Glacial Erosion: Processes, Rates & Landforms

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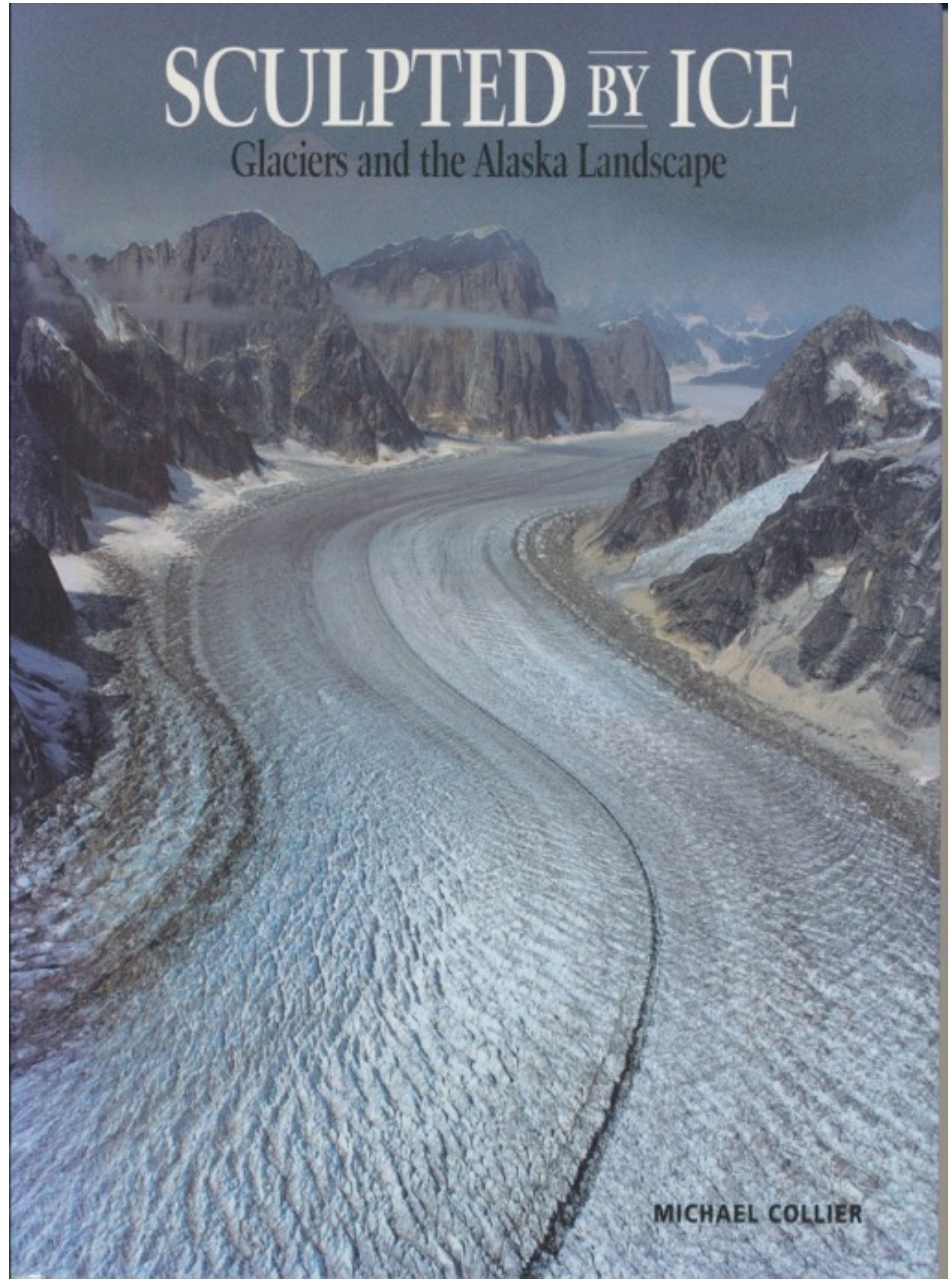
ESS 431 & 505, Mon. 14 Nov 2016

Why study glacial erosion?

aesthetics and a lot more…



Great Gorge, Ruth Glacier, Denali National Park, Alaska

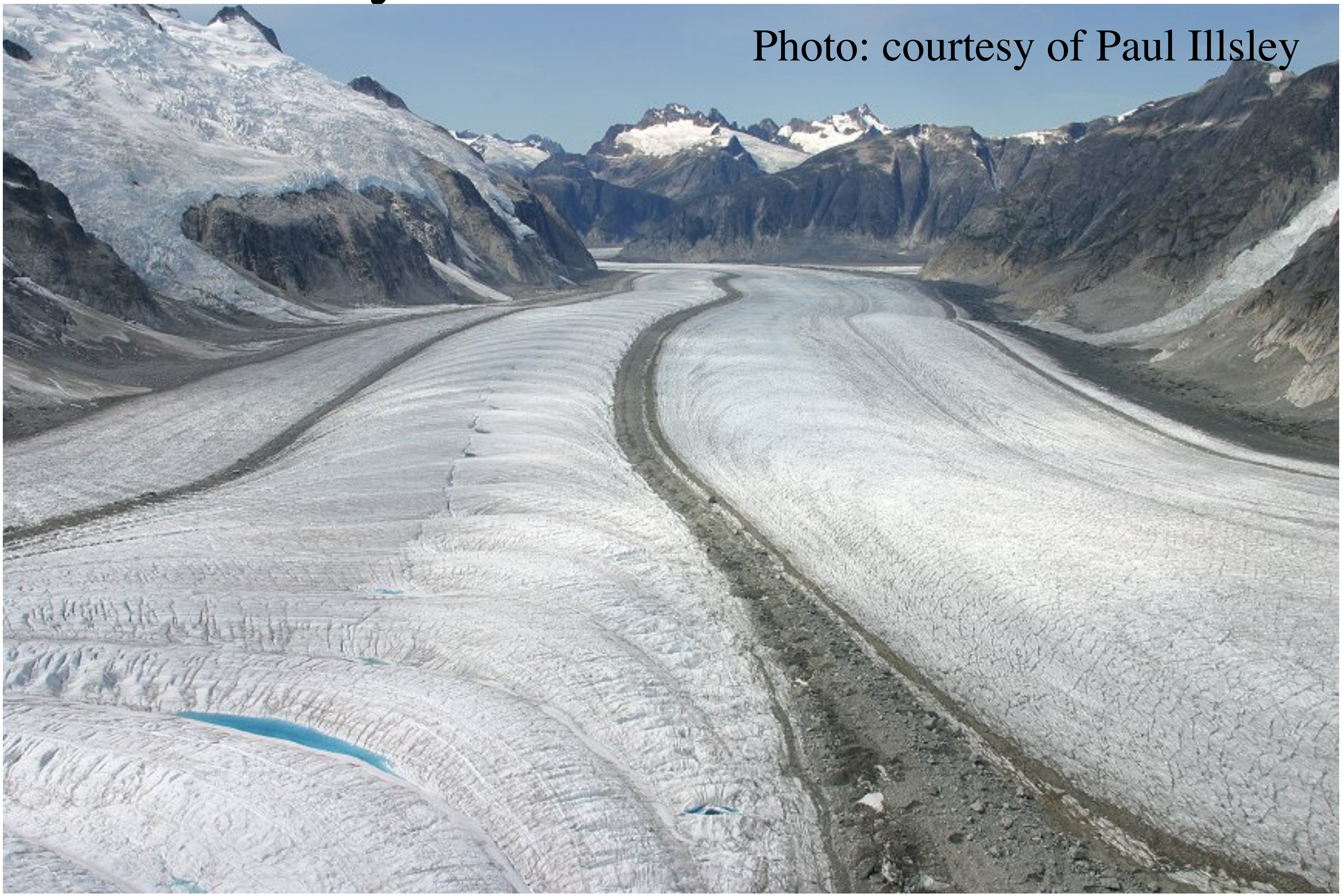
Published by Alaska Natural History Association, Anchorage, 2004

Alpine character of high mountains:

