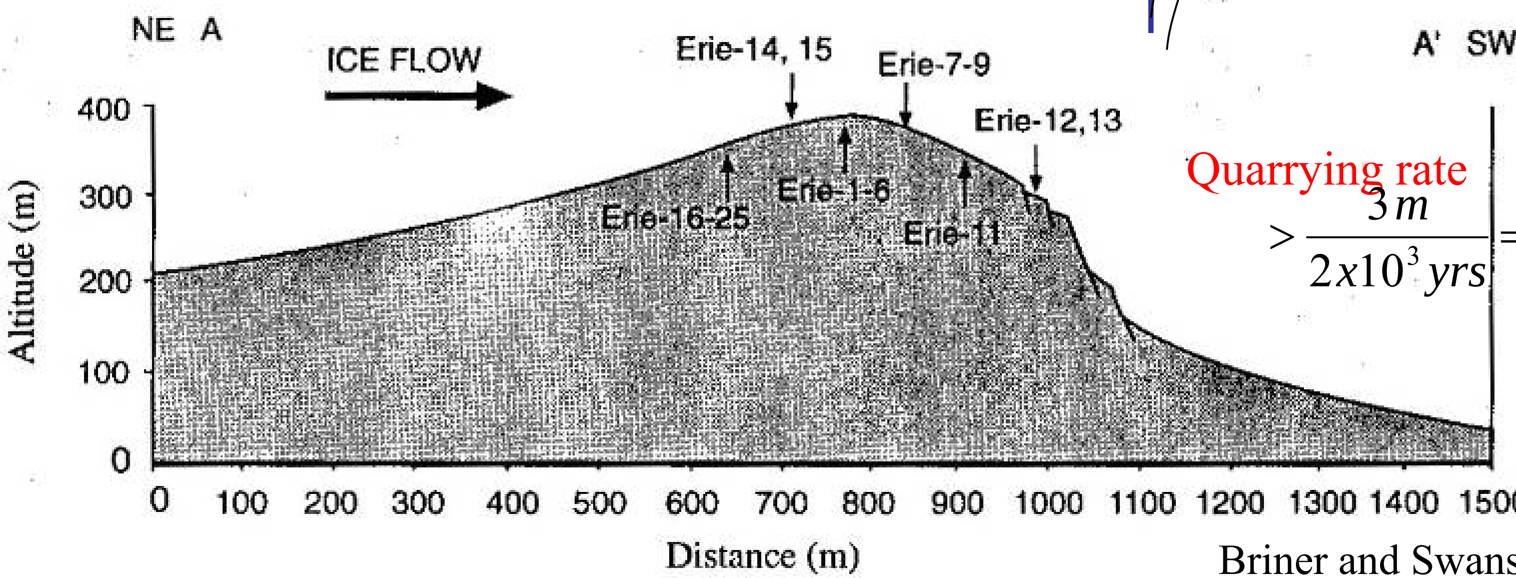
Asymmetry of exfoliating granite domes

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



Abrasion rate

