ESS 431 Glacial Erosion. Dec. 3, 2018

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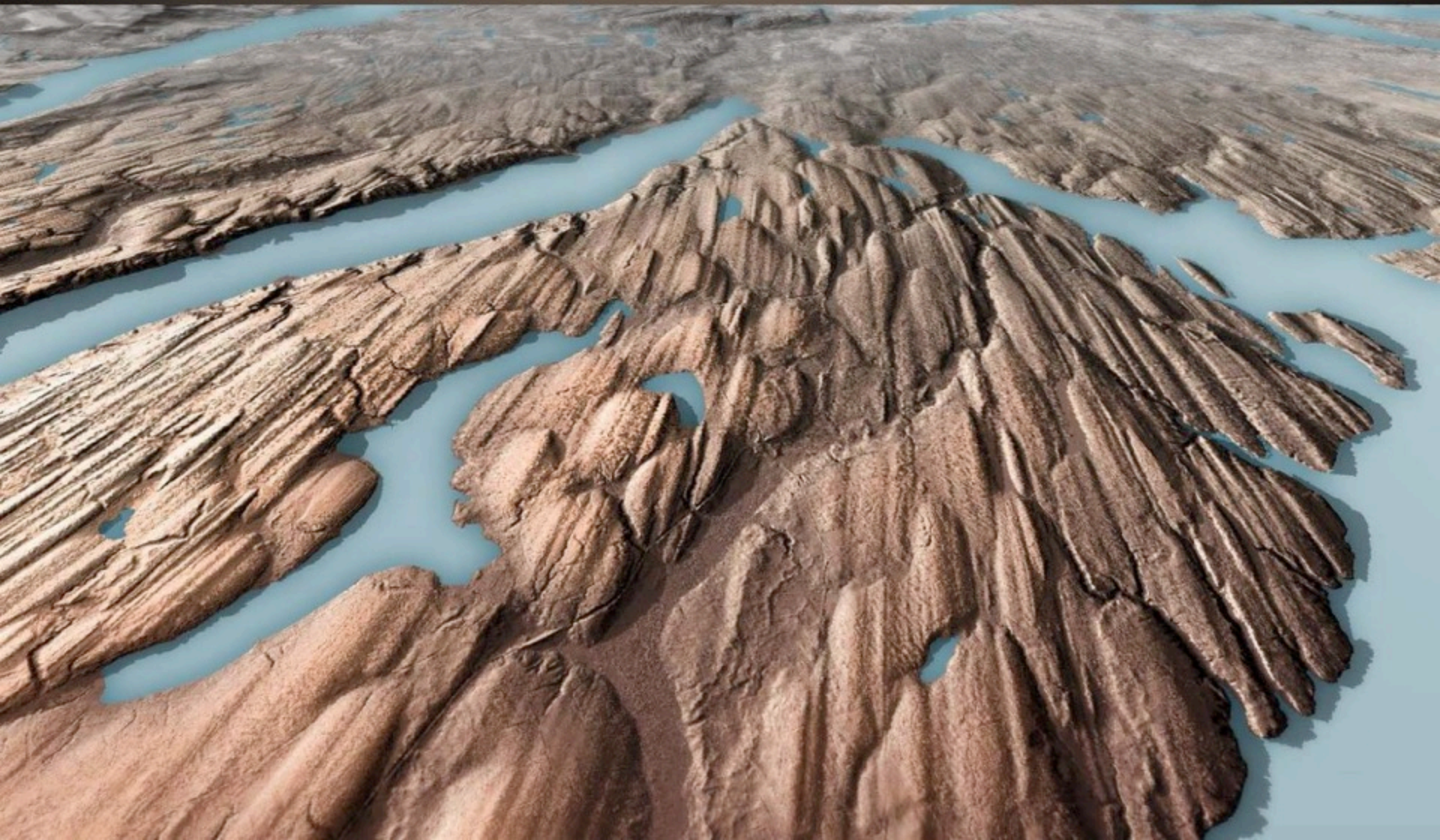
Glaciers: Efficient at shaping the land we live on, carving mountains and producing large quantities of sediments



GLACIAL DRUMLINS
Great Bend of the Hood Canal

Former Puget Lobe. A 1 km of ice over the Seattle area, just 14 and 16 thousand years ago

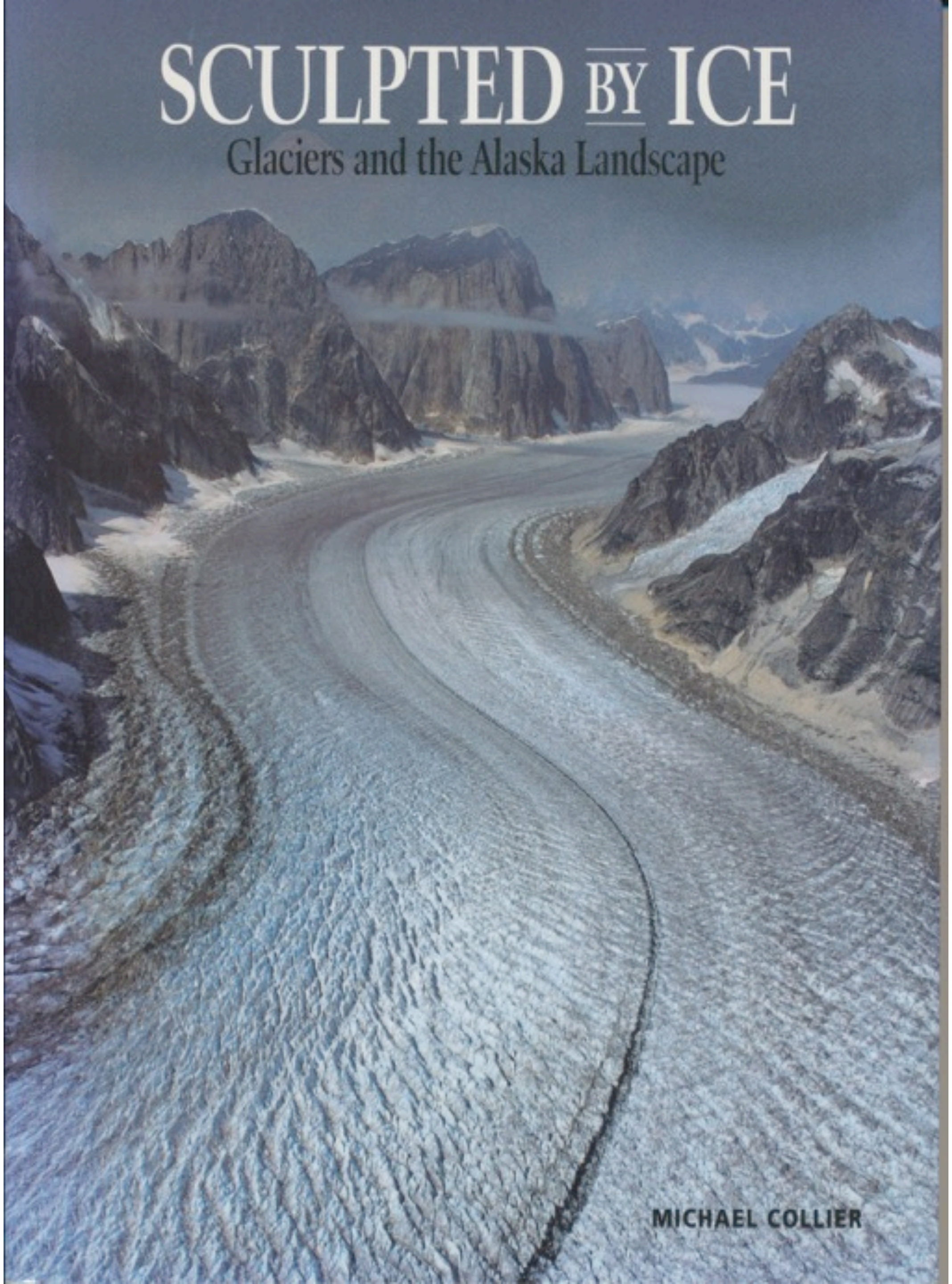
Outline

- Products: large to small
- Insights into processes
  - glacial (regelation, sliding)
  - erosional mechanisms (abrasion, quarrying, etc.)
  - Rates
- Implications

Background: Glacial polish with nano-scale chemcial coating

Why study glacial erosion?

aesthetics and a lot more…



Great Gorge,
Ruth Glacier,
Denali National
Park, Alaska
Published by Alaska
Natural History
Association,
Anchorage, 2004

Alpine character of high mountains: Legacy of glaciers, master sculptors of alpine terrain

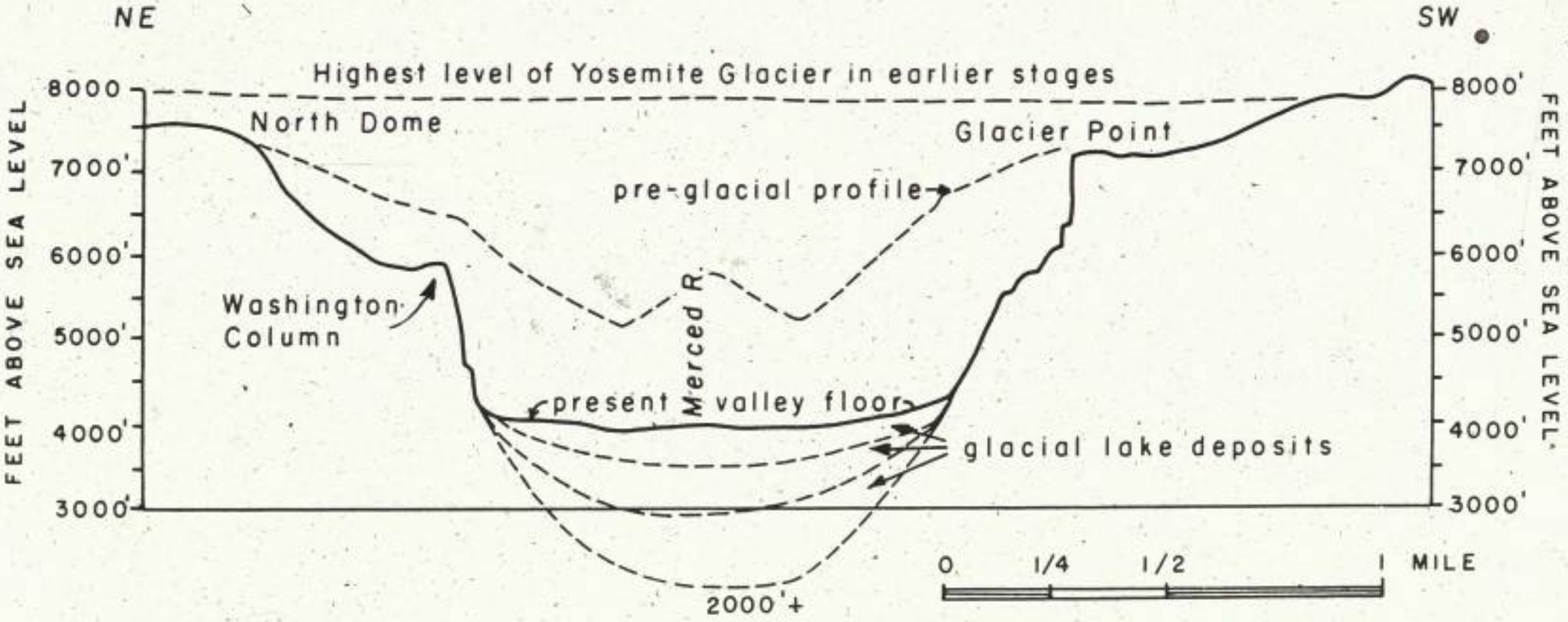
Glacial cirques, tarns, arêtes, & horns in the Sierra Nevada, California

Icons of Glacial Topography:

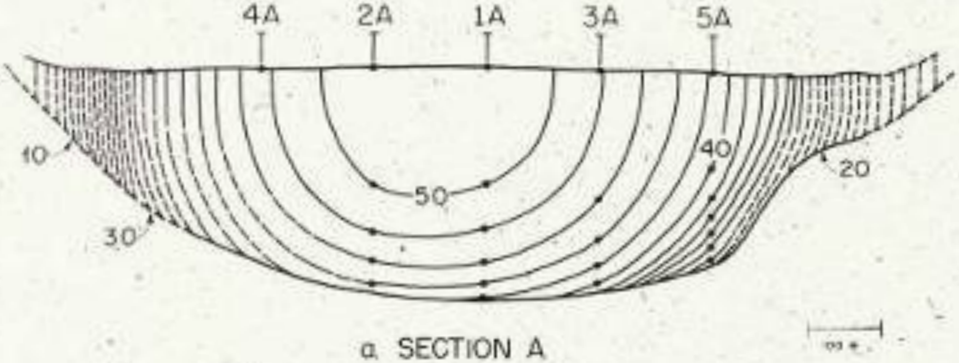
U-shaped valleys, fjords, & hanging valleys

Yosemite Valley

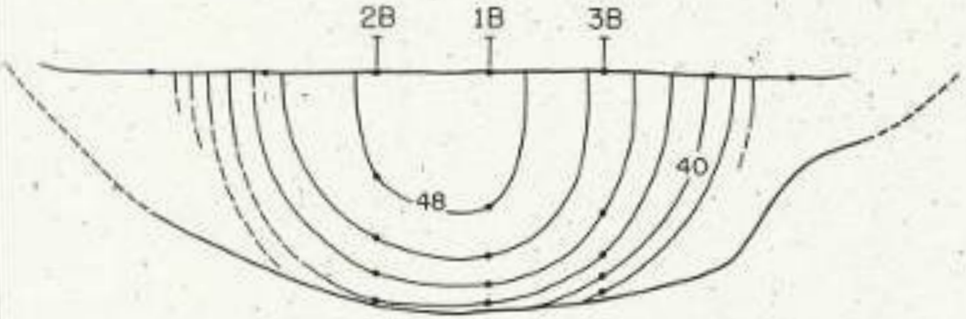
FIGURE 6. Cross-profile of Yosemite Valley between North Dome and Glacier Point (after Matthes, 1930, p. 86, with corrections from Gutenberg and others, 1956, fig. 8).



Ice speed in cross sections at Athabasca Glacier, Alberta, Canada



a. SECTION A



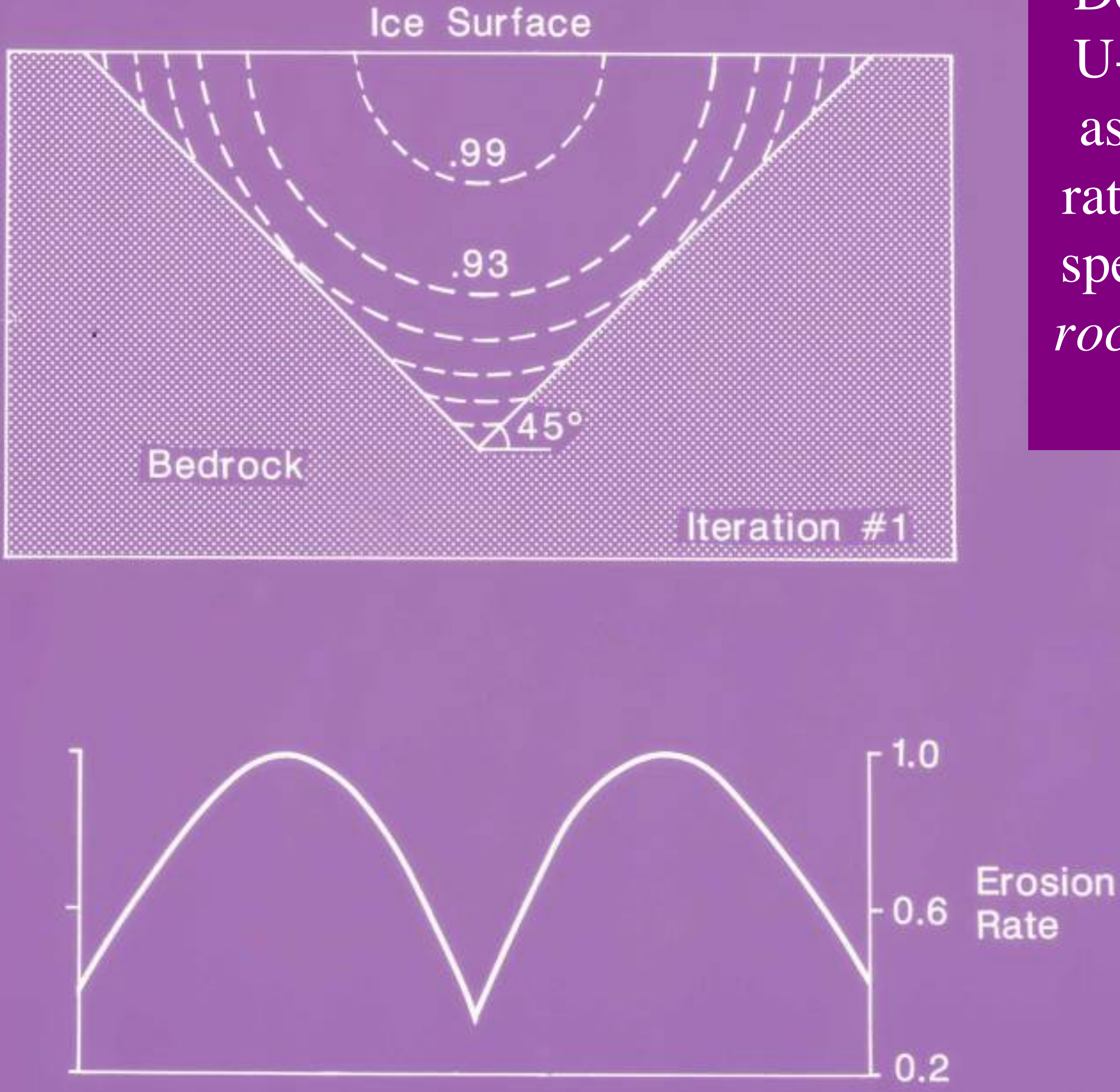
b. SECTION B

c. THEORETICAL

Distribution of longitudinal velocity in valley-glacier cross-sections: (a) measured in section A, (b) measured in ction B, (c) computed by Nye (1965) for a parabolic channel of width ratio 2. Nye's solution has been scaled to cover pproximately the same range of velocity as observed. Units are m a^{-1}.

C. F. Raymond

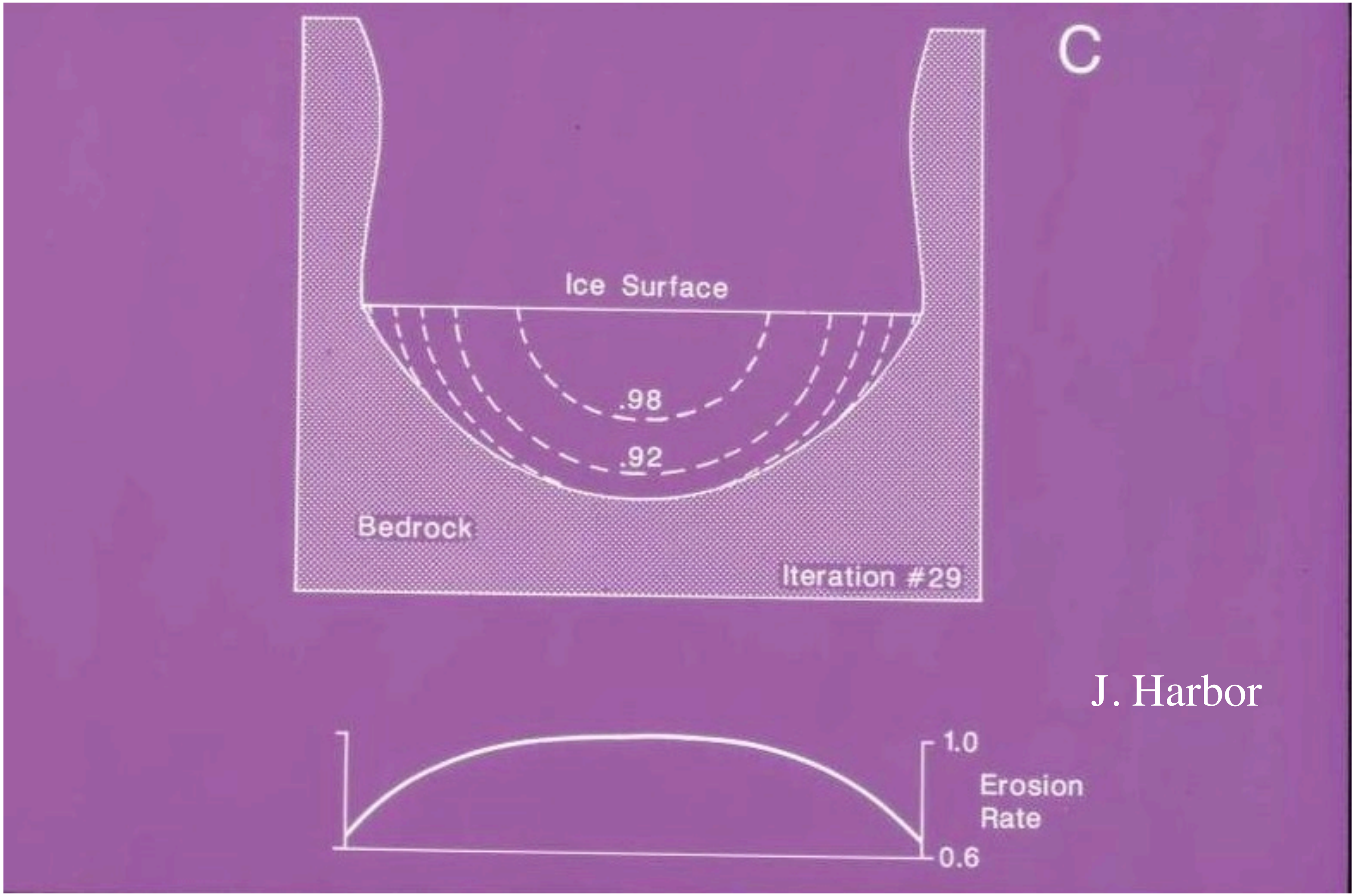
Development of a U-Shaped Valley, assuming erosion rate scales with ice speed *(and that the rock is uniform and erodable)*



J. Harbor

Erosion into Strong Homogeneous Bedrock

(under constant ice flux & without hillslope processes)