Legacy of glaciers, master sculptors of the land

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

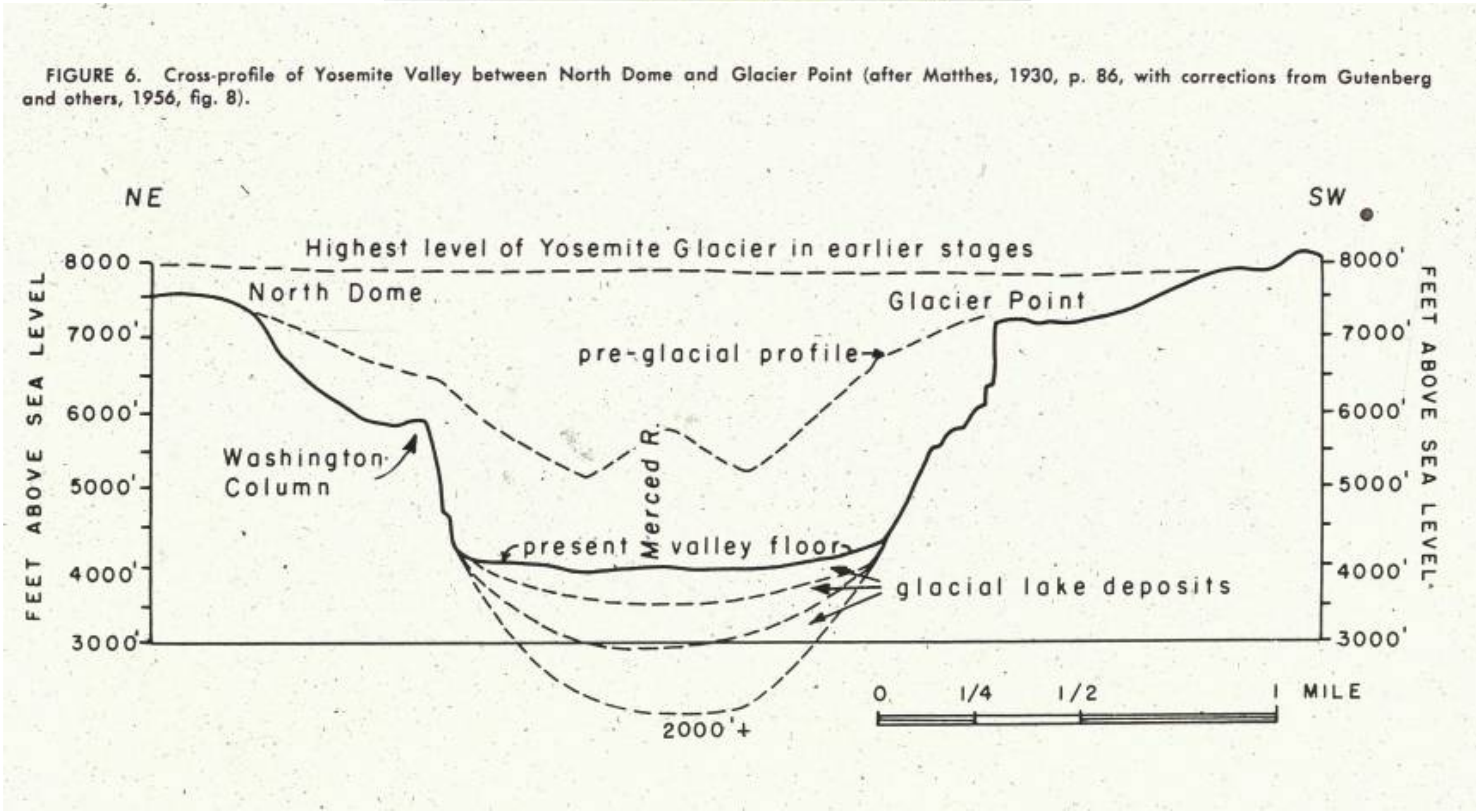
Gilkey Trench, Juneau Icefield



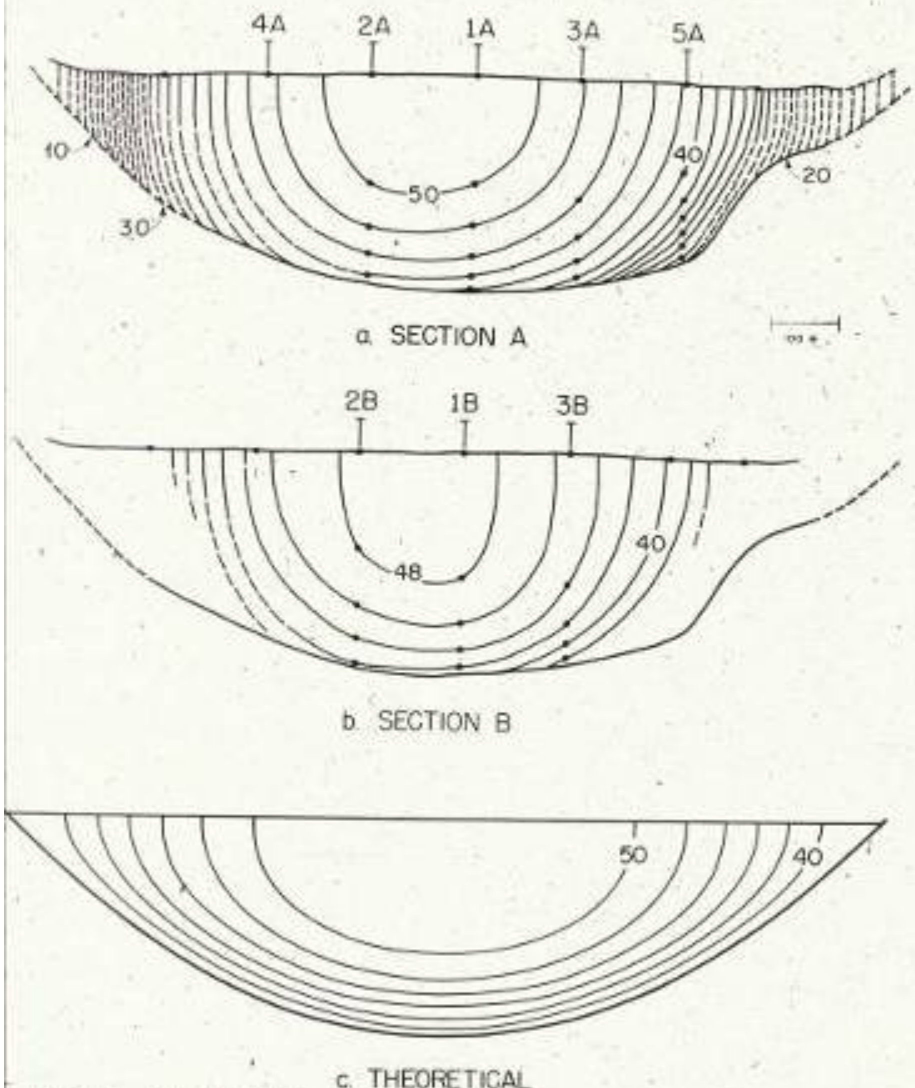
Glacial Topography:

U-shaped valleys, fjords, & hanging valleys

Yosemite Valley



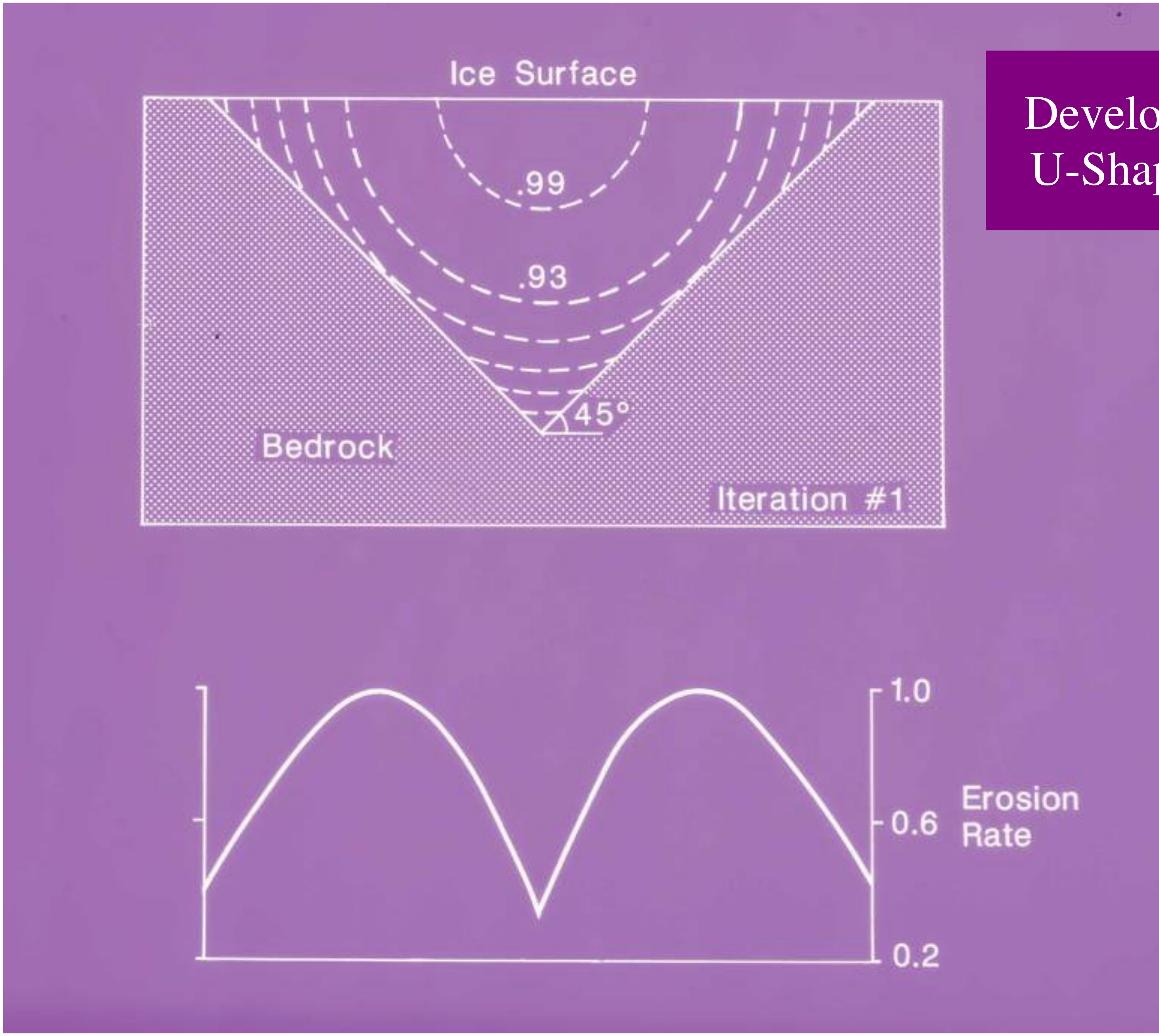
Speed in a Glacier Cross Section



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}.