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

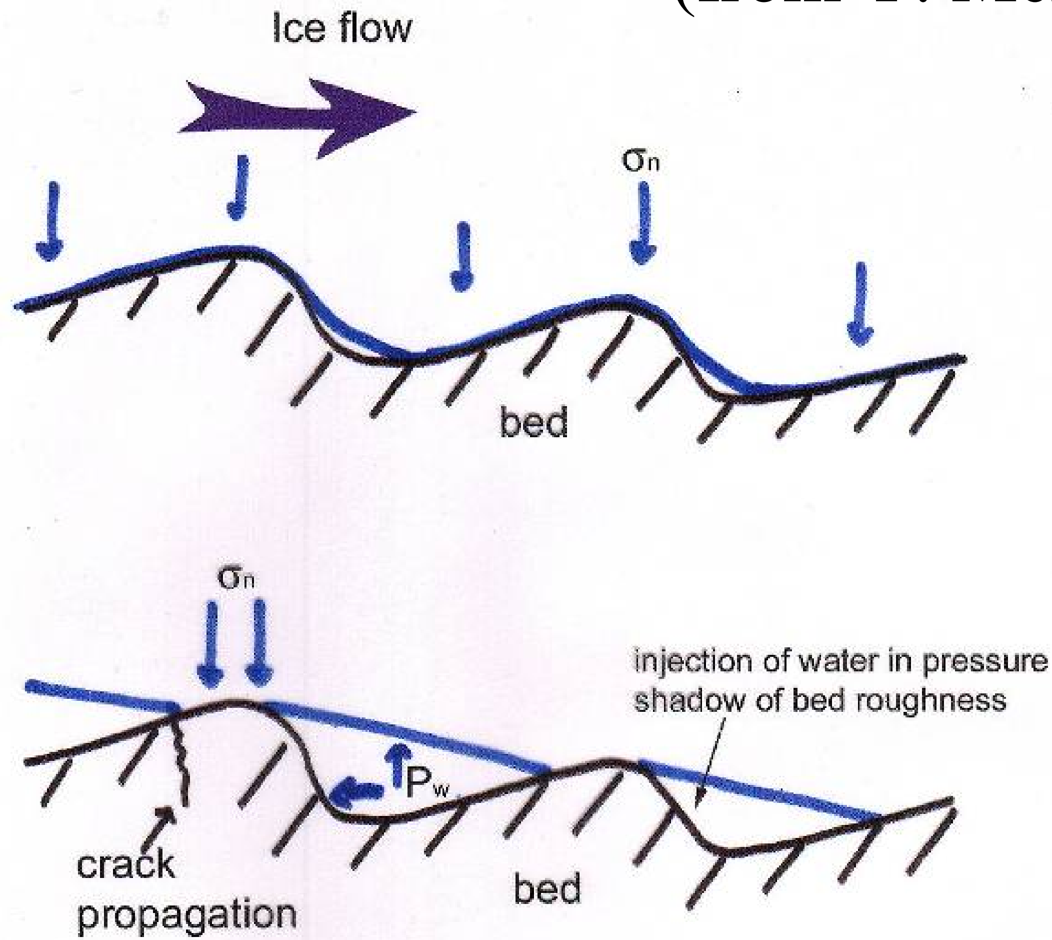


Quarrying rate

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

Briner and Swanson, 1998