J. Harbor

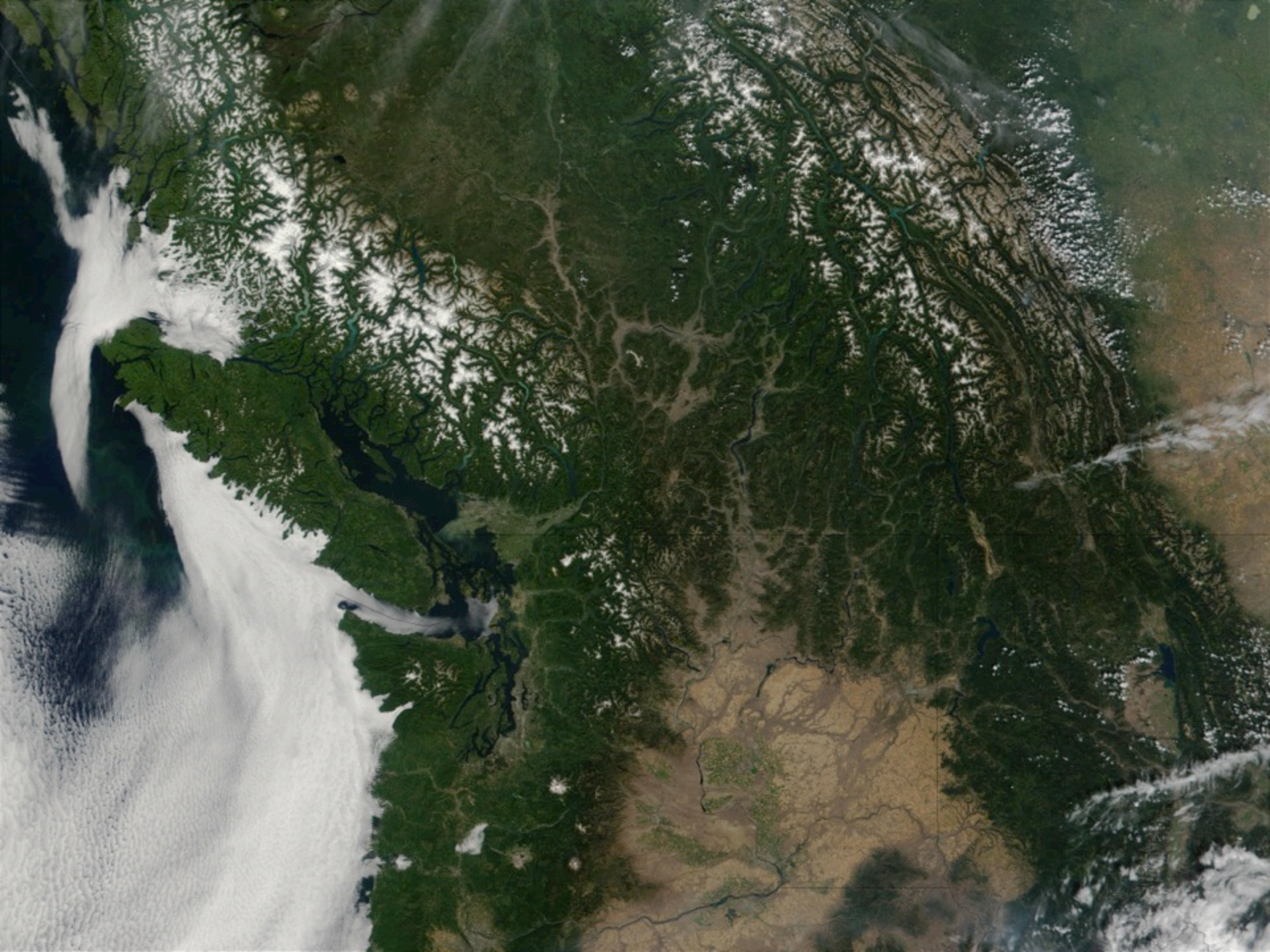
Gejranger, Norway

Cirques

Size is rather uniform and varies from region to region, but New Zealand example on left suggests two sizes. *Ice cream scoop topography, but what sets the scoop size? Also, are cirques deeply incised because glaciers linger there longer than in valley or because headwall or other processes are particularly efficient.*

Fig. 205. Cirques cut into the summit of the Uinta Range during the last Ice Age. Looking west-southwest over the 12,000-foot crest, immediately west of Leidy Peak.

Deep cirque carved into massive, strong granites (tall, near vertical faces), Patagonia

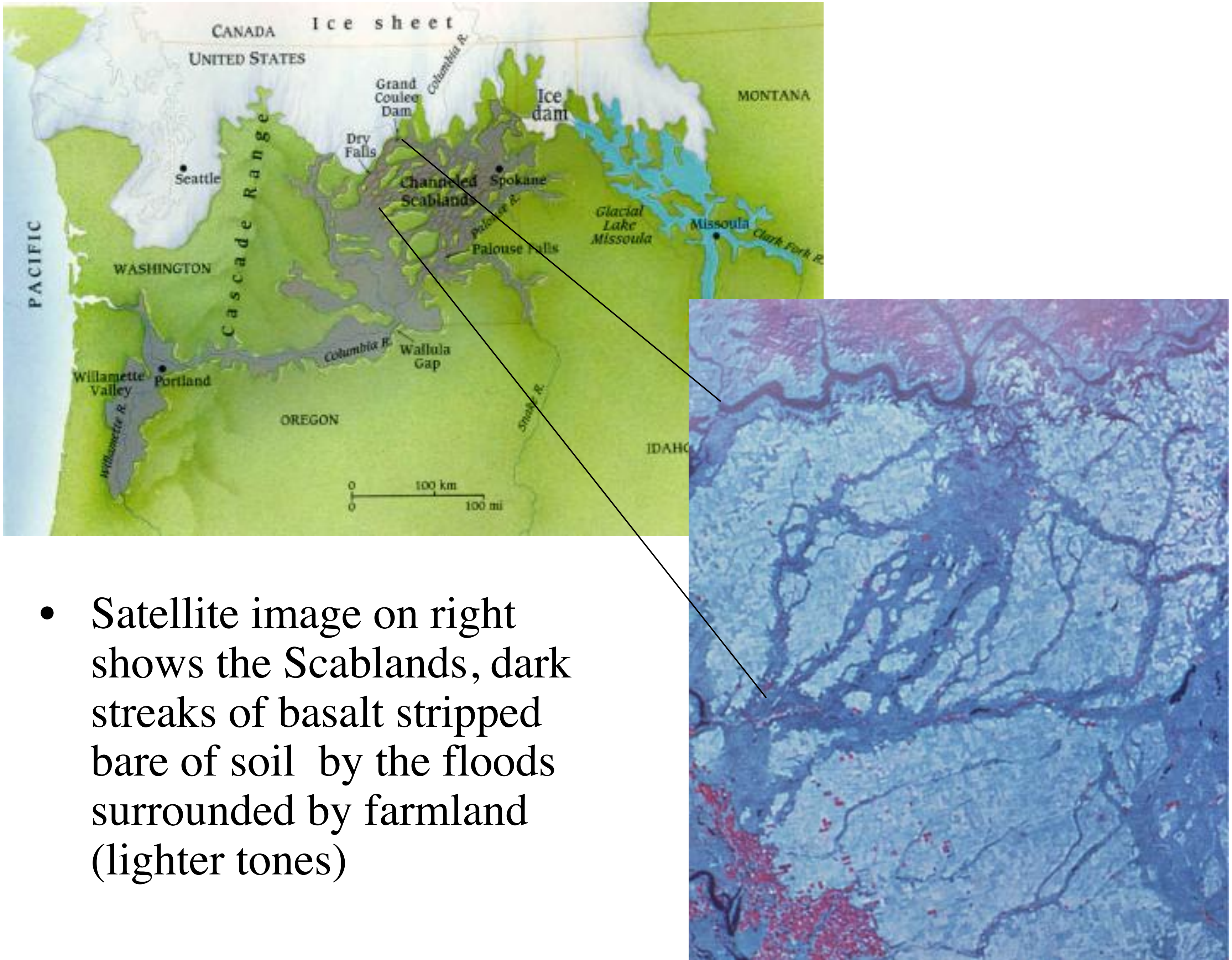


Relevance to Society

Agriculture: Hay--Wash’s bread basket: Palouse Country, below),
Wine—Wineyards are almost entirely on glacially derived sediment

Water
Lakes
Aquifers
(incl. Seattle & Spokane’s water supply)
Polution
(Hanford)

Evidence of ice from British Columbia and the resulting megafloods are clear from space



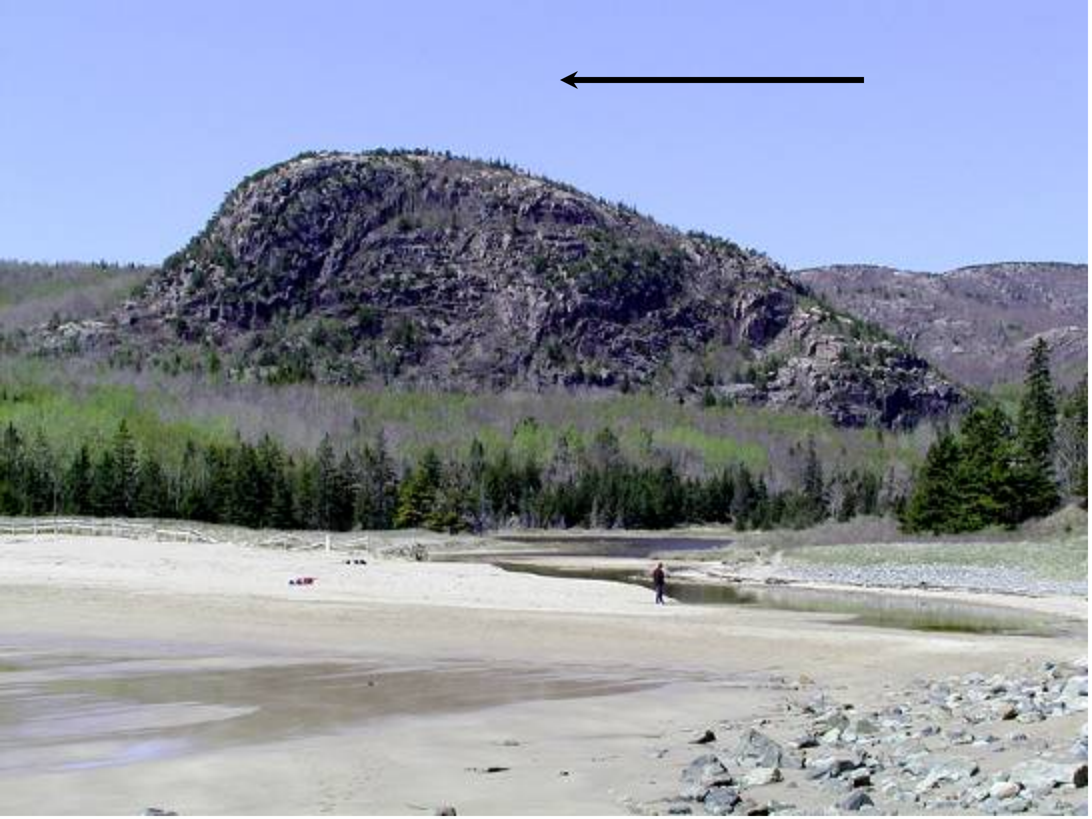
- Satellite image on right shows the Scablands, dark streaks of basalt stripped bare of soil by the floods surrounded by farmland (lighter tones)