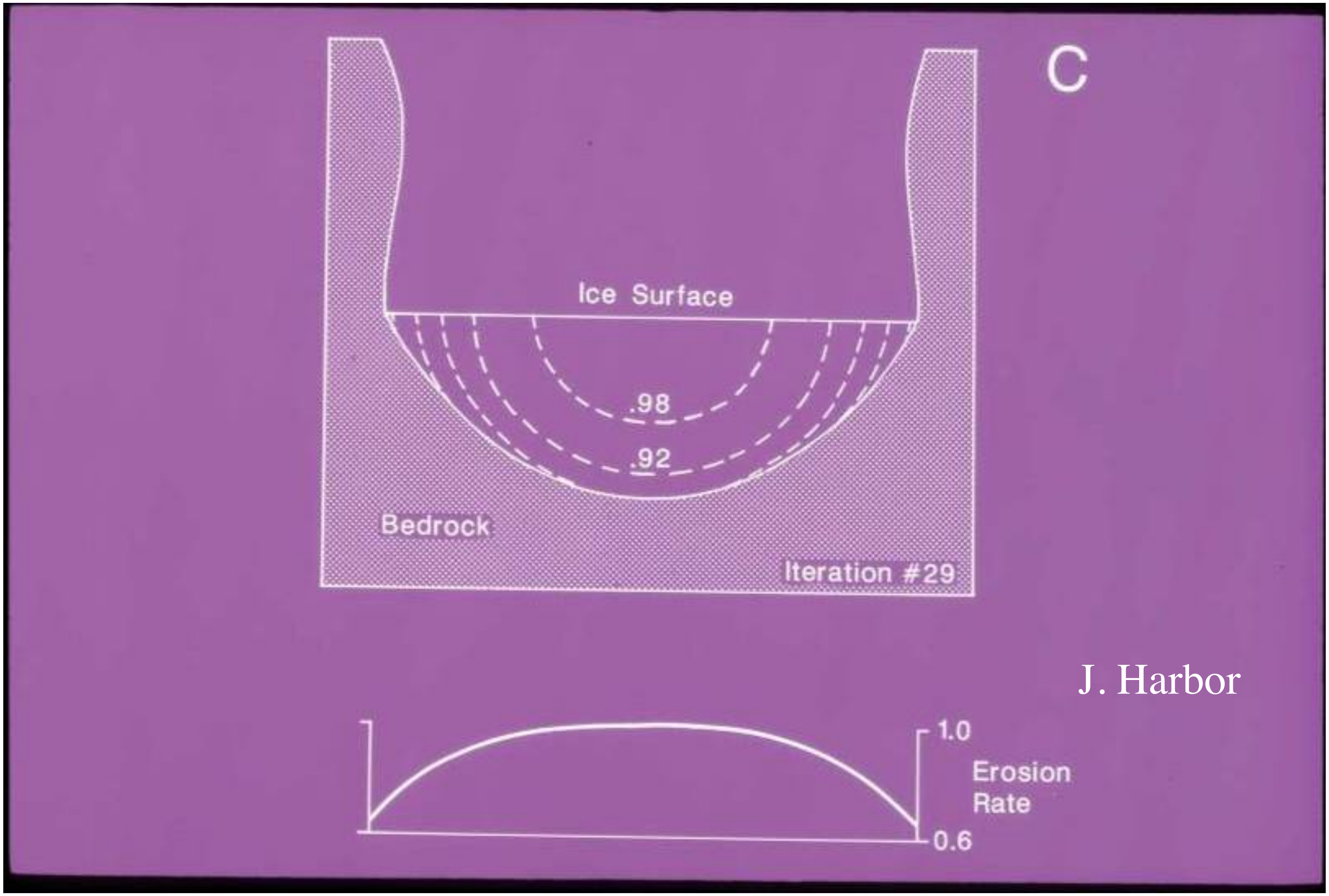
C.F. Raymond

Development of a U-Shaped Valley



J. Harbor

Erosion into Strong Homogeneous Bedrock



Lauterbrunen Valley, Switzerland

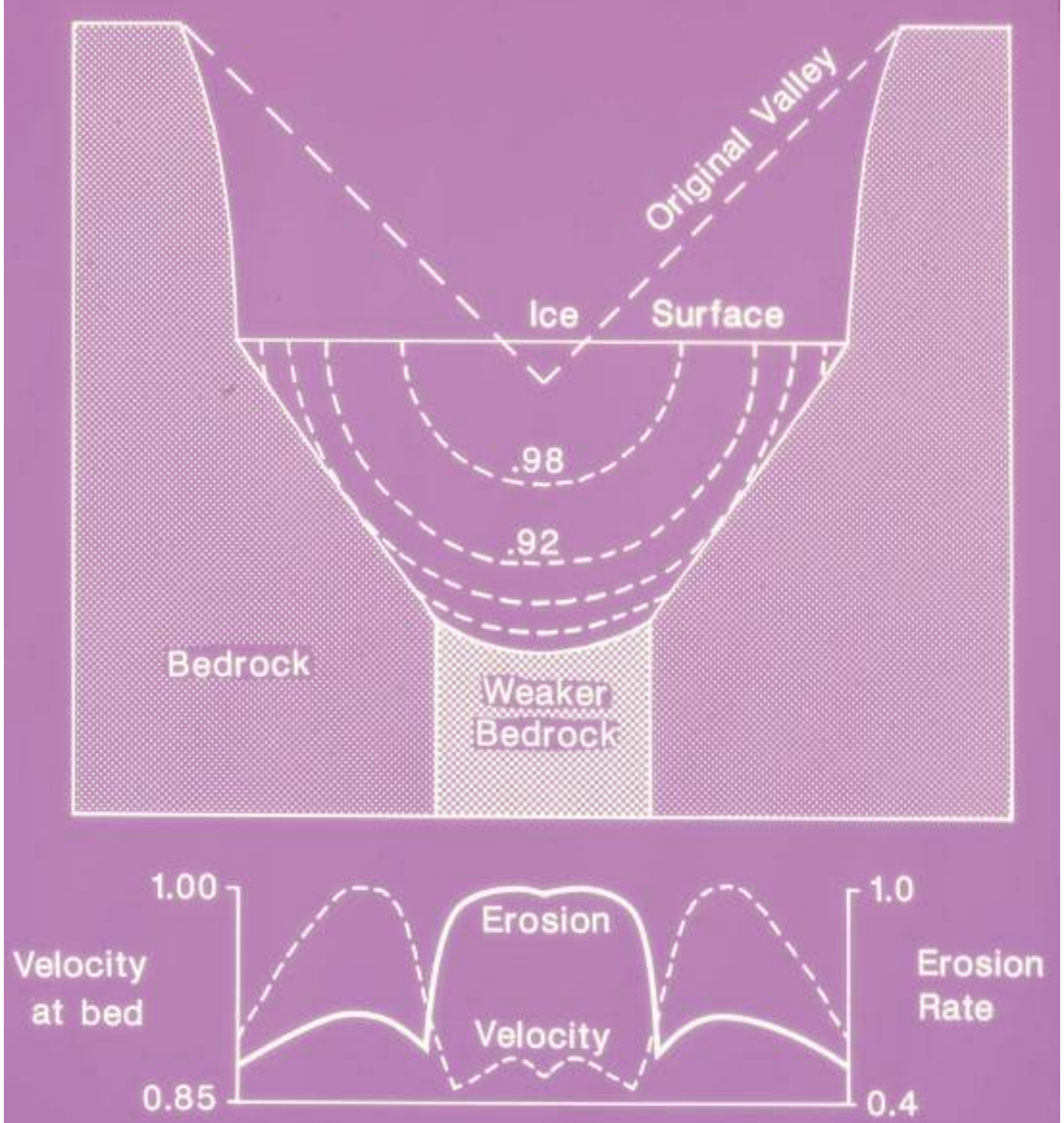
Sognefjord, Norway


Gejranger, Norway

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

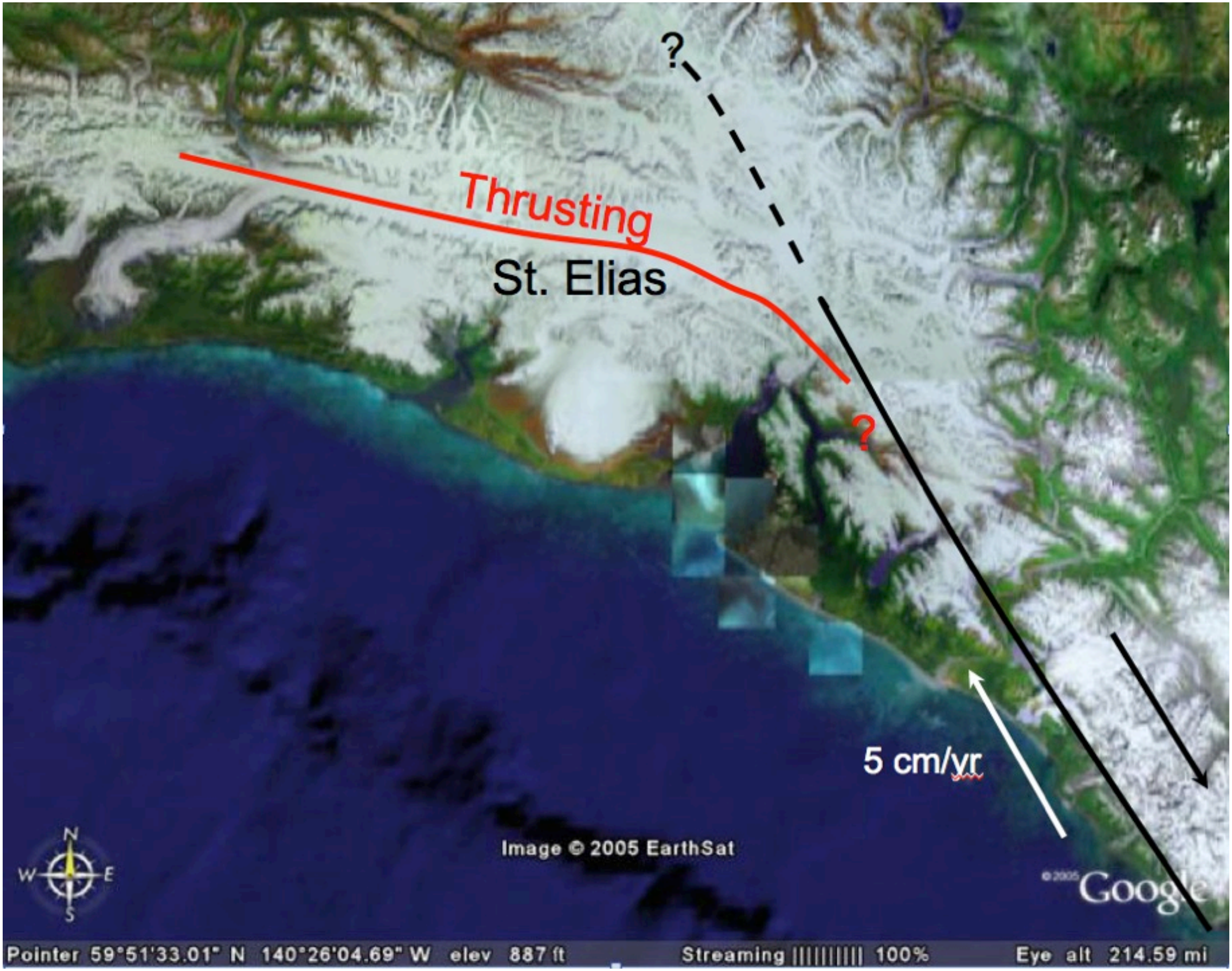
http://www.xrez.com/h3dsphere_giga.html

Erosion into a Fault



J. Harbor


N
W
E
S
Image © 2005 EarthSat
© 2005 Google
Pointer 59°51'33.01" N 140°26'04.69" W elev 887 ft
Streaming |||||||||| 100%
Eye alt 214.59 mi