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

Grinnell Glacier

2002
courtesy F. Ng

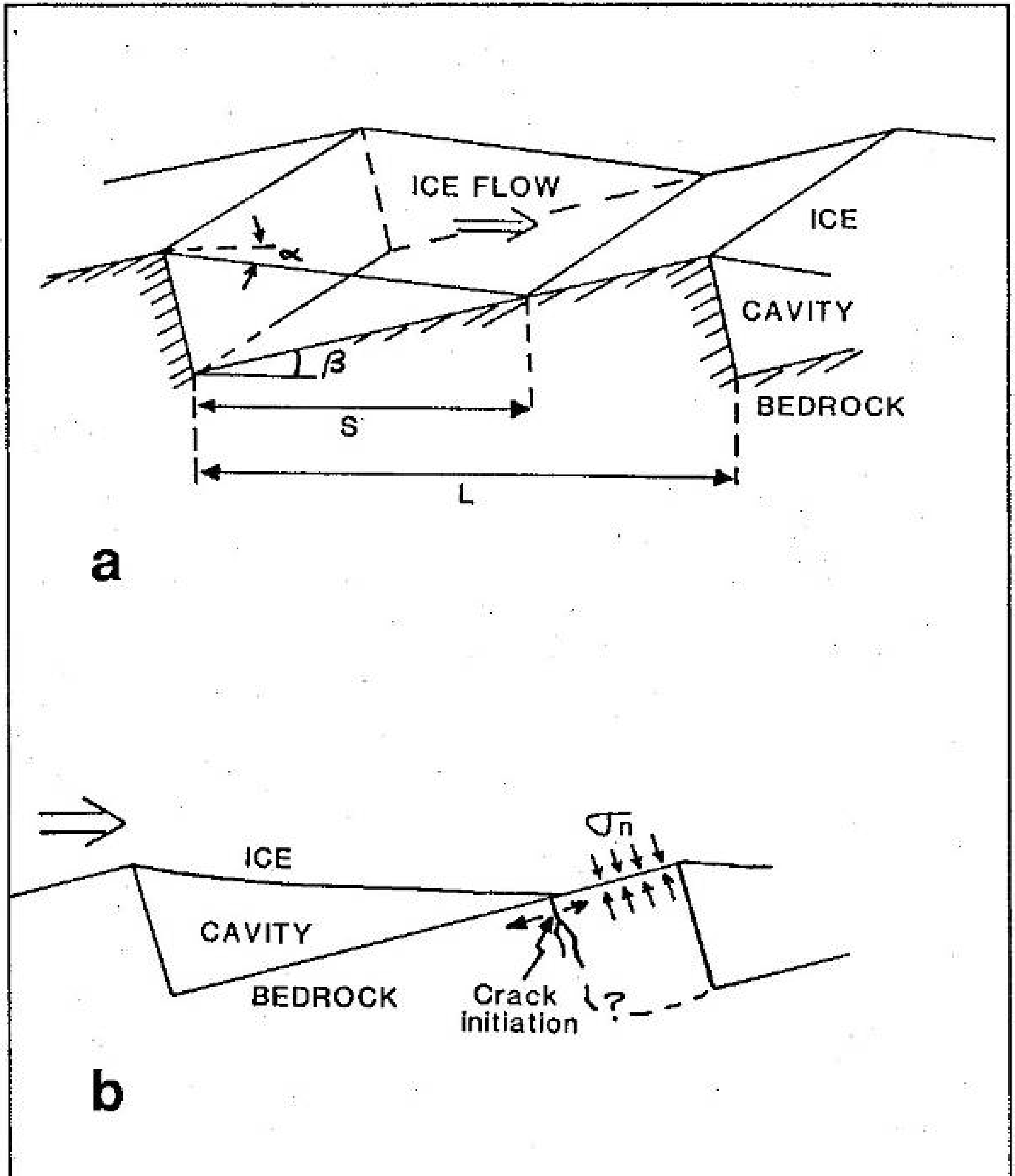
Work in subglacial cavities in early 1980s