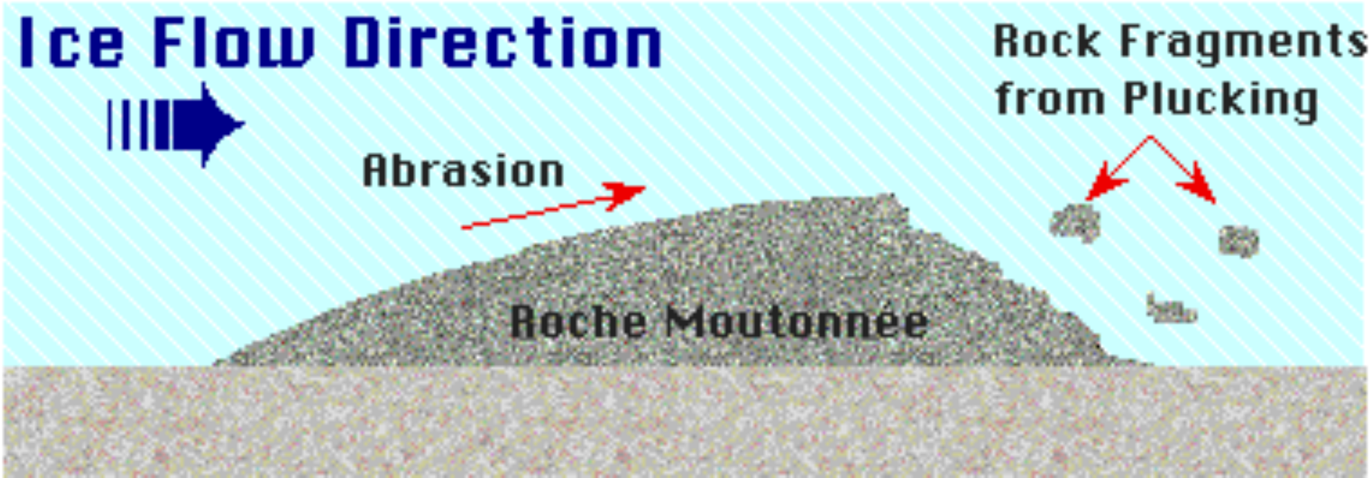
Erosion Processes - 1

Quarrying – Plucking large rock fragments

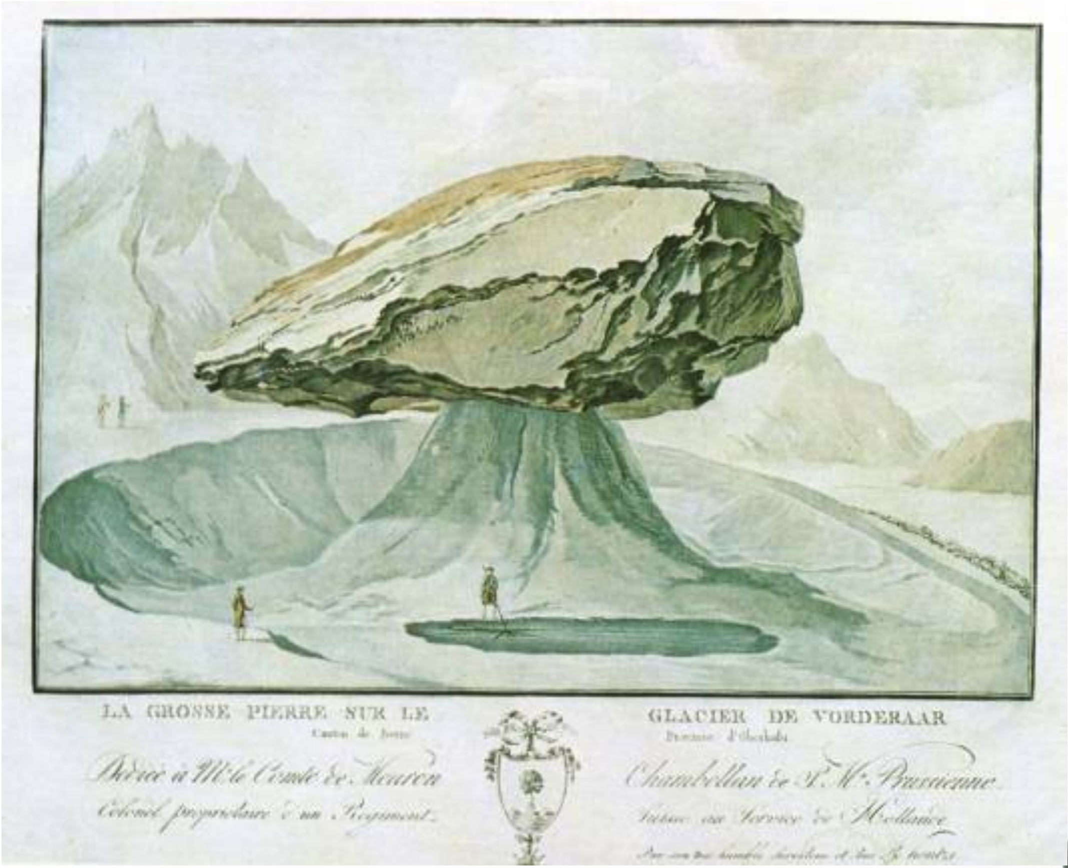
- **Evidence:** fractured bedrock, large glacial erratics
- **Diverse lines of evidence points to quarrying being dominant bedrock erosion processes**:
  - asymmetry of erosional forms
  - asymmetry of cosmogenic ages: old ages on abraded surfaces (quarrying rates > 10 times abrasion rates)
  - theoretical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

Roches Moutonnées





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



Erosion Processes - 2

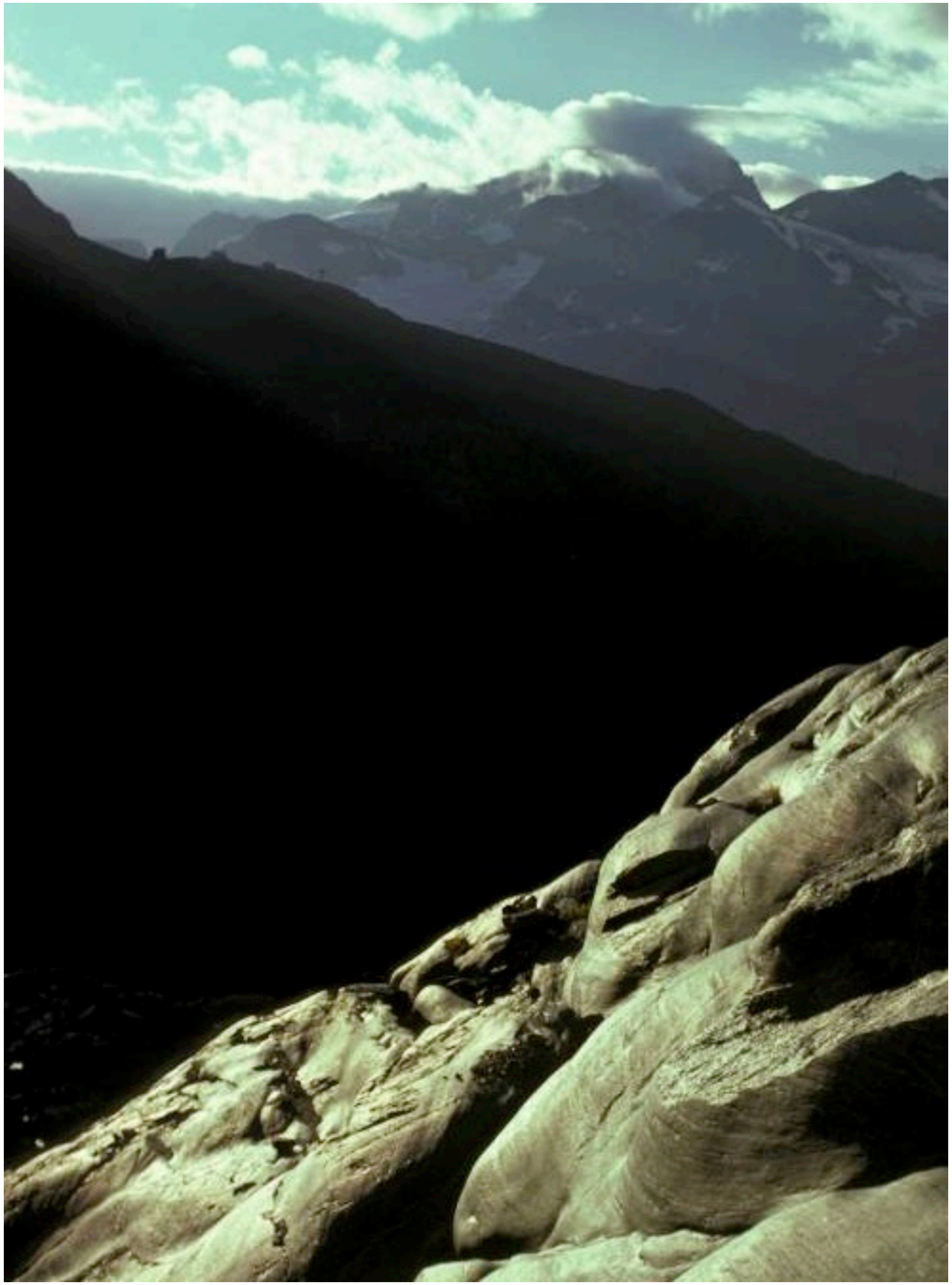
- Abrasion: dominant producer of fine sediments, but may account for < 10% of bedrock erosion.

- 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.