?
Thrusting
St. Elias
?
5 cm/yr
Image © 2005 EarthSat
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© 2005 Google
Pointer 59°51'33.01" N 140°26'04.69" W elev 887 ft
Streaming |||||||||| 100%
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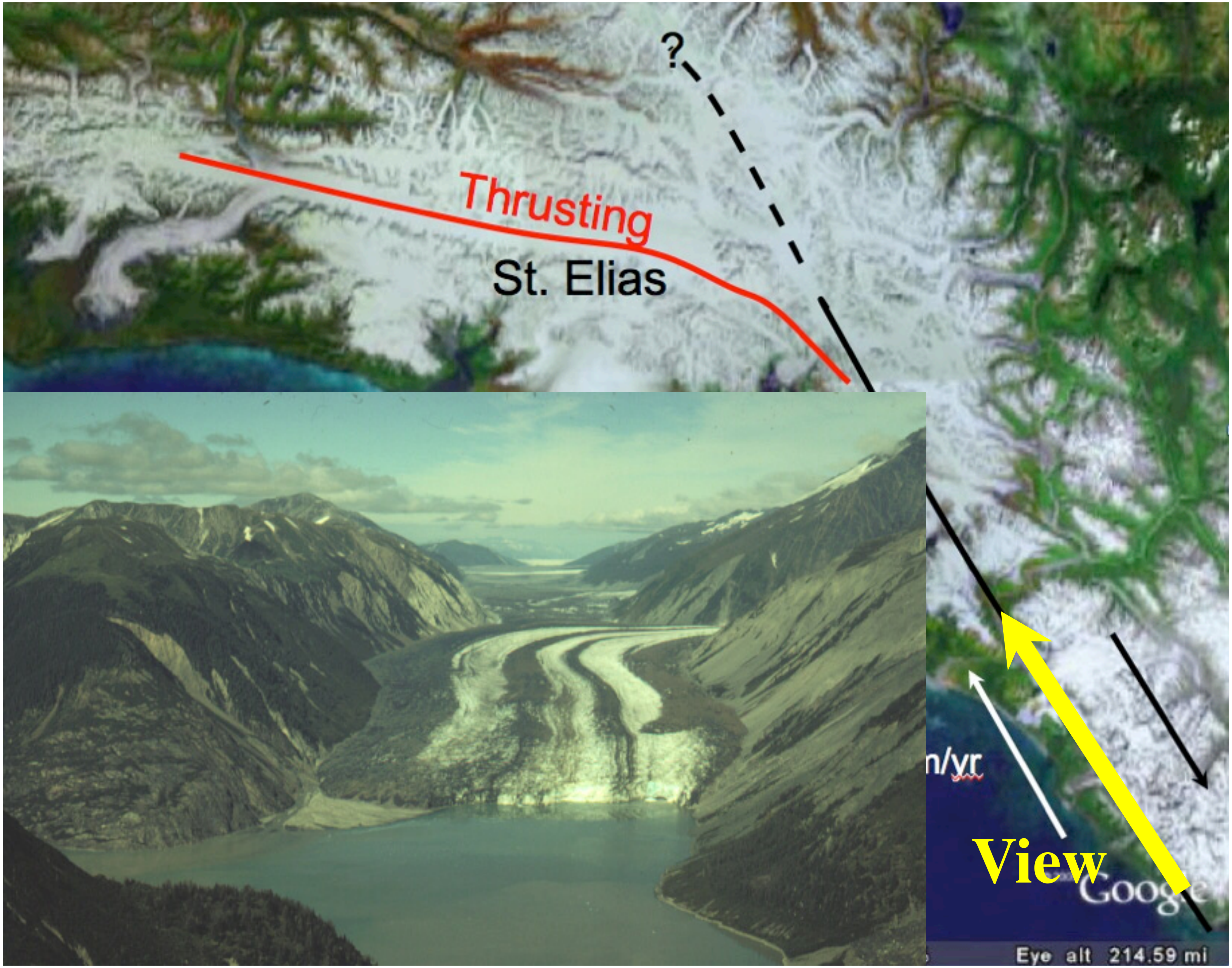
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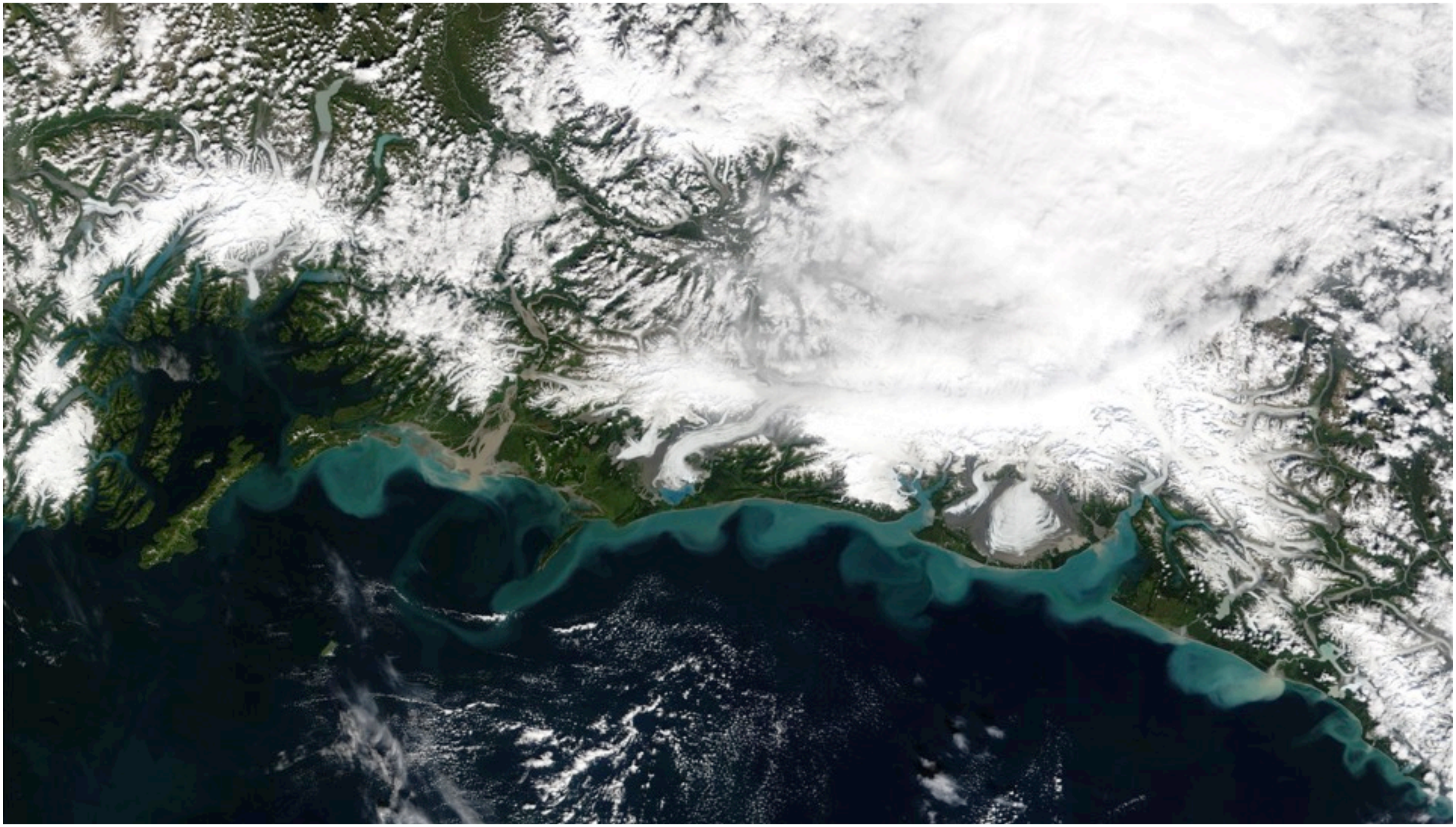
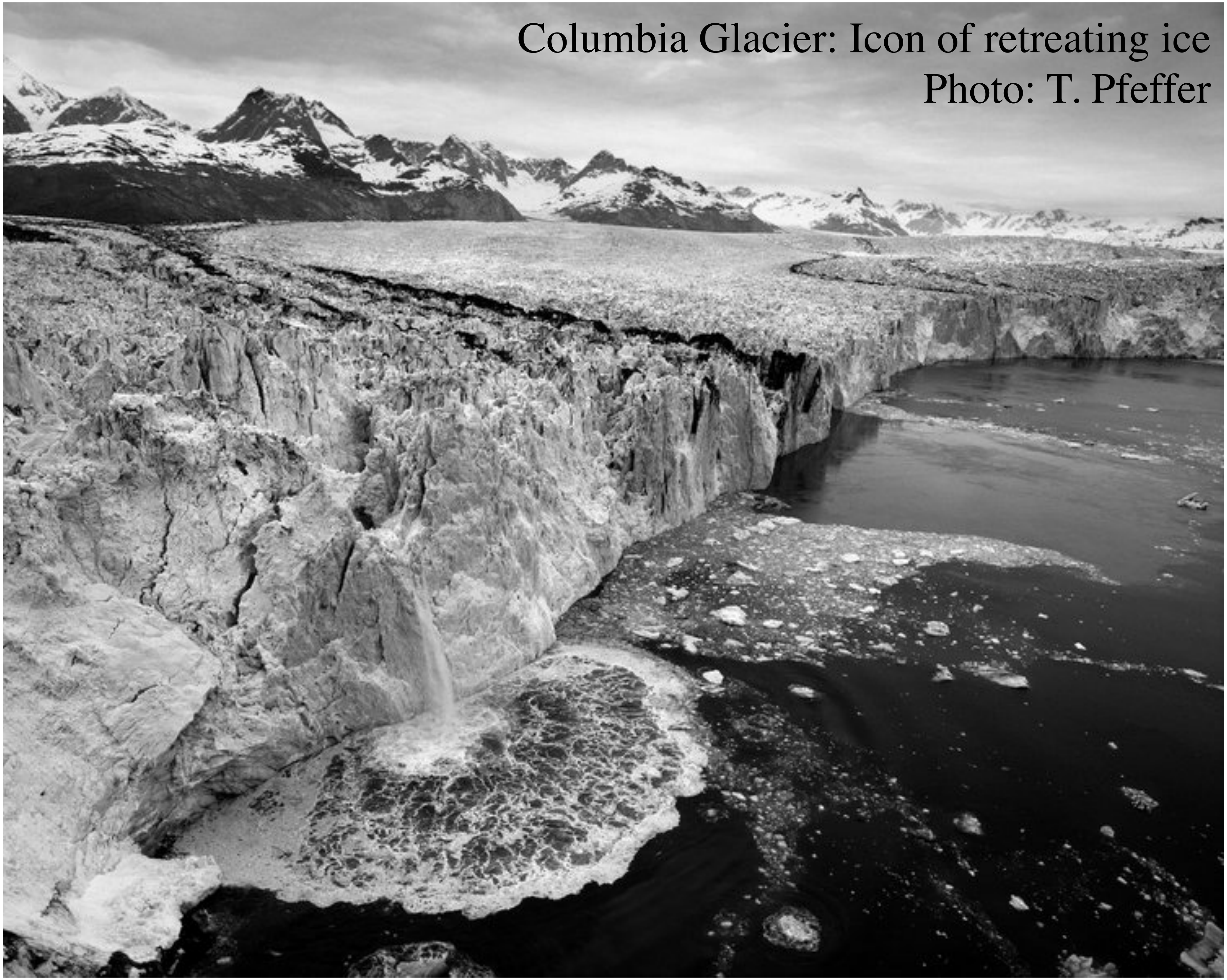
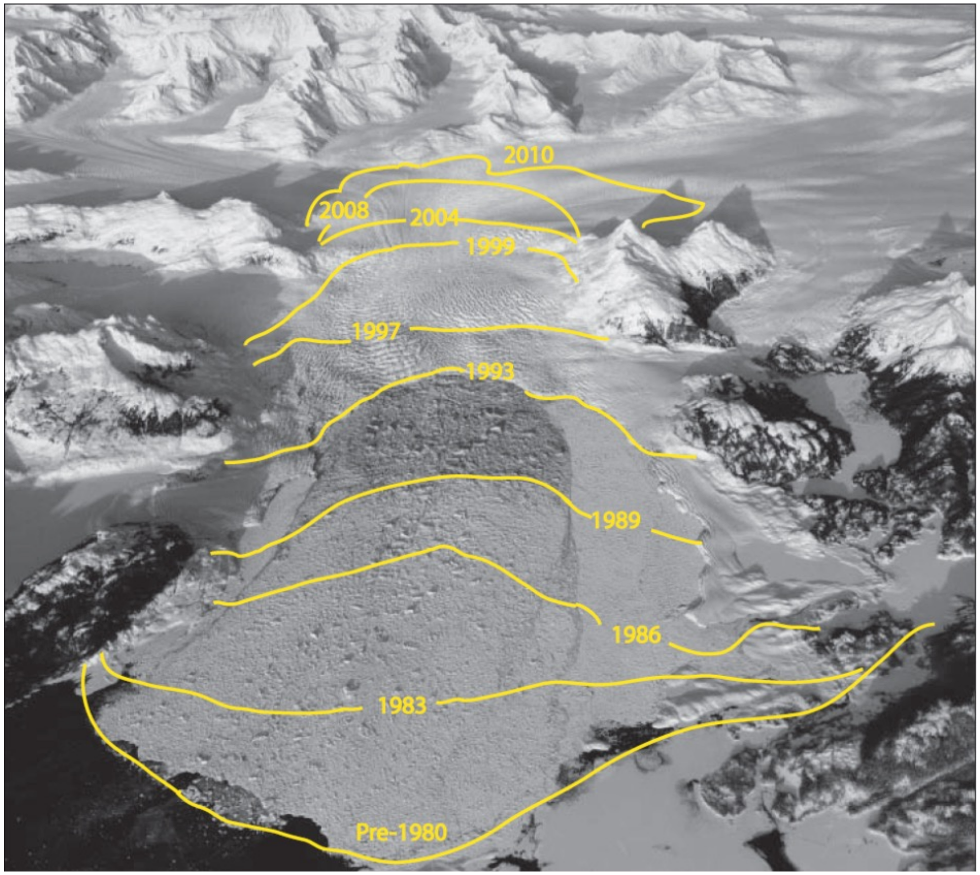
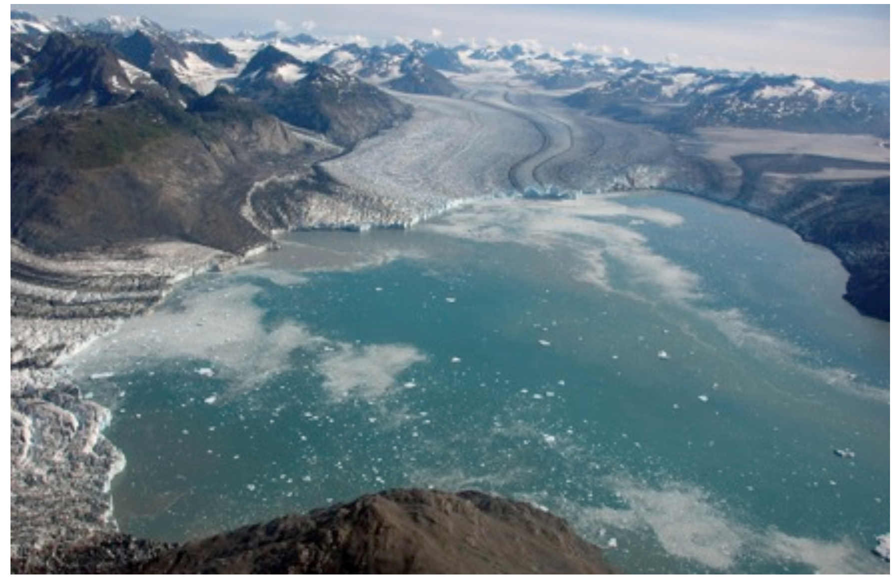