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

Extensive cavities 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

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

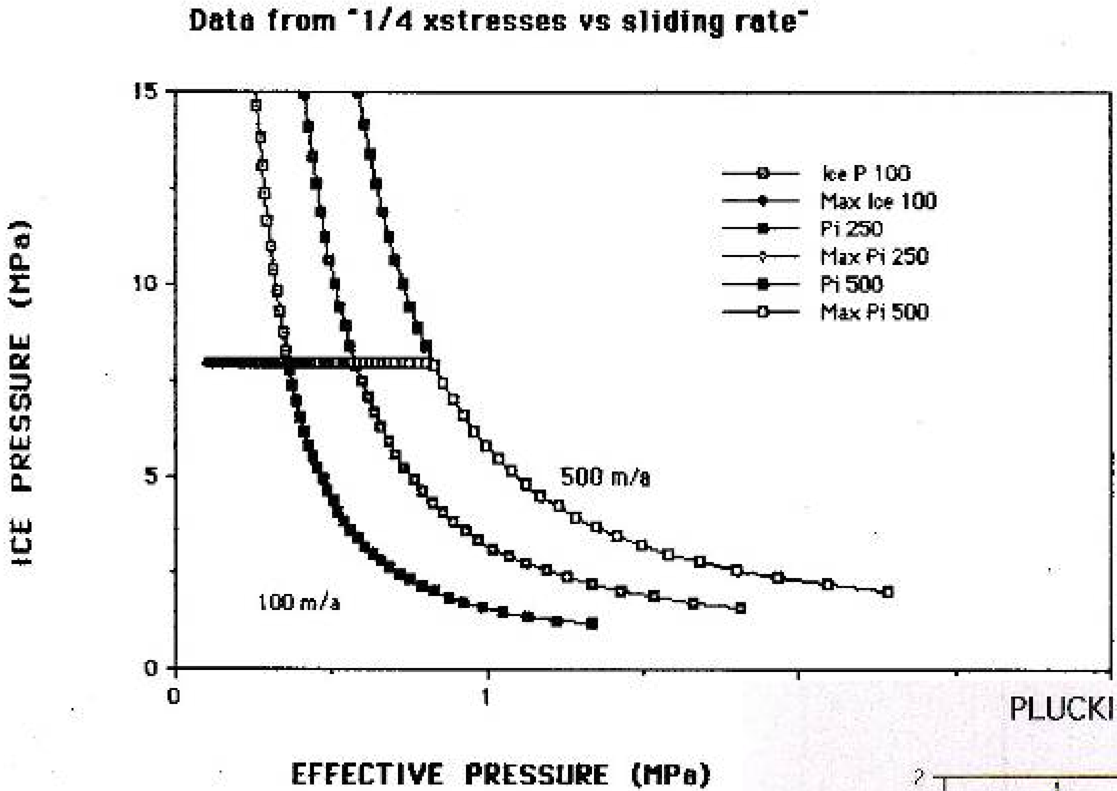


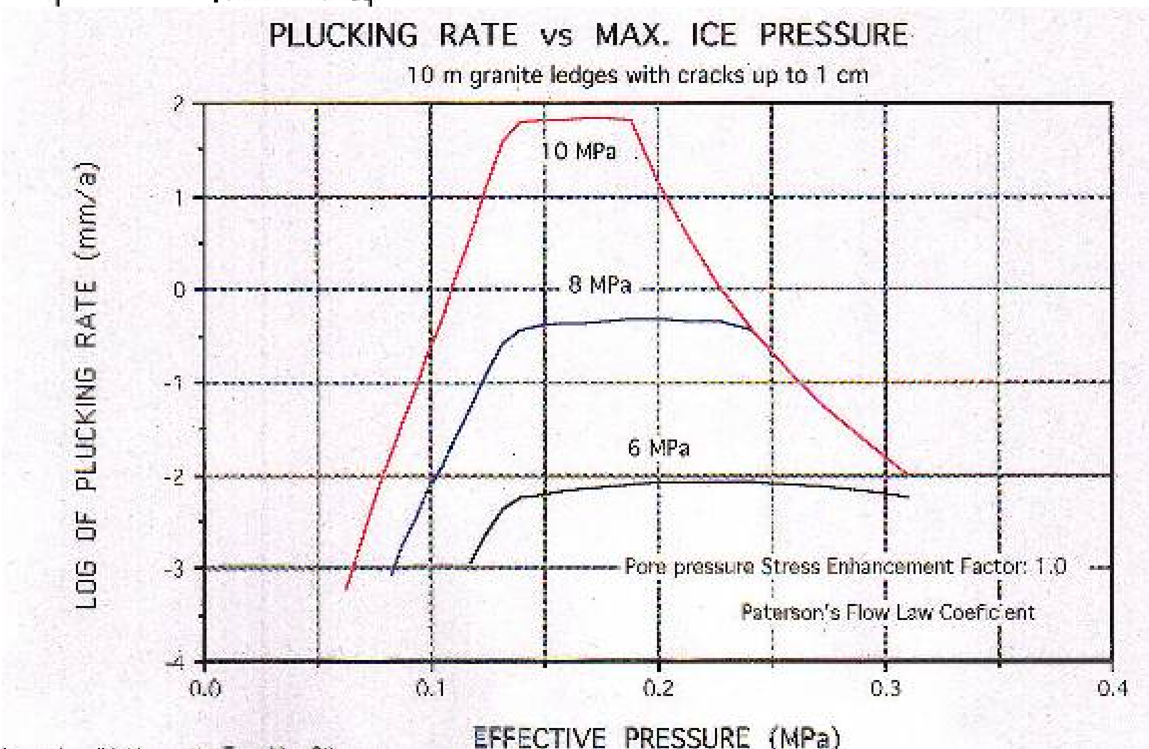
Idealization of glacier bed geometry in quarrying model (Hallet, 1996)