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

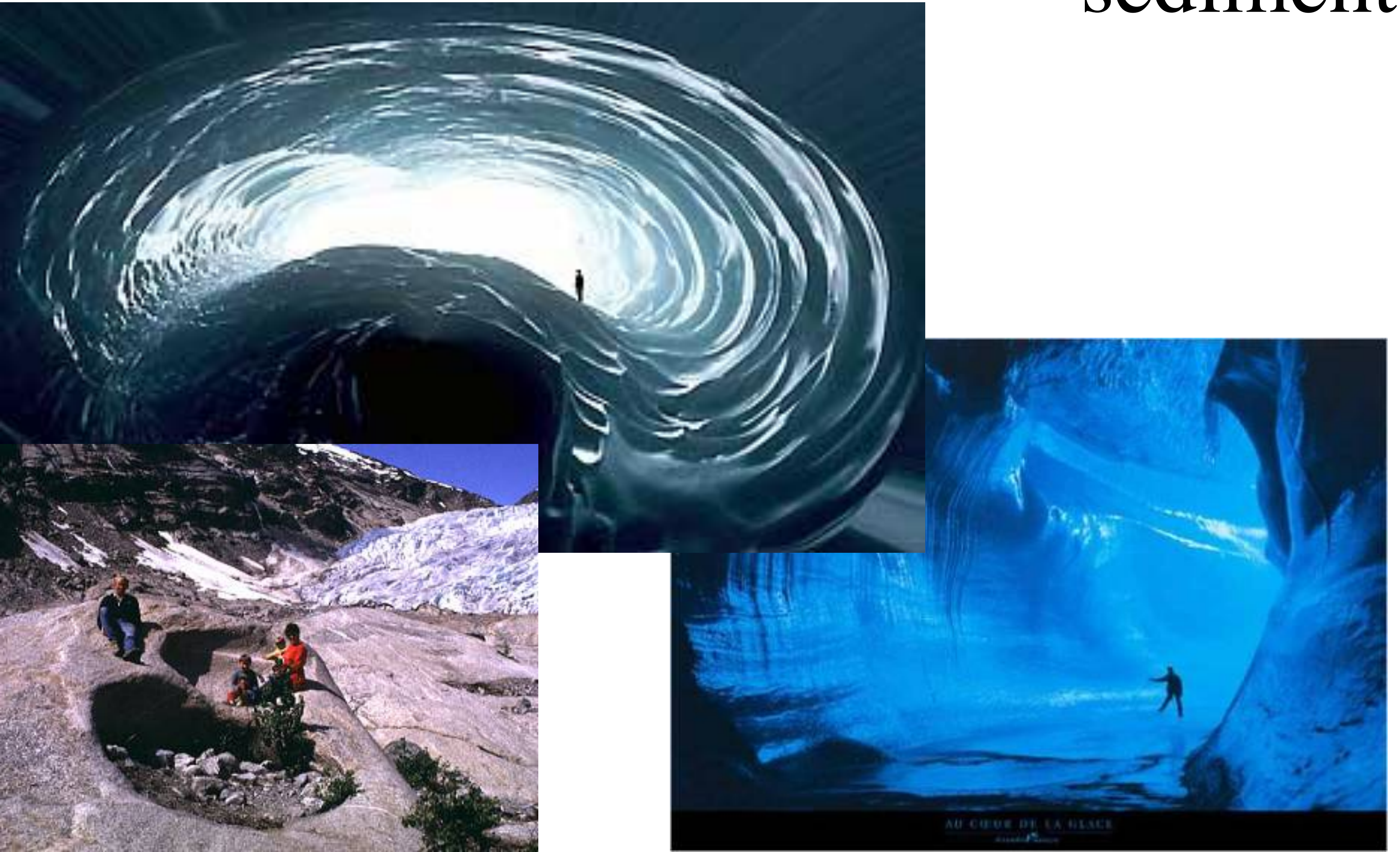
Striations & Polish

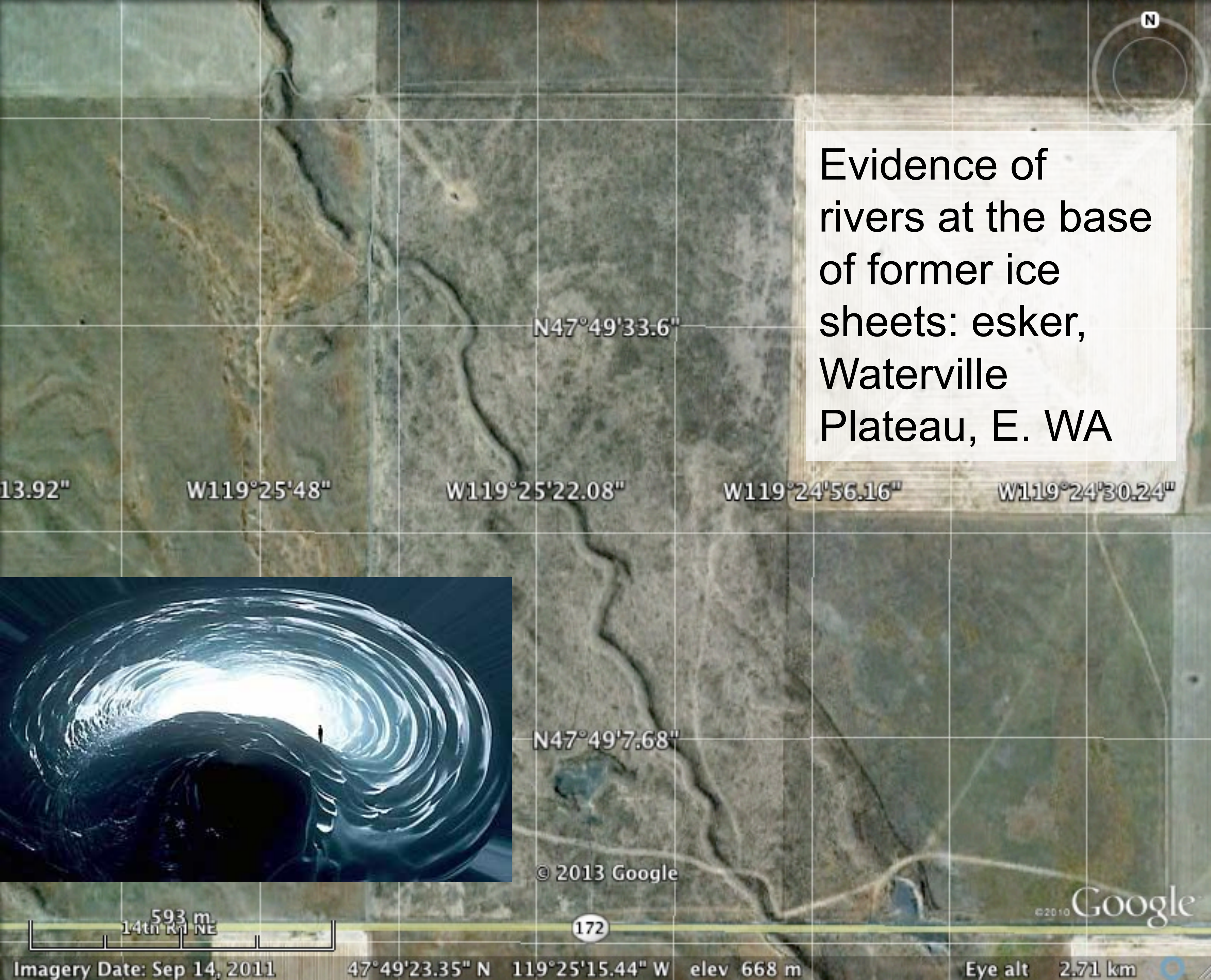


Smooth, striated bedrock forms produced by abrasion dominate the view looking down valley. Relatively rough and fractured bedrock surfaces produced by quarrying would dominate the view looking up-valley.

Near Zermatt, Switzerland

Subglacial rivers erode ice, rock and sediment





Evidence of rivers at the base of former ice sheets: esker, Waterville Plateau, E. WA

Broad Controls on Rates of Glacial Erosion

Erosion rate, E, increases with sliding velocity, U ($E \sim 10^{-4} U$), and ice flux. This flux is, in the 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, and pervasive damage that tend to reflect the tectonic setting)

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

Deep fjord sliced into upland that is hardly eroded: cold glacial ice protects uplands while incising and broadening valleys

http://www.xrez.com/h3dsphere_giga.html

A closer look at erosion mechanisms

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

Abrasion: factors affecting rate

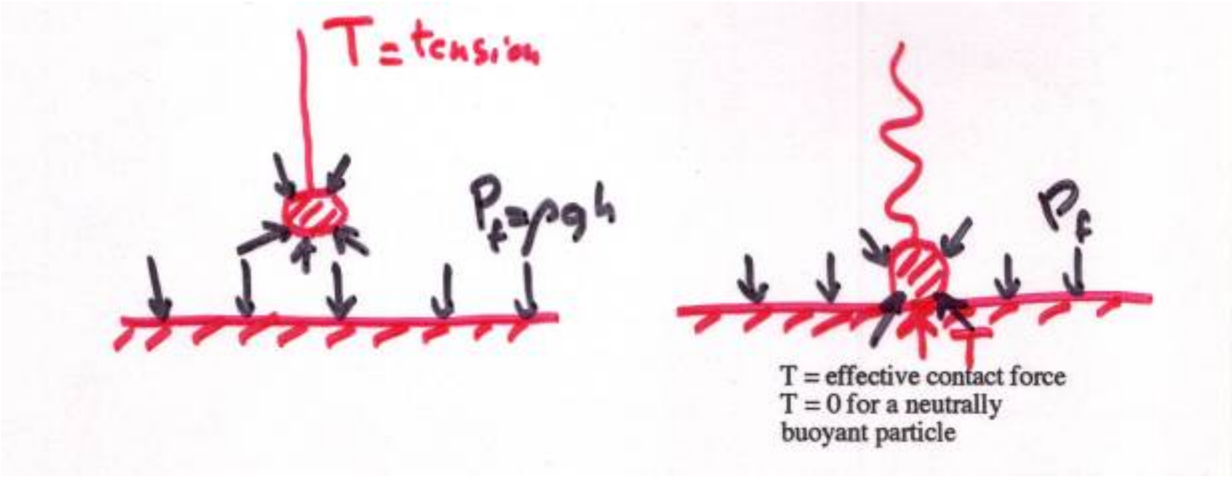
- # cutting tools: rock fragment concentration
- fragment velocity

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



T = effective contact force
T = 0 for a neutrally
buoyant particle

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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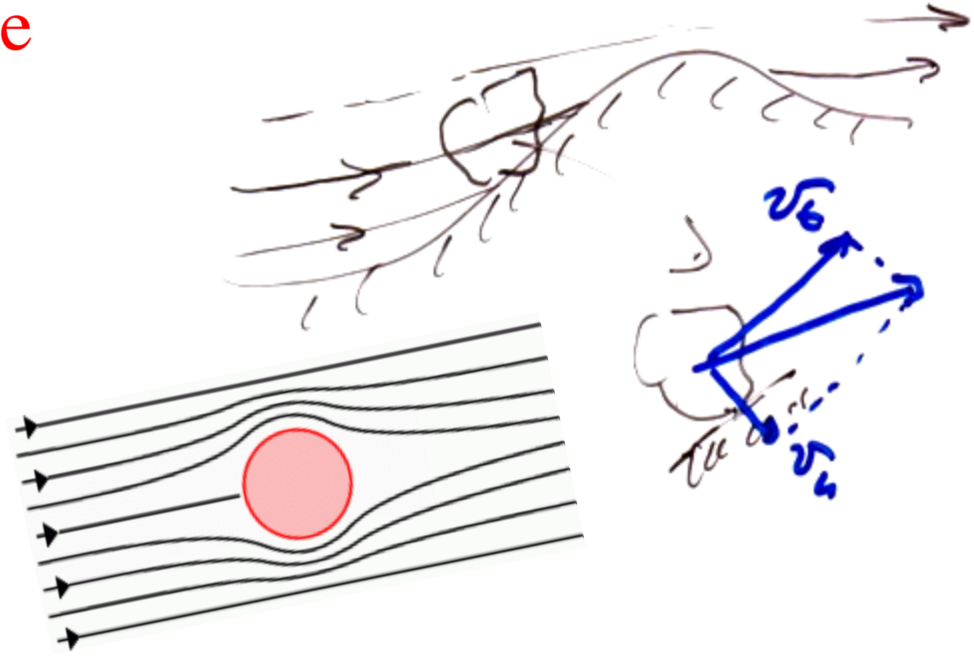
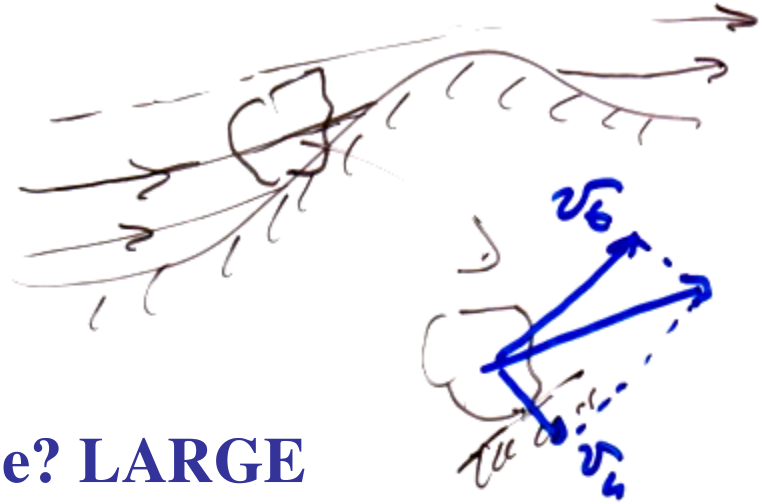
Factors affecting contact force

- Ice pressure: not important, nor is glacier thickness (controversial, common misconception)
- Gravity: not important - vertical bedrock surfaces are often striated, as are overhangs
- Viscous forces

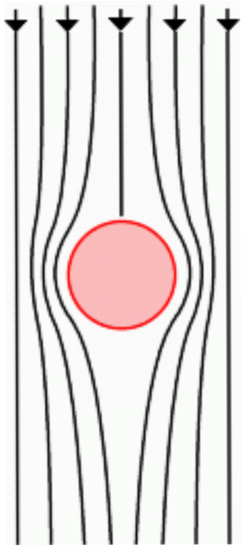


Viscous force: a rough estimate

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 ($3\text{x}10^{12}$ 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:

6 π 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 increase 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, where μ is the coefficient of friction (rock-on-rock)

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

- Thus, the rate of glacial abrasion ($\text{Å} = \alpha F_c v_p C$) is proportional to the rate at which work is being done on rock/rock friction, and to the square of the velocity.

What can we learn by looking under glaciers?

Grinnell Glacier, Montana

Work in subglacial cavities in early 1980s

Scurlock Photo 2008

Looking up glacier at ice sliding over a rock ledge under 10-20m of ice at Grinnell Glacier: signs of active rock fracture

Measuring ice speed with circular saw blade cantilevered against ice roof under 10-20m of ice at Grinnell Glacier: ~15 m/yr

Early observations related to abrasion: Junfräujoch, Swiss Alps

From Carol (1947, J. Glaciol.)