STEEP (St. Elias Erosion and tectonics Project): Cooperation between climate, glaciers, erosion and active tectonics has led to the highest coastal mountain range and the largest temperate glaciers on the planet: *large scale self-organization*


Columbia Glacier: Icon of retreating ice
Photo: T. Pfeffer





Ship-borne research has only become possible in last decade because of icebergs

Columbia Glacier, Fjord & Sediments

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 92, NO. B9, PAGES 9051–9058, AUGUST 10, 1987

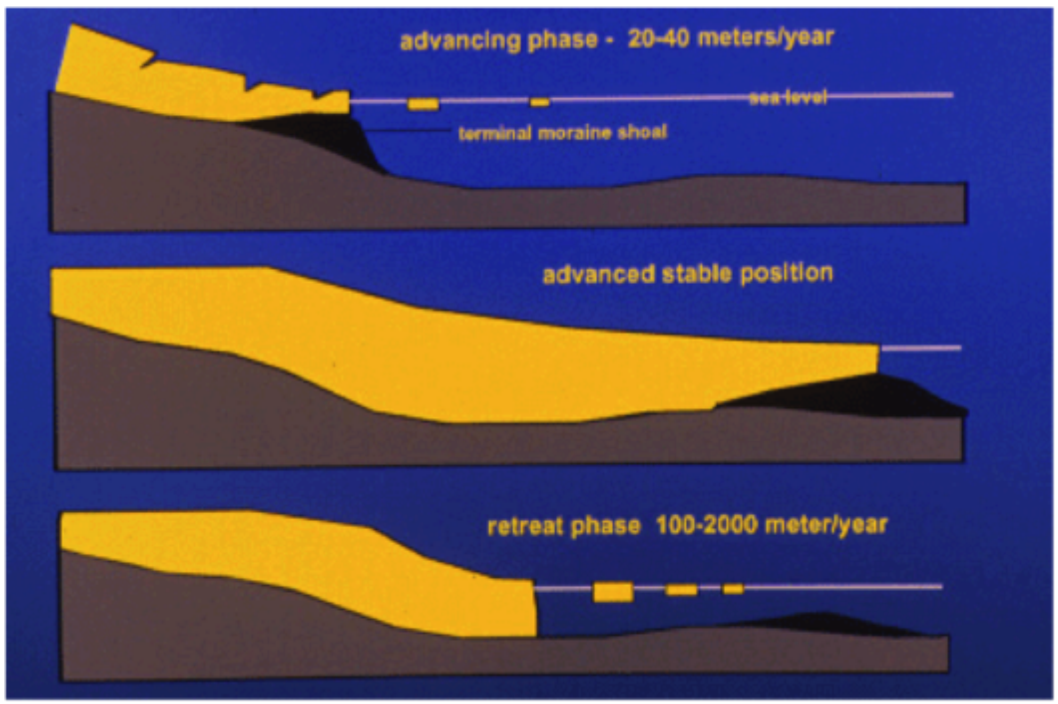
Fast Tidewater Glaciers

M. F. MEIER

Institute of Arctic and Alpine Research and Department of Geological Sciences
University of Colorado, Boulder

AUSTIN POST

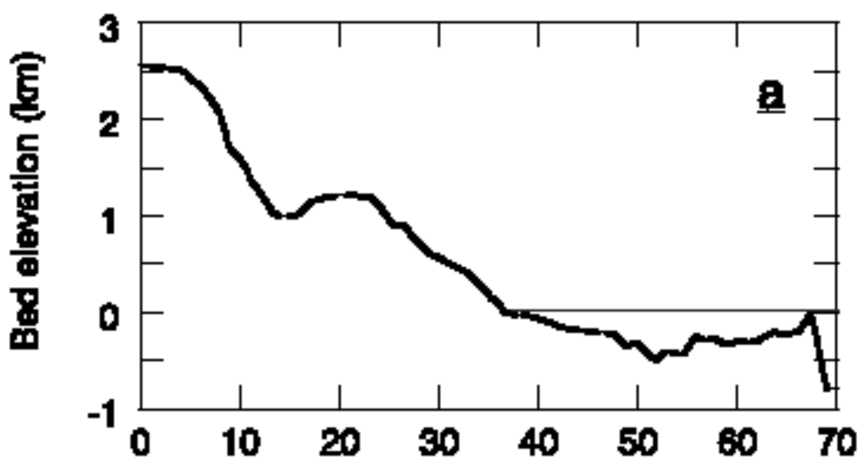
U.S. Geological Survey, Tacoma, Washington

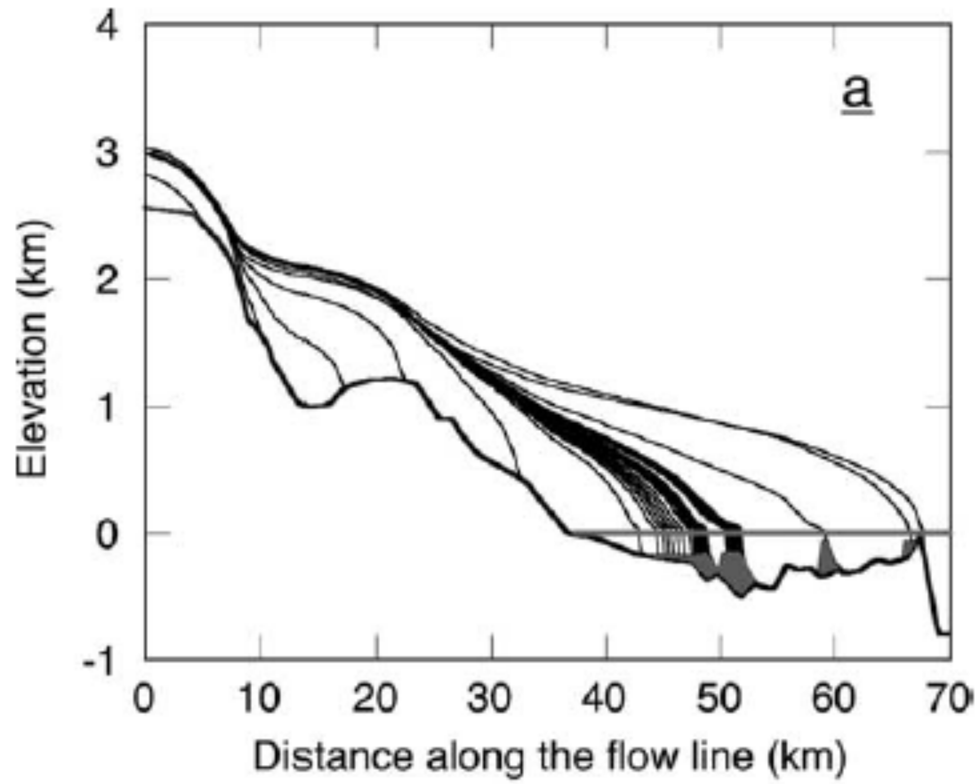


Controls on advance of tidewater glaciers: Results from numerical modeling applied to Columbia Glacier

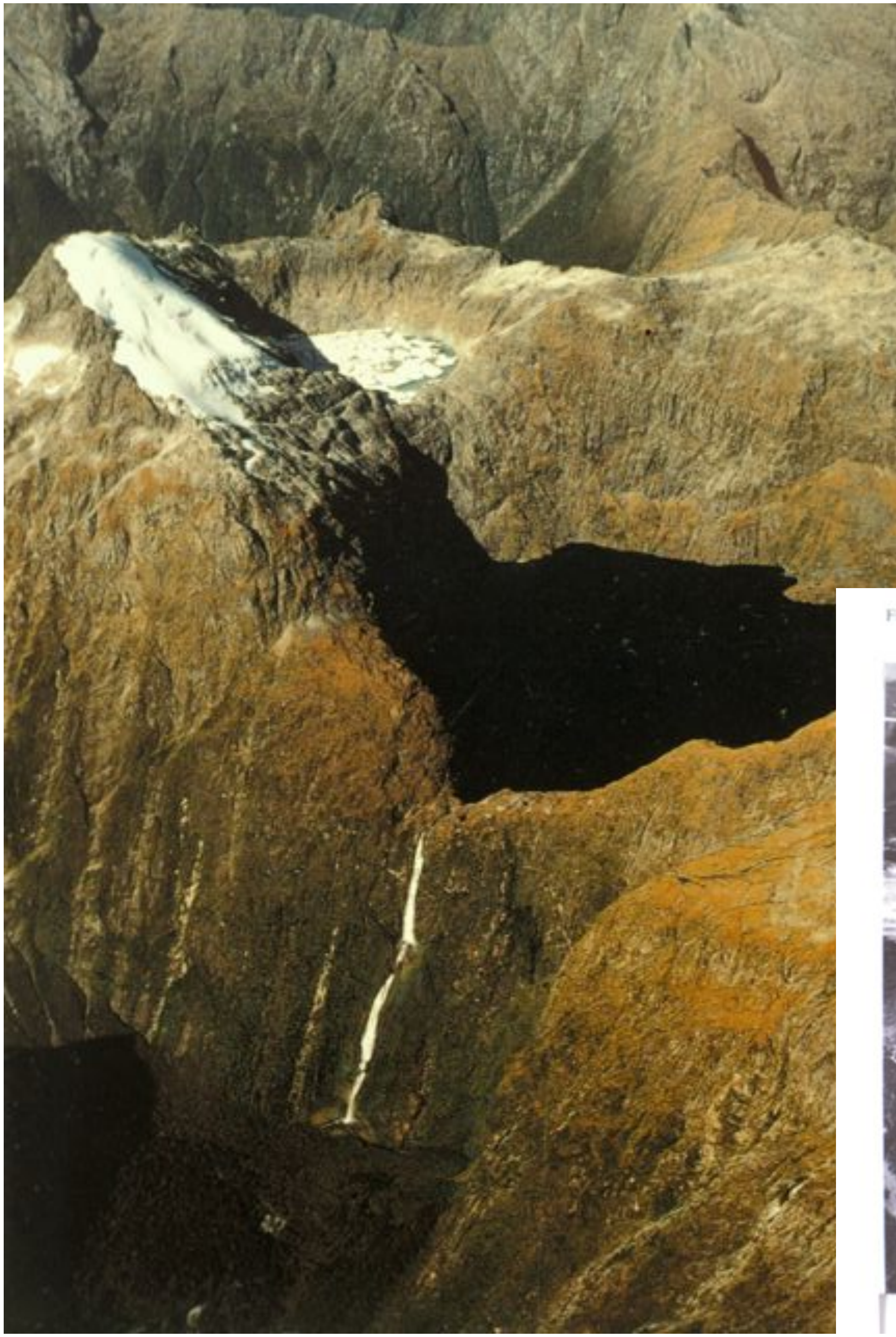
F. M. Nick, C. J. van der Veen and J. Oerlemans

(JGR, 112, F03S24, doi:10.1029/2006JF000551, 2007)





"The results suggest that irrespective of the calving criterion and accumulation rate in the catchment area, it is impossible for the glacier terminus to advance into deeper water (>300 m water depth) unless sedimentation at the glacier front is included."