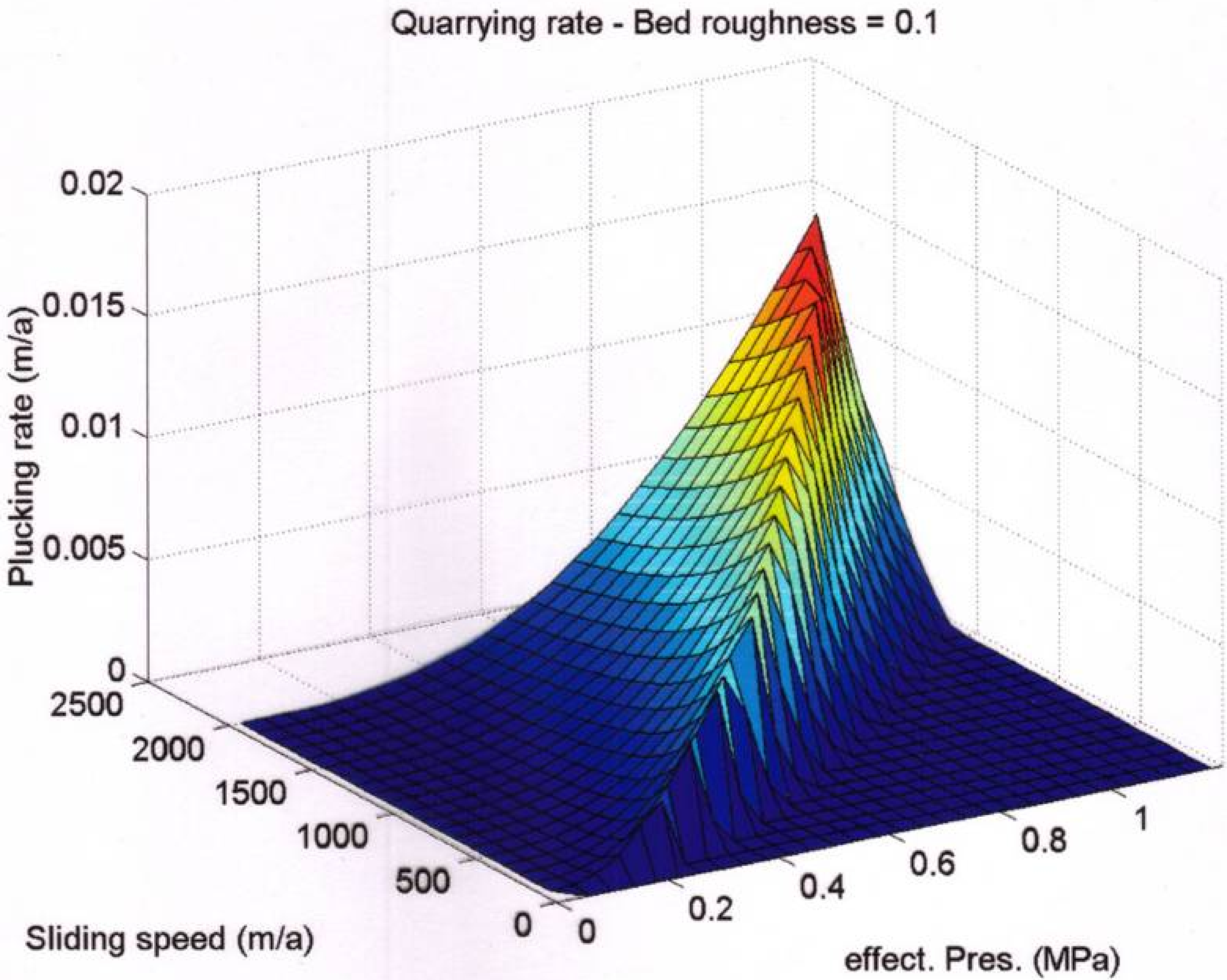
Quarrying model results

Left: ice pressure on ledge edges