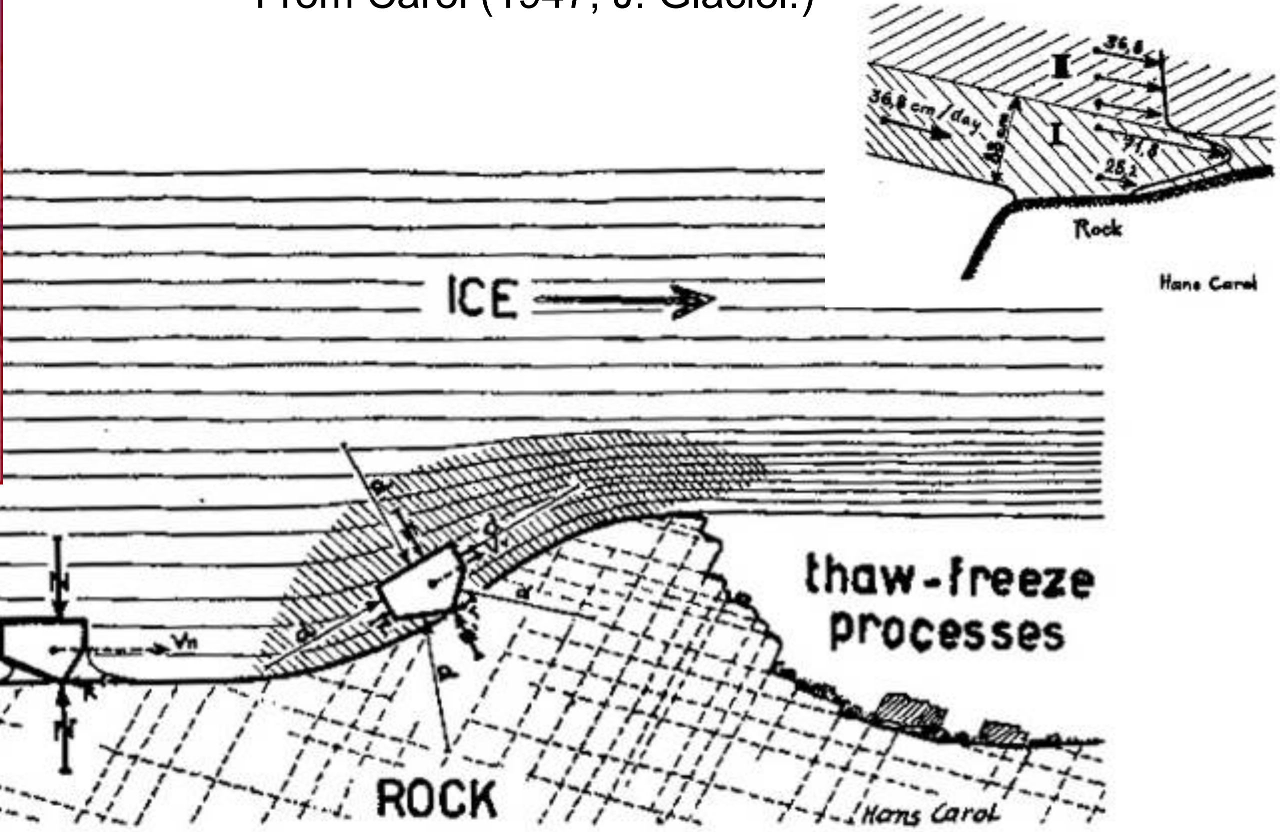


Fig. 7. Diagrammatic representation of a roche moutonnée forming under a living glacier. The hatching indicates the area of semi-fluid conditions

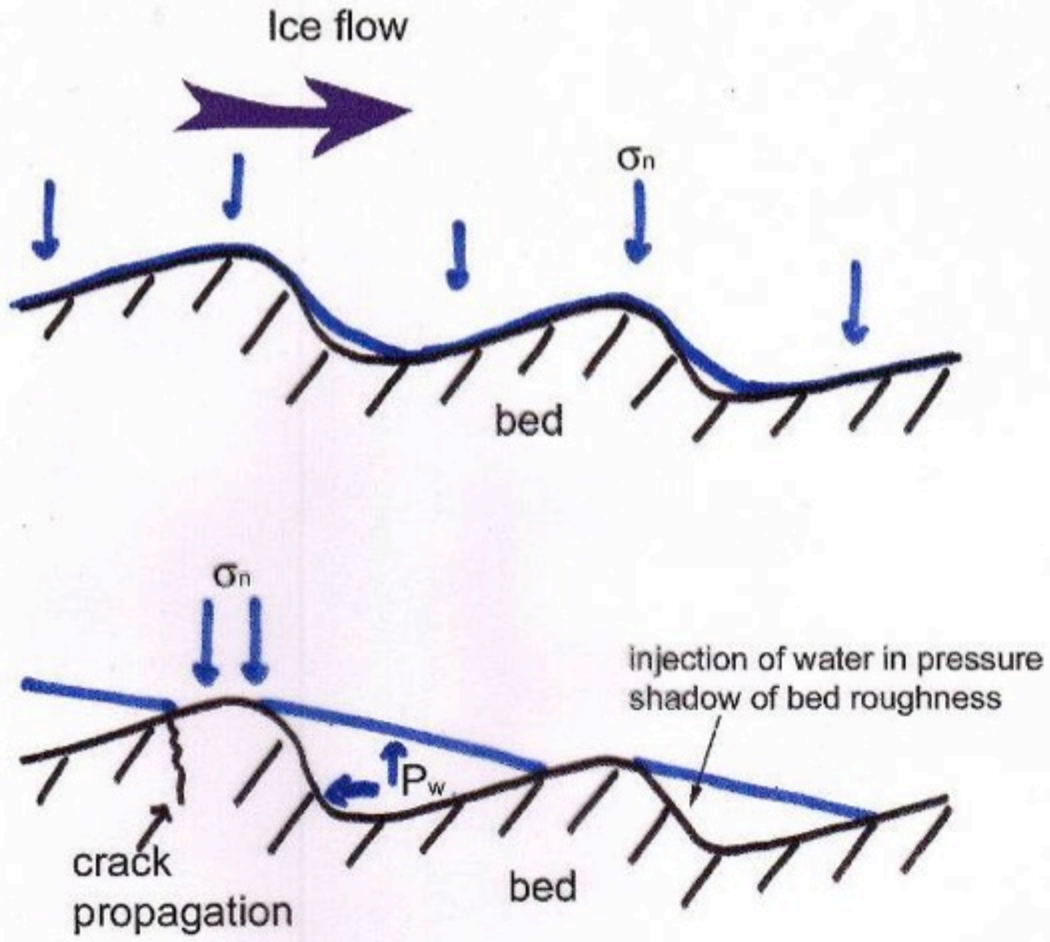
N pressure of superincumbent ice upon eroding stone
R, frictional resistance
Vn, normal speed of ice-flow
dd, hydrostatic pressure
n, reduced pressure upon stone
r, reduced frictional resistance

150 m-thick, clean ice sliding over bare bedrock, Bondhusbreen

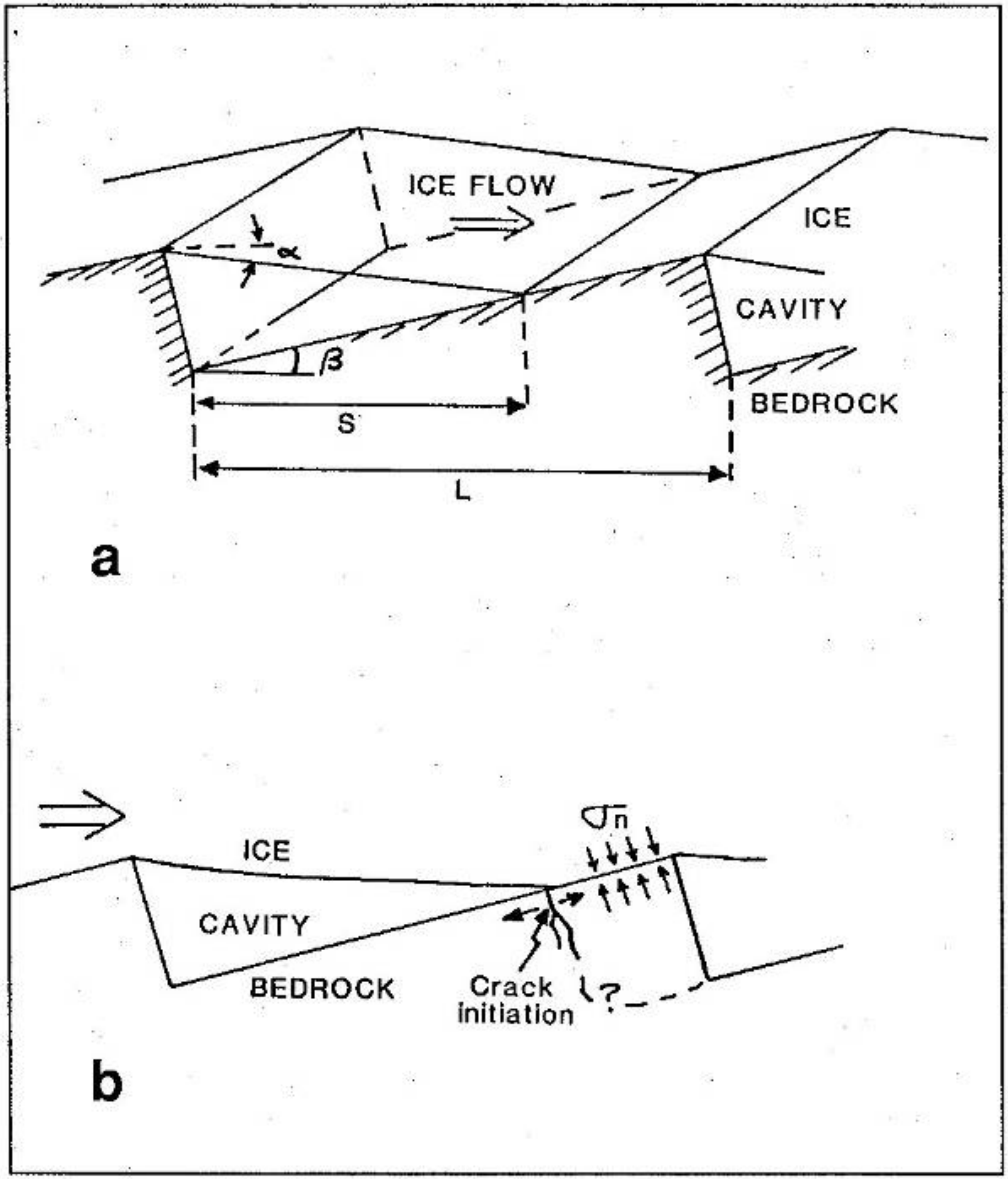
Extensive cavities under 10-20m of ice at Grinnell Glacier

Cavitation, stress concentration and quarrying

(sketch from Y. Merrand)

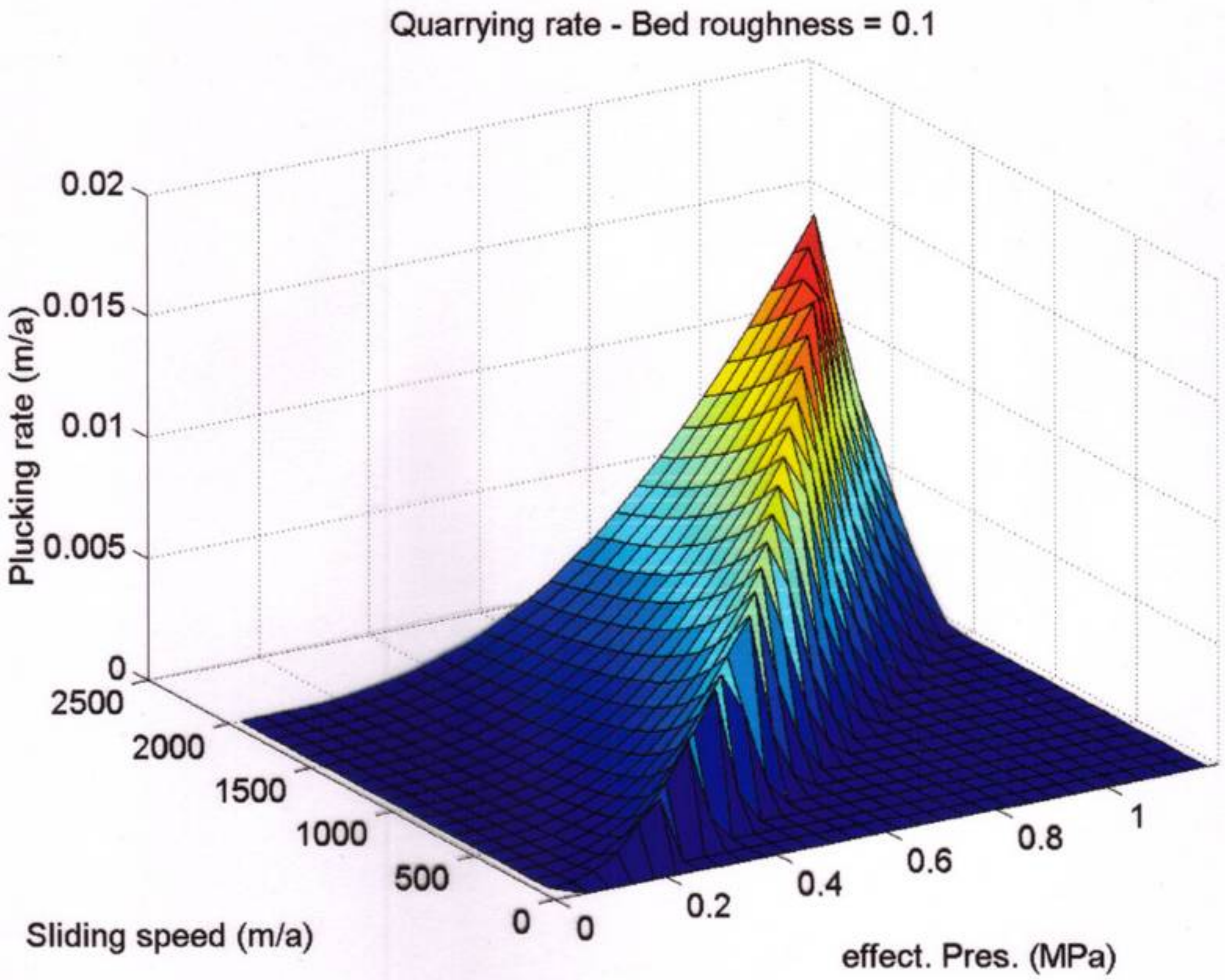


Results in high water pressure, drowning of bed roughness, high rate of sliding, large deviatoric stress about roughness element and crack growth