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, Argentina (note talus at base of cliff, rhs)

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)

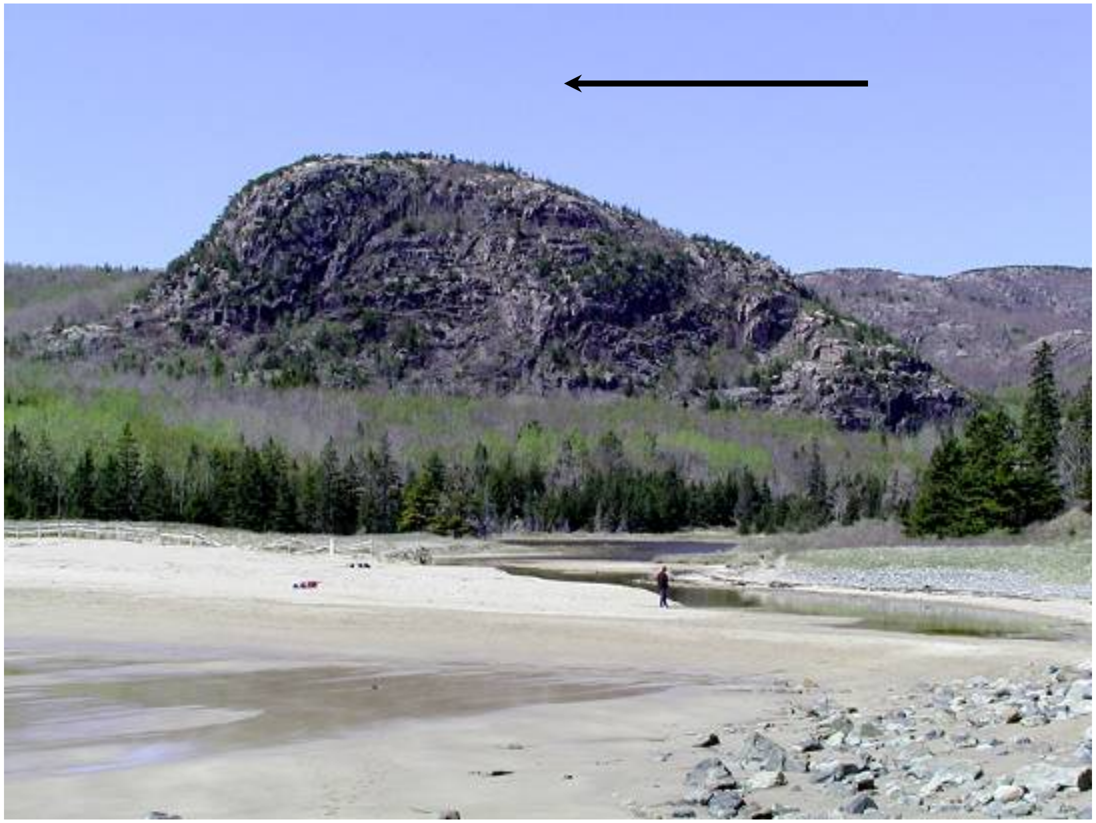
- **Global Carbon Budget:** glaciers/ice sheets affect rate of atmospheric CO_2 uptake by modulating rates *carbonate precipitation and organic carbon delivery to oceans*

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

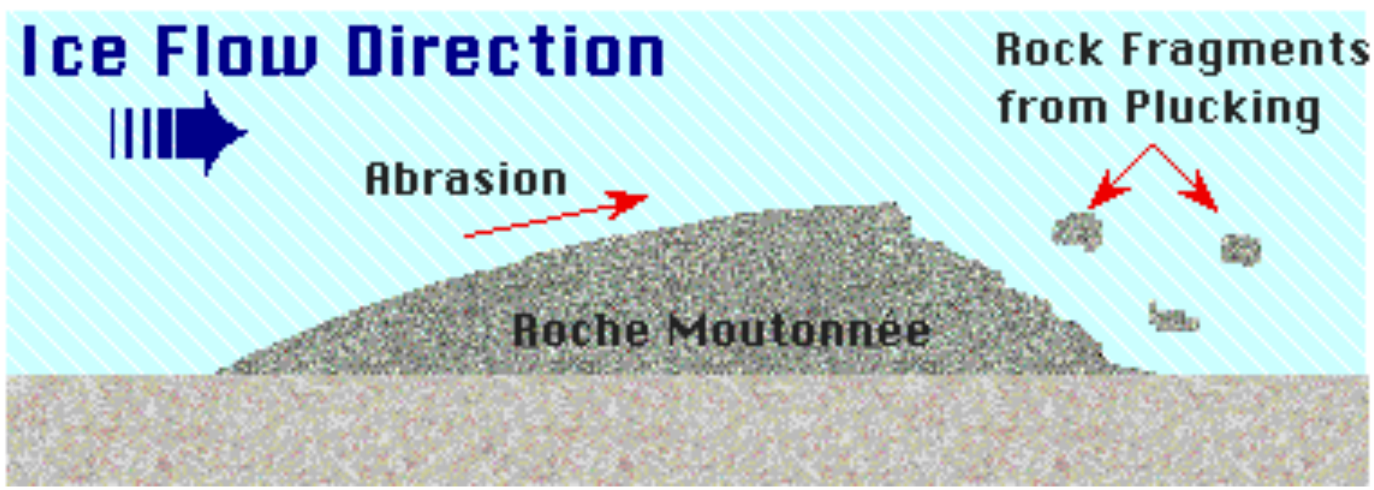
Erosion Processes - 1

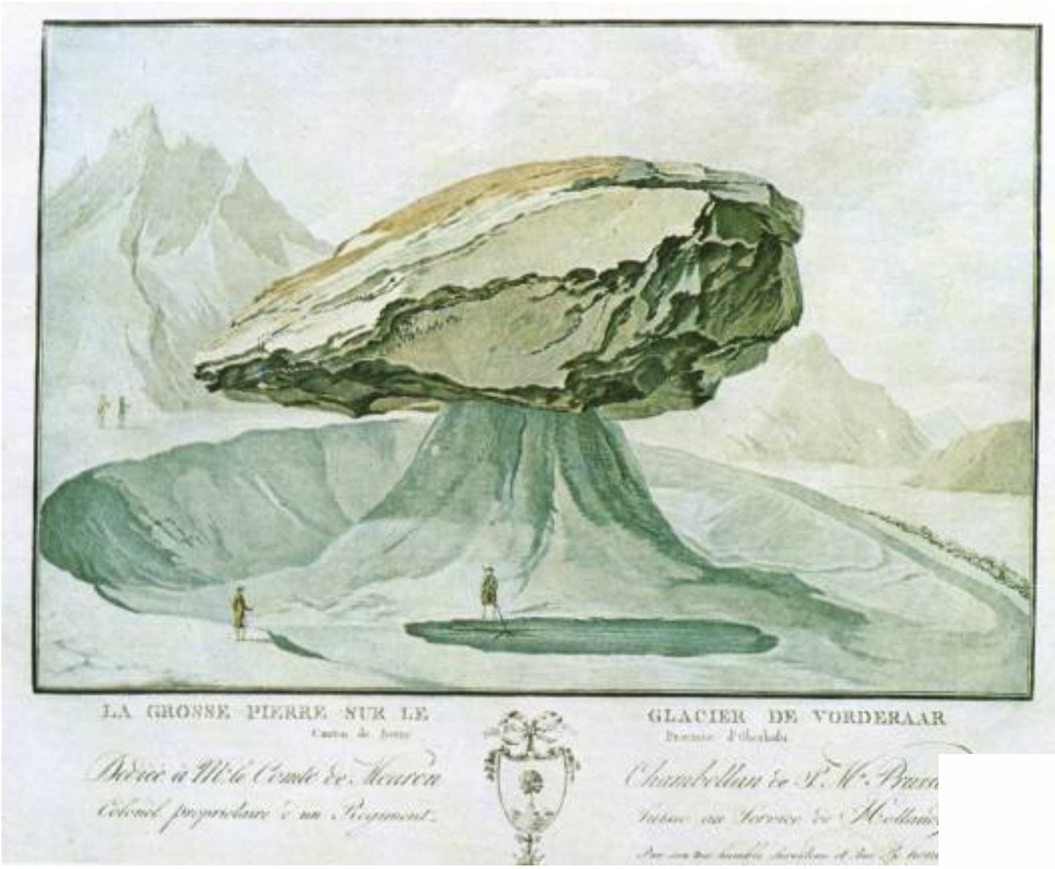
Quarrying - Plucking:

- **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.

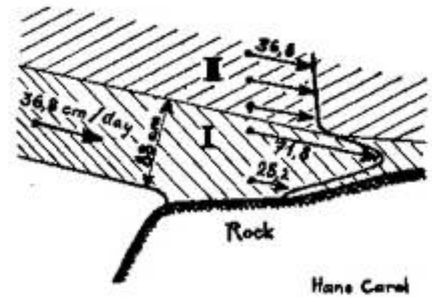
- Subglacial fluvial activity: bulk (>90%) of sediment transport to glacier snout, but role in bedrock erosion is poorly known

- 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.)



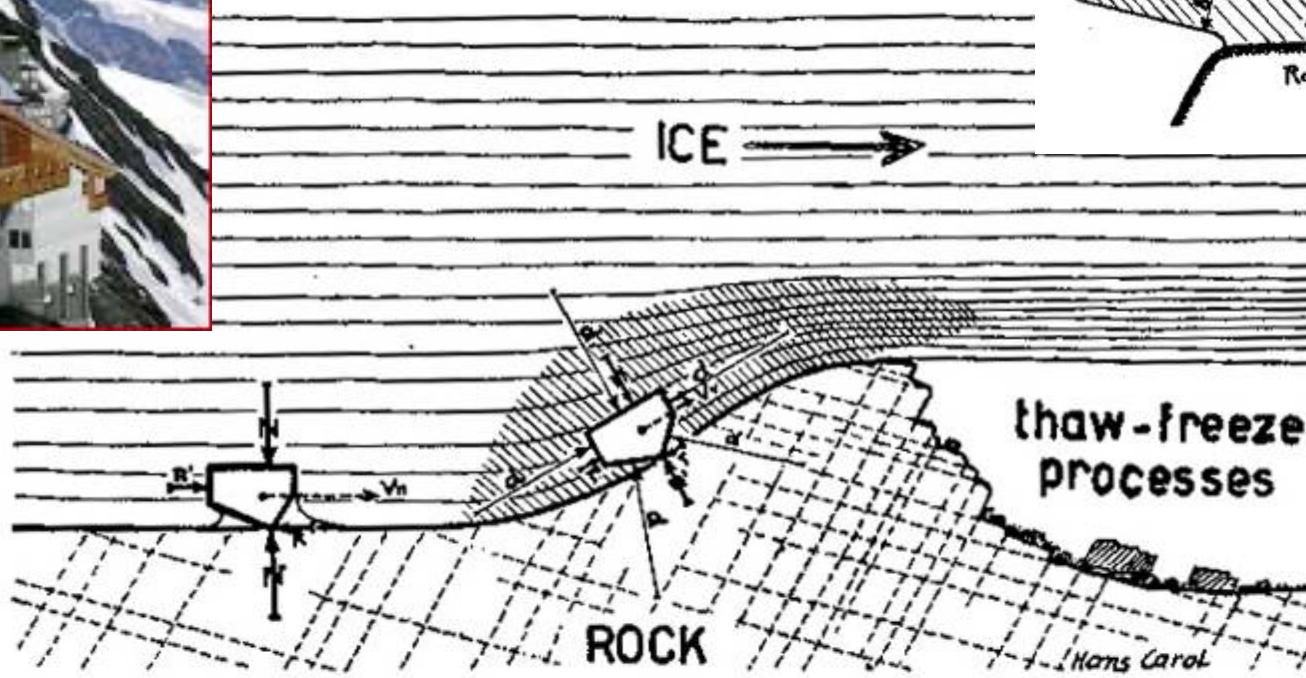
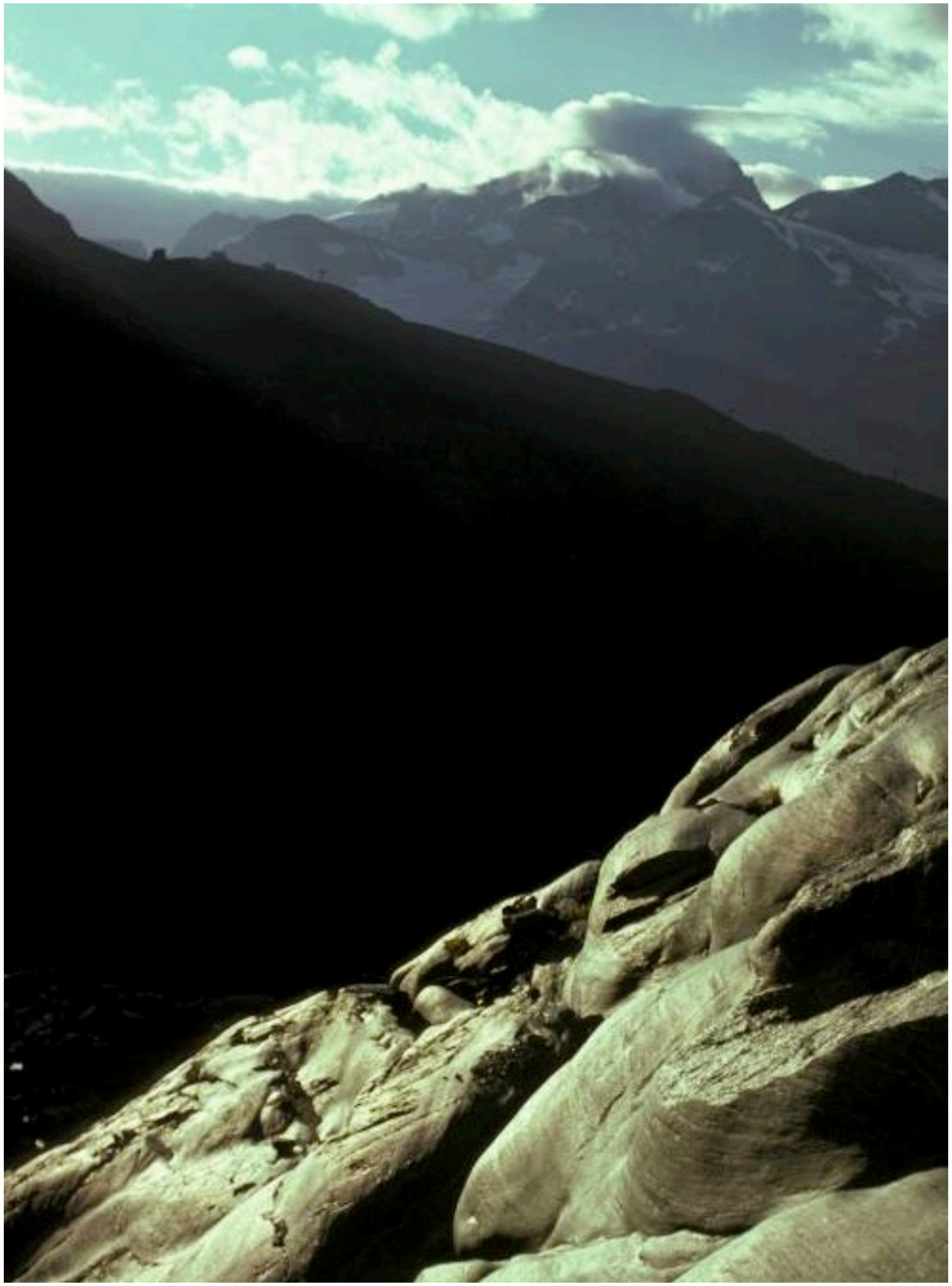