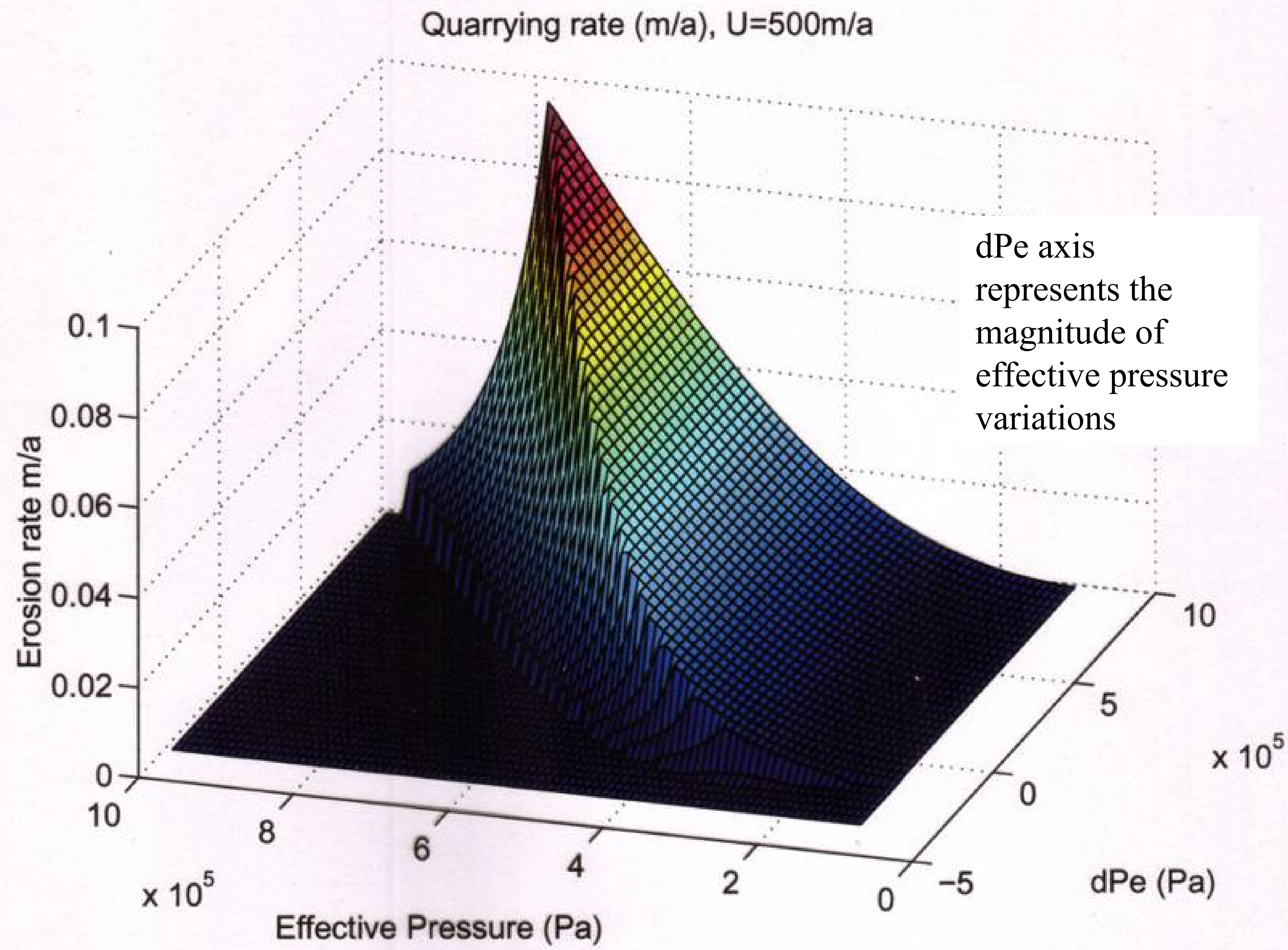
Below: calculated rate of quarrying (plucking)