Idealization of glacier bed geometry in quarrying model

(Hallet, 1996)

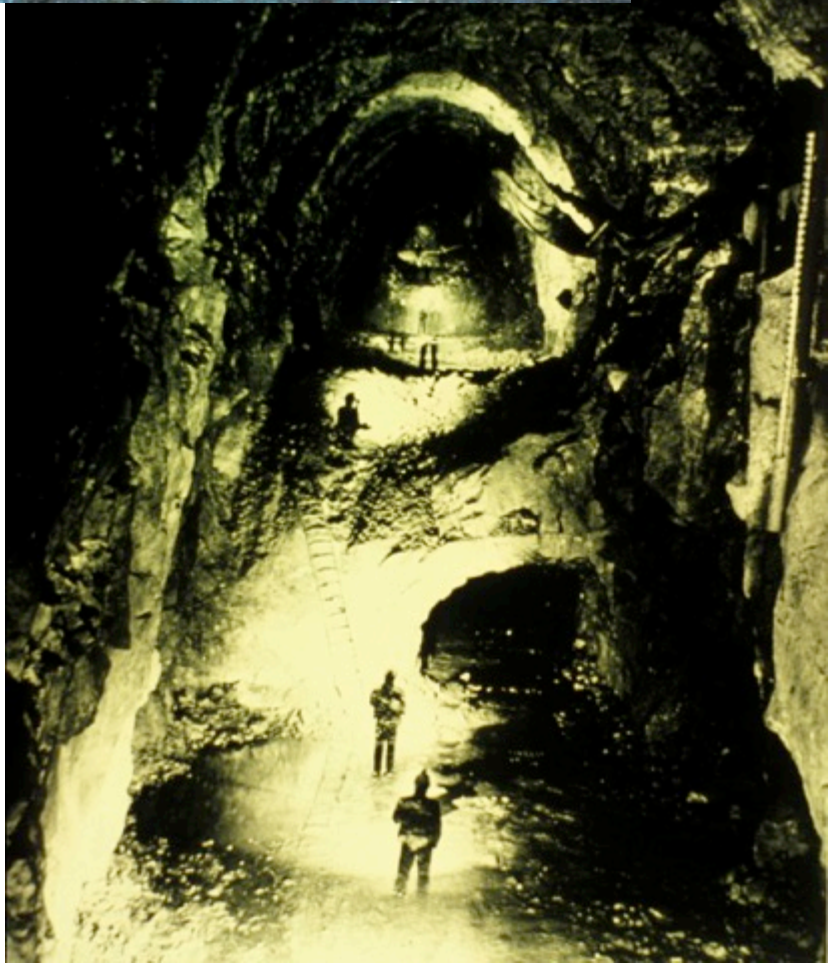


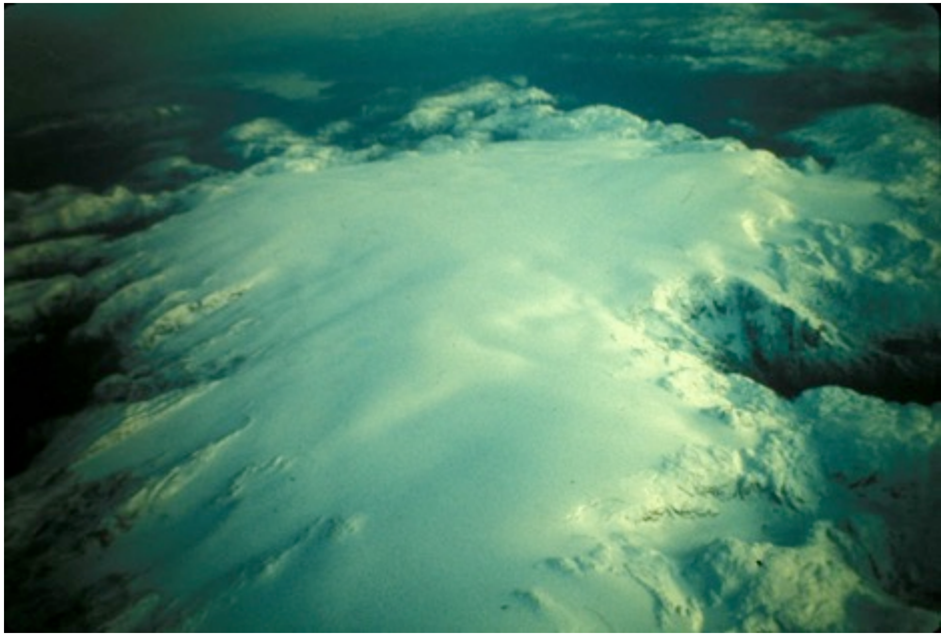
Quarrying model results from Yann Merrand