Fig. 7. Diagrammatic representation of a roche moutonnée forming under a living glacier. The hatching indicates the area of semi-fluid conditions

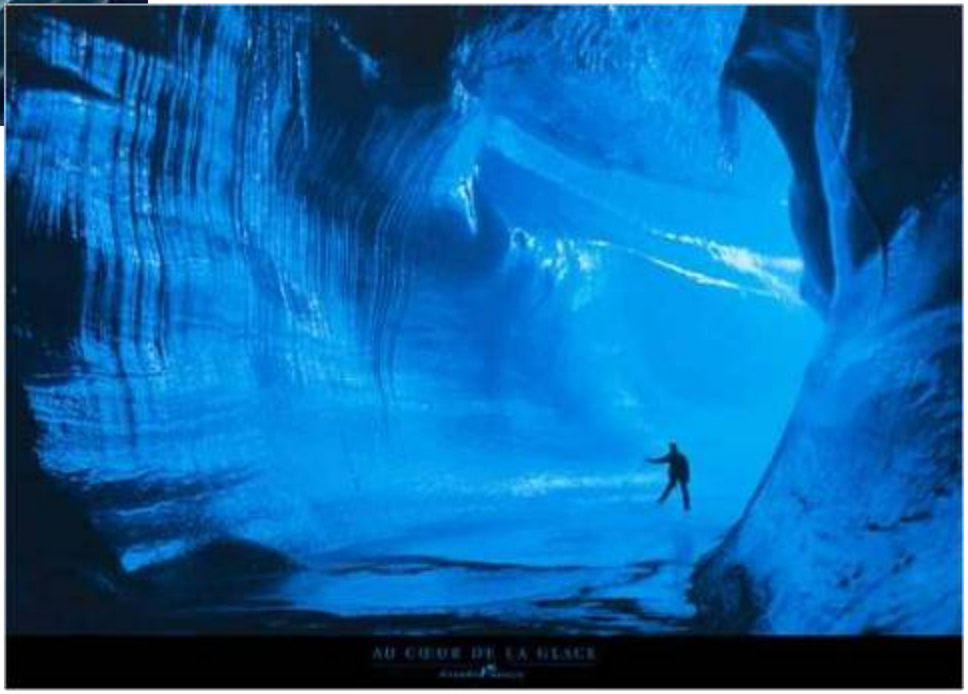
N pressure of superincumbent ice upon eroding stone
R, frictional resistance
Vn, normal speed of ice-flow
dd, hydrostatic pressure
n, reduced pressure upon stone
r, reduced frictional resistance



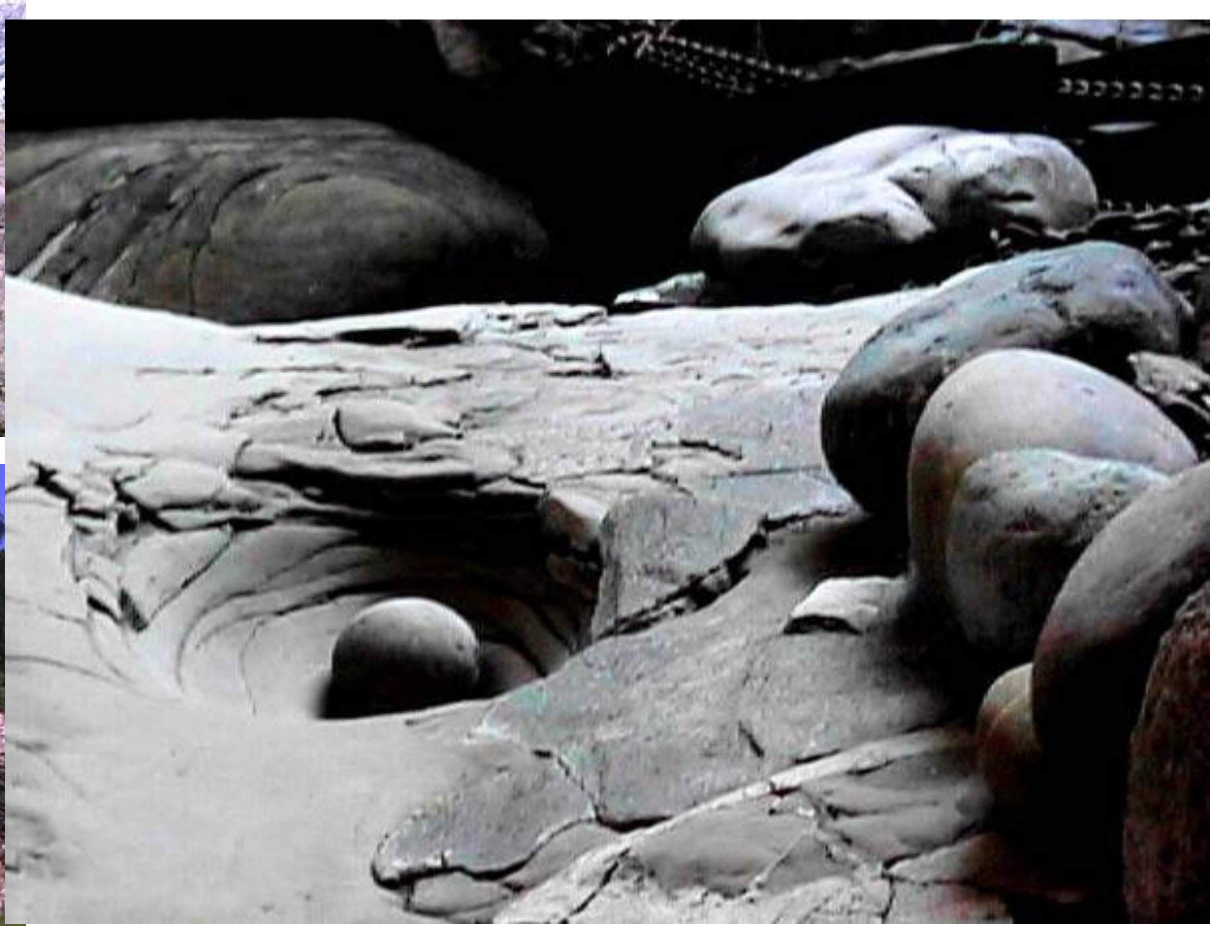
Smooth, striated bedrock forms produced by abrasion dominate the view looking down valley. Relatively rough and fractured bedrock surfaces produced by quarrying would dominate the view looking up-valley.

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 <u>NOT</u> 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

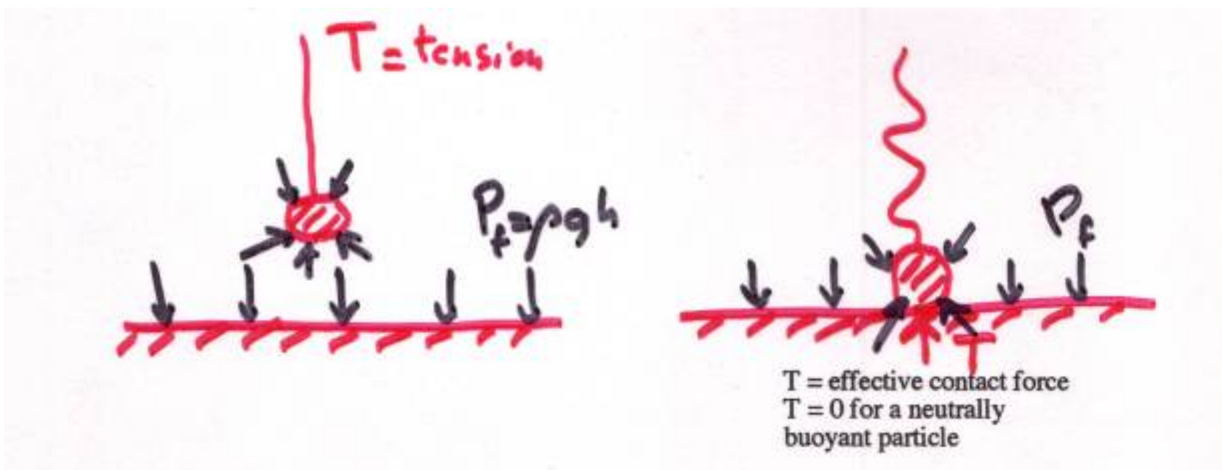
- # cutting tools: rock fragment concentration
- fragment velocity

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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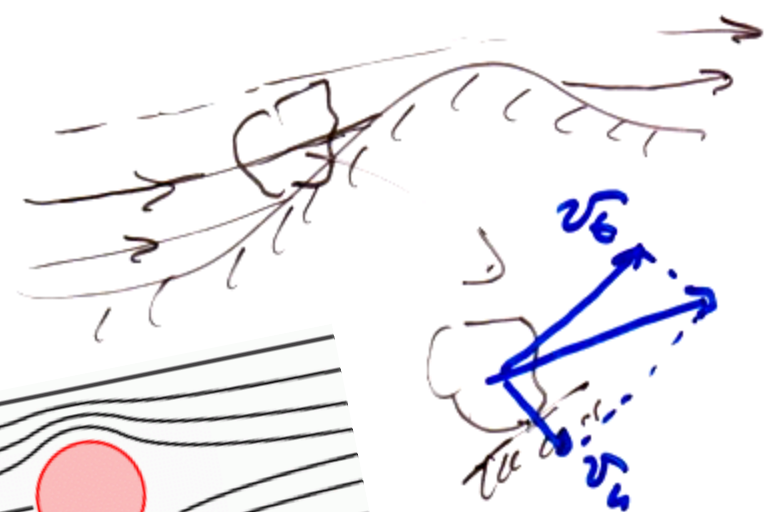
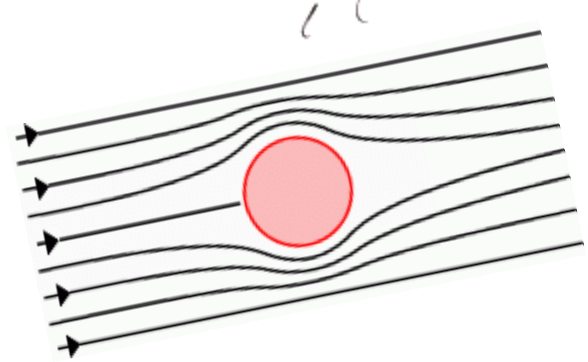
Factors affecting contact force

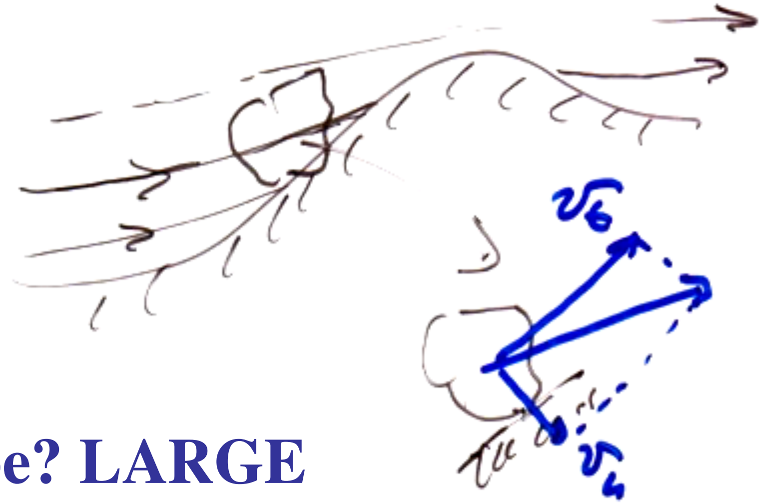
- Ice pressure: not important, nor is glacier thickness (controversial, common misconception)
- Gravity: not important - vertical bedrock surfaces are often striated, as are overhangs
- Viscous forces



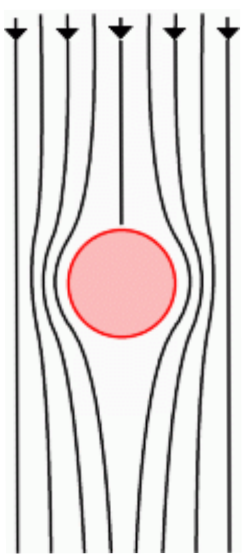


Viscous force: a rough estimate

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 (3×10^{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:

$6\,\pi$ 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:

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

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.

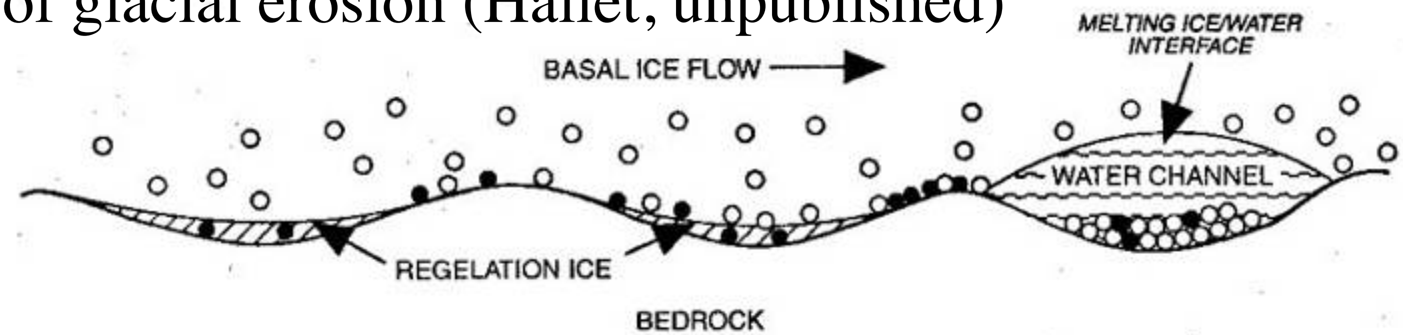
Simple linear model (2)

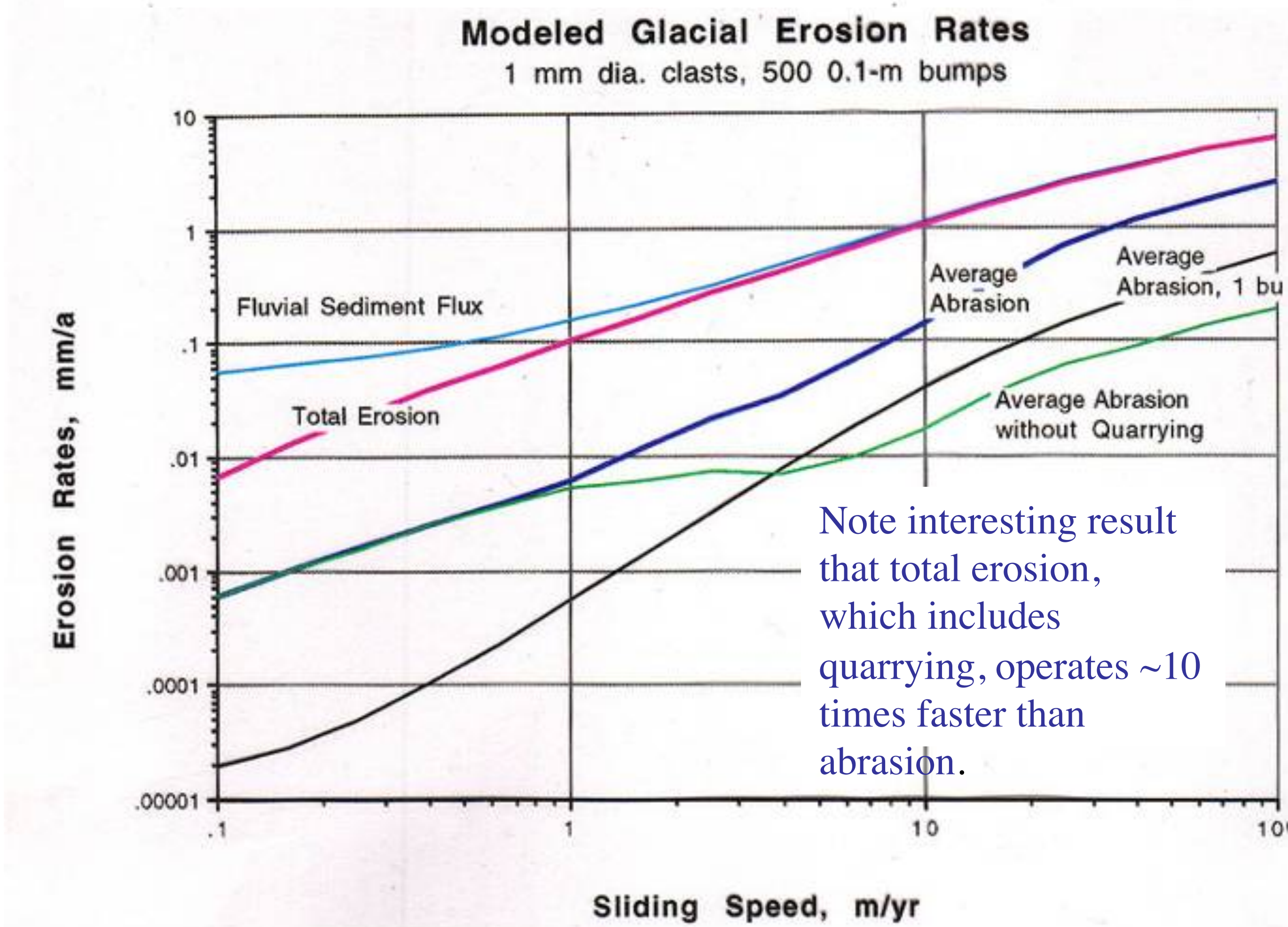
- note: $\mu F_c v_p$ - Work done by one particle per unit time in frictional motion over the bed, where μ is the coefficient of friction (rock-on-rock)

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

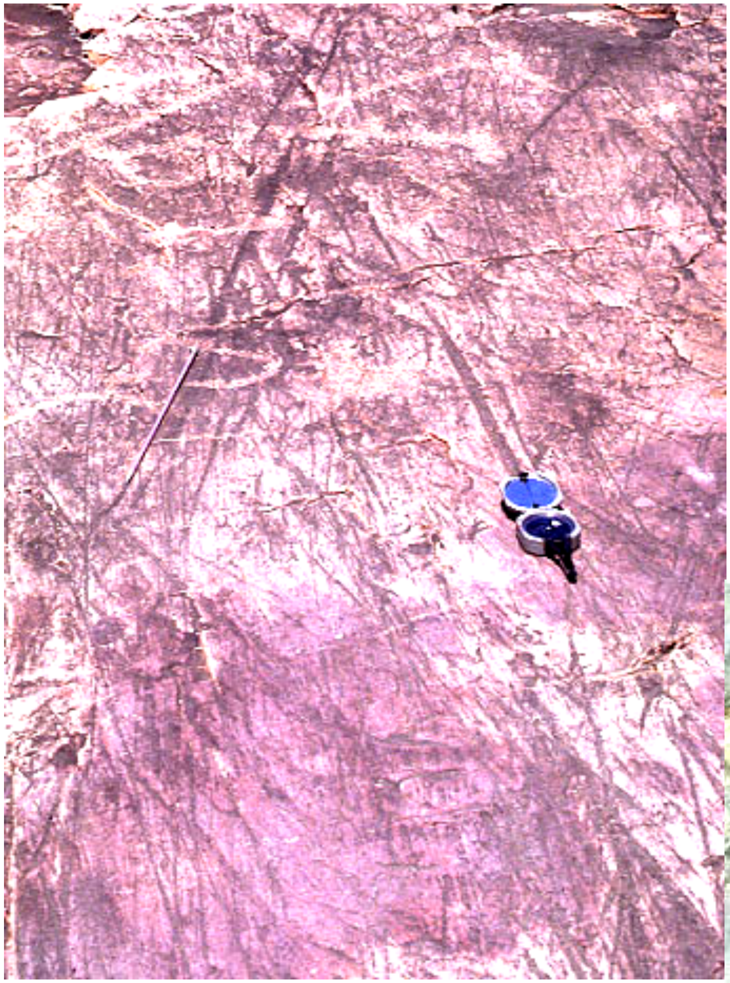
- Thus, the rate of glacial