Quarrying model results from Yann Merrand

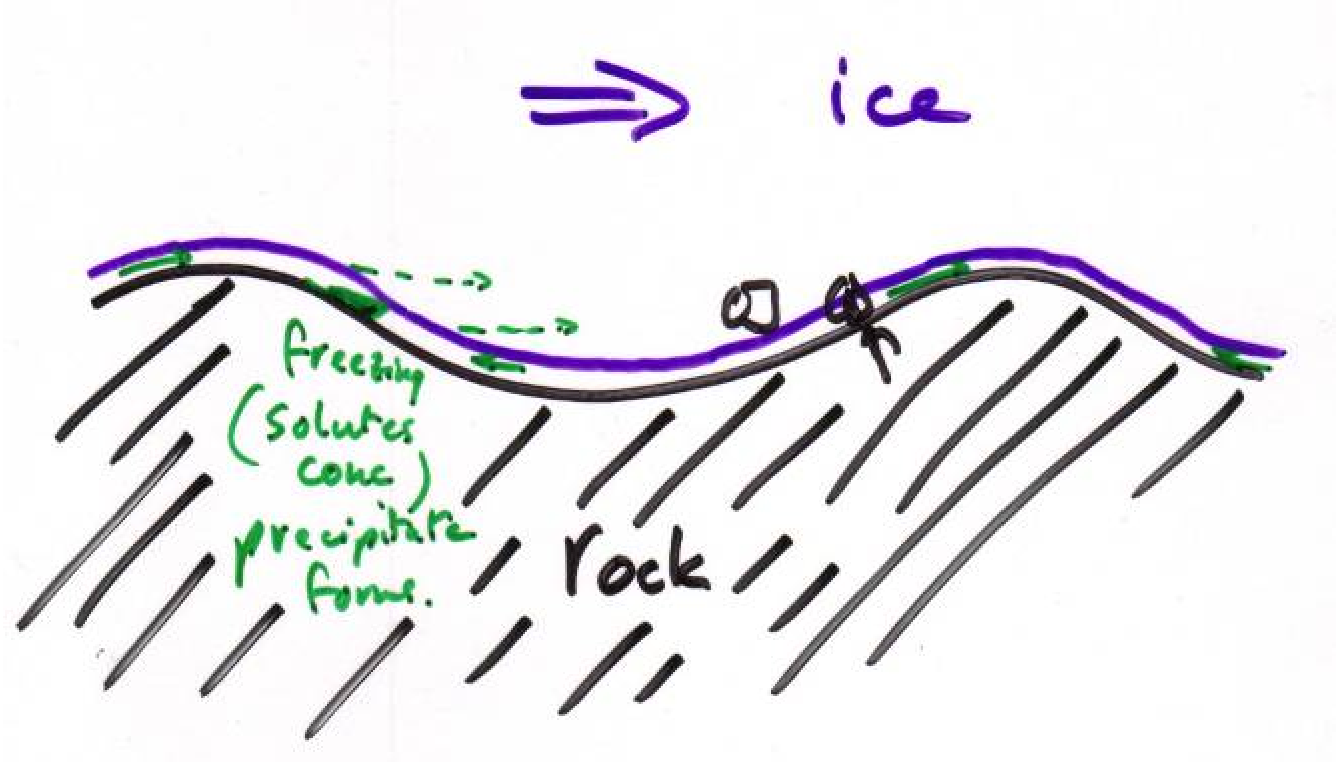


dPe axis represents the magnitude of effective pressure variations

Quarrying model results from Yann Merrand

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.



Subglacial carbonate precipitates

Tierra del Fuego, from J. Rebassa

Glacial polish progressively weathering and spalling off

Glacial polish resists weathering and forms a cohesive layer

Chemical case-hardening: filling micro-cracks?