Views under thicker ice using hydroelectric tunnels

Big boulder (~1 m-dia) in subglacial stream, Glacier d’Argentiere, France

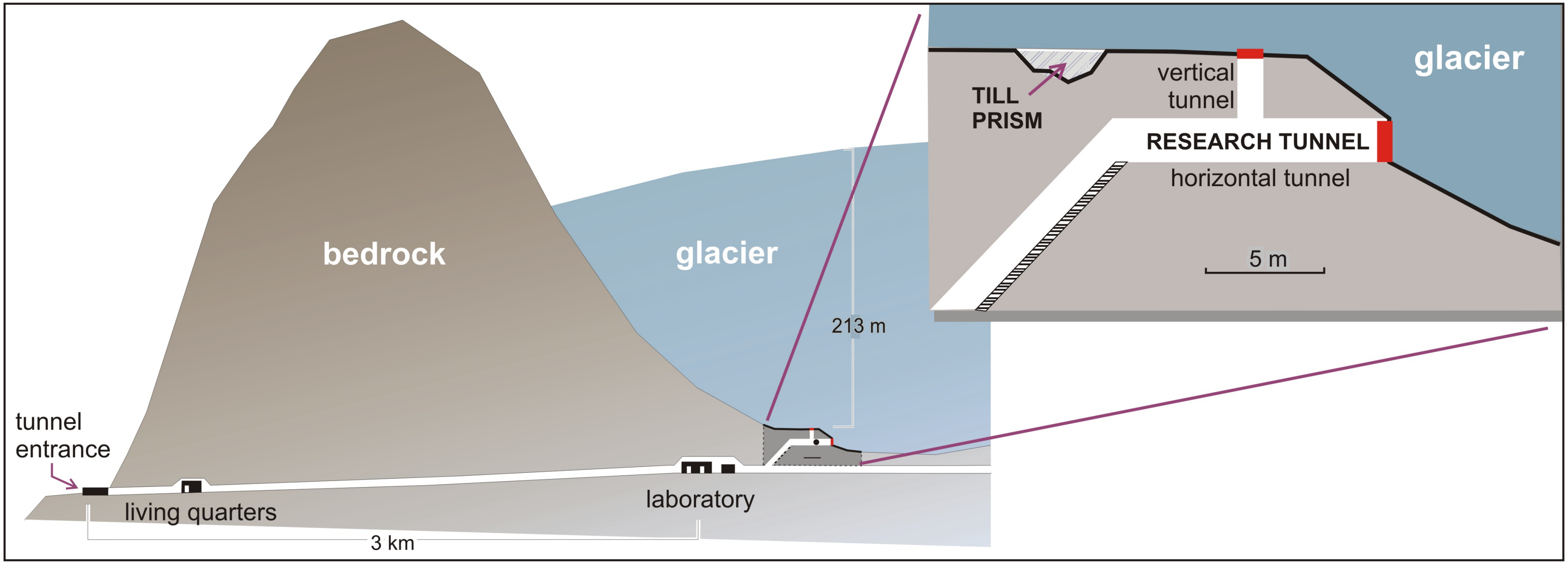
Bondhusbreen, S. Norway





Subglacial sediment trap
emptied annually

Checking aspects of theory under glaciers



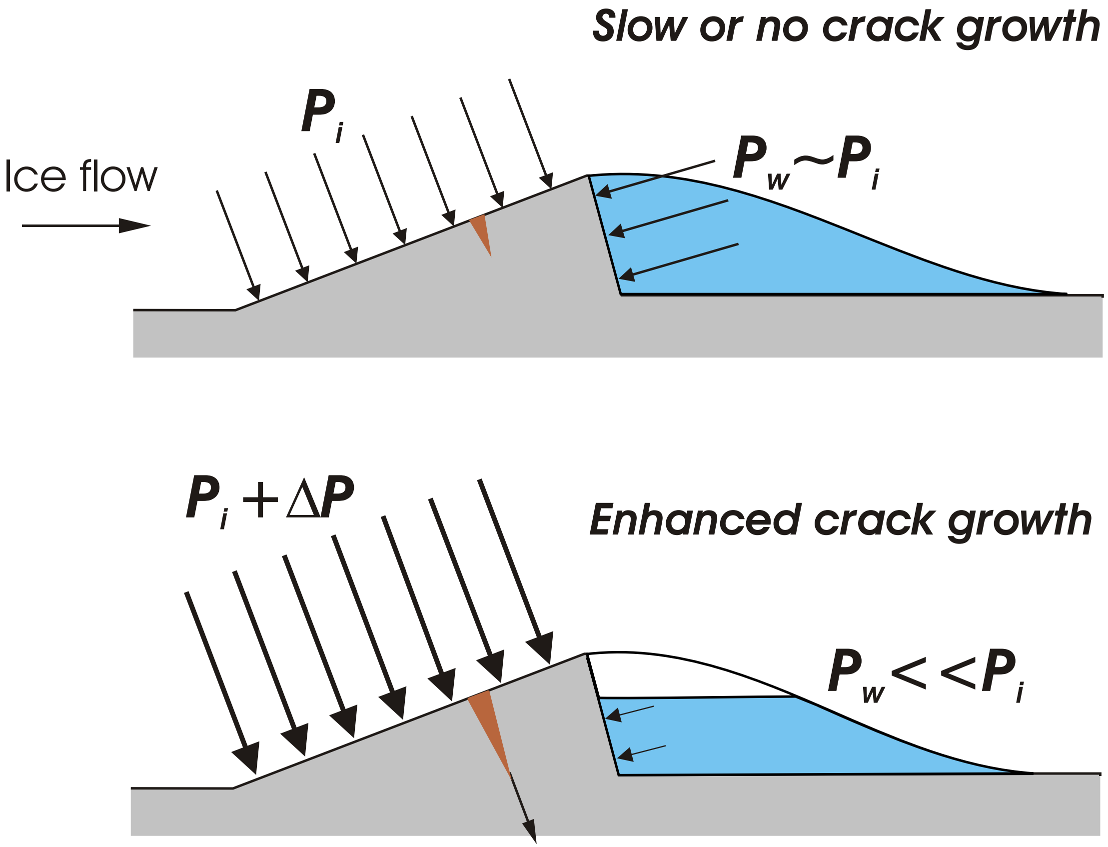
Under 210 m of ice at Engabreen, Norway

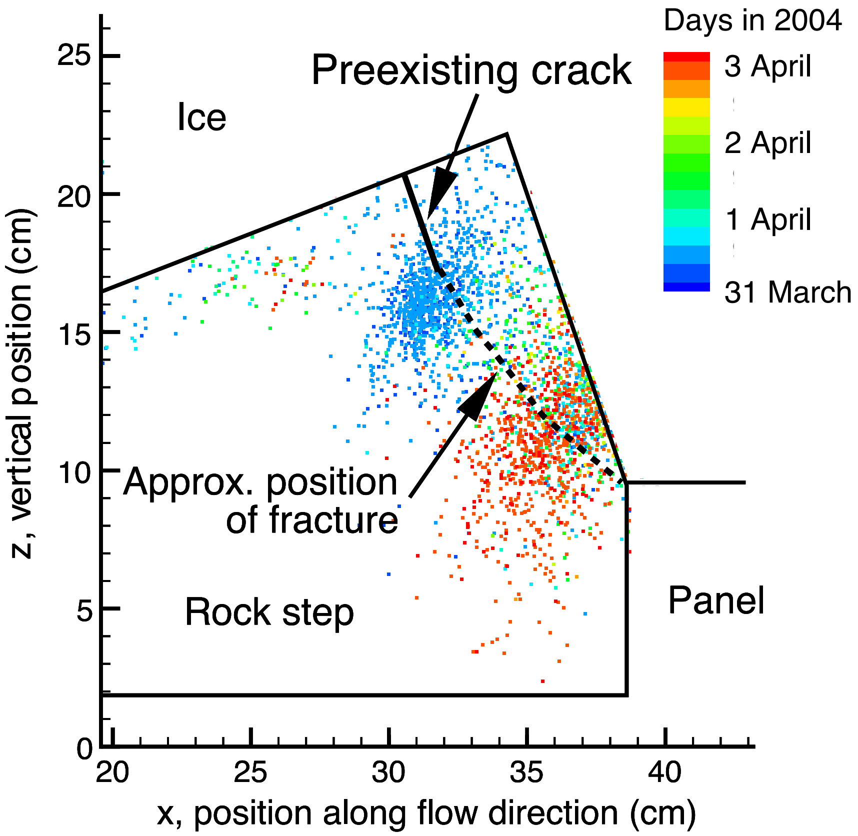
Sketch courtesy of Cohen and Iverson

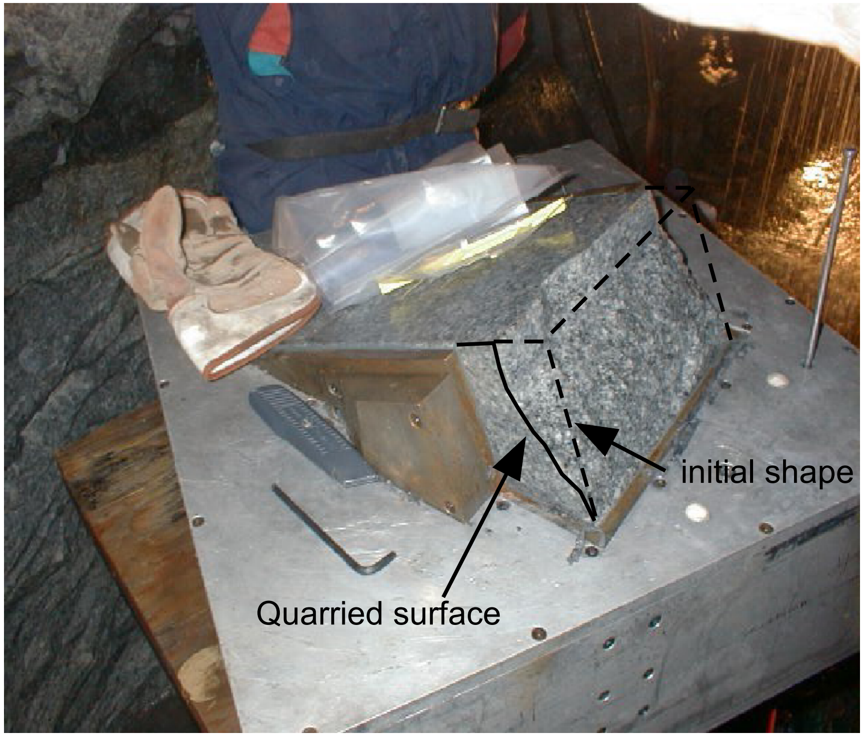
Field evidence for water pressure transients increasing rates of quarrying

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

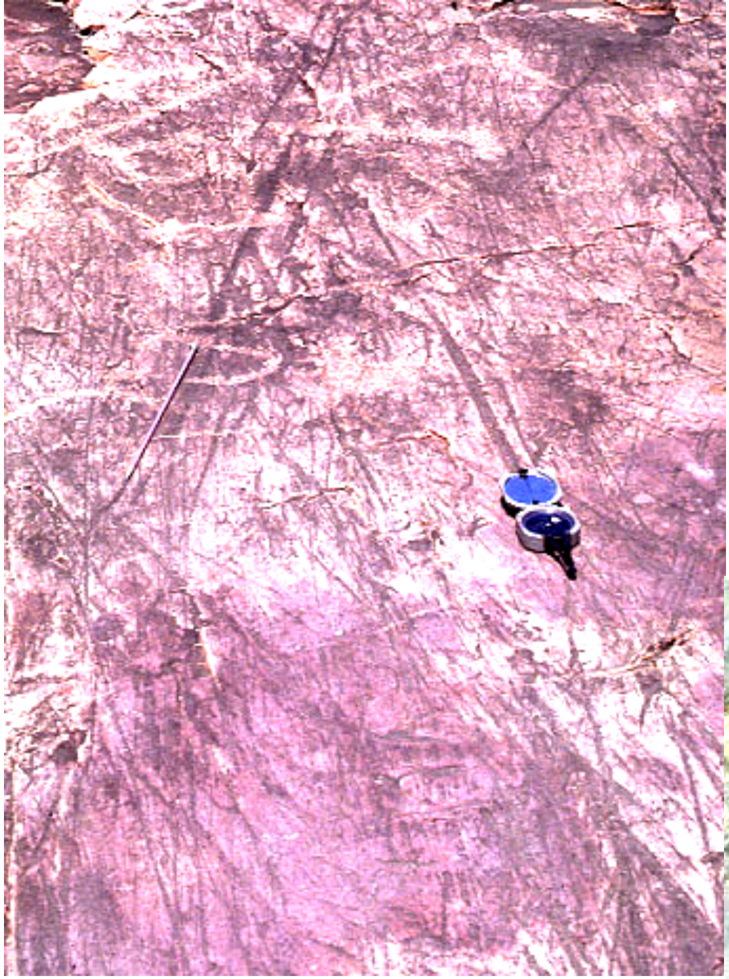



Days in 2004
3 April
2 April
1 April
31 March
Preexisting crack
Ice
Approx. position
of fracture
Rock step
Panel
z, vertical position (cm)
0
5
10
15
20
25
20
25
30
35
40
x, position along flow direction (cm)


initial shape
Quarried surface

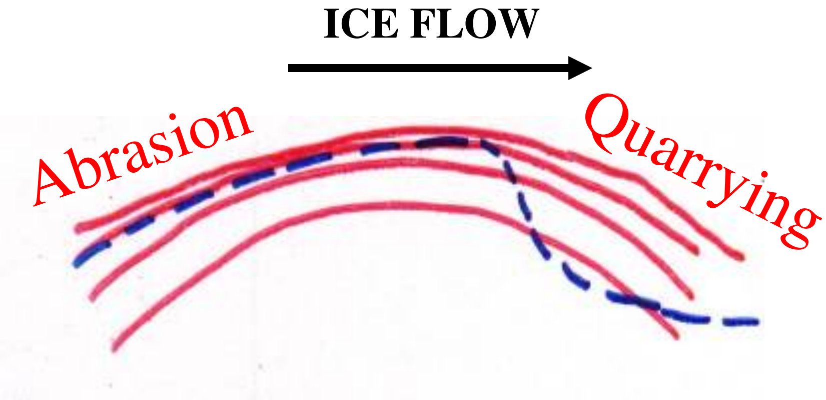
Abrasion is slow

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.



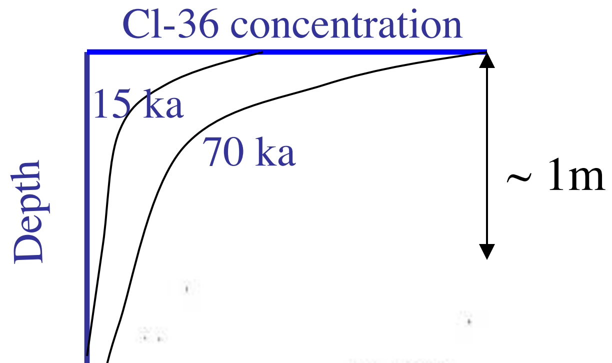
They suggest that abrasion is very slow, since earlier striations are not removed. Abrasion is limited to mms in 10^2-10^3 yrs.

Relative importance of abrasion and quarrying



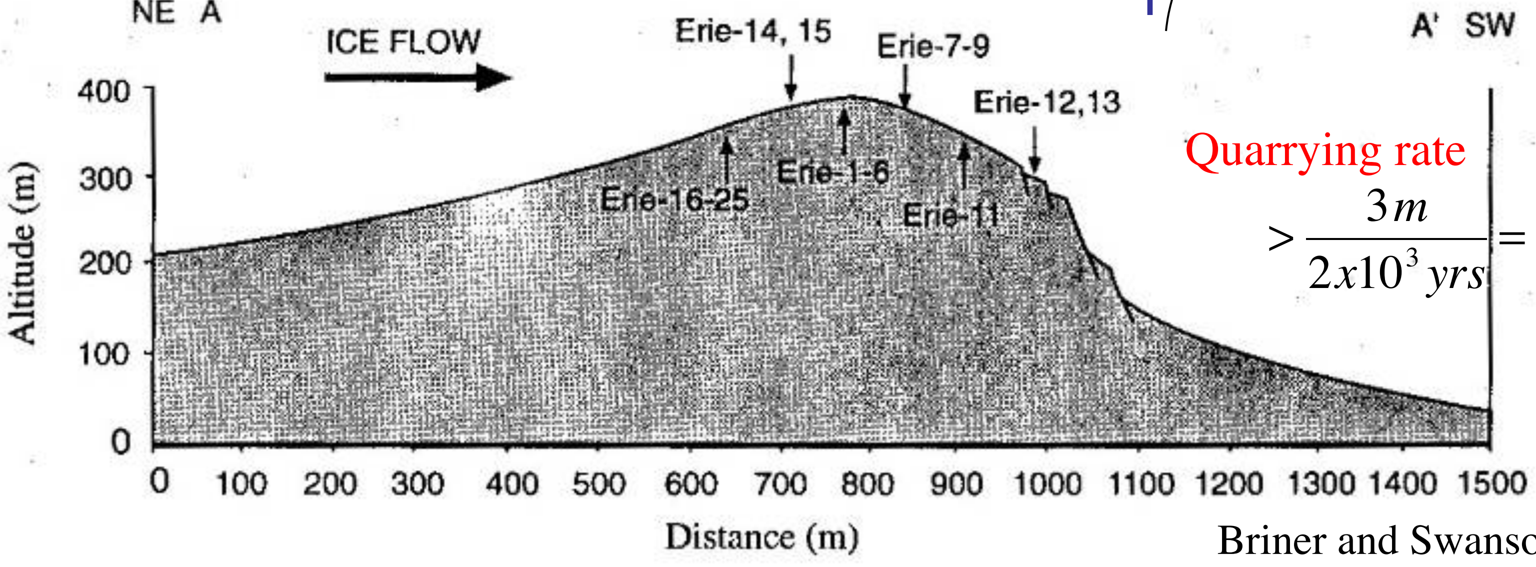
Asymmetry of exfoliating granite domes

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



Abrasion rate

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



Quarrying rate

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

Briner and Swanson, 1998

Sliding physics (regelation) & subglacial chemical processes

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

(Ng & Hallet, 2002, J. Glaciol., 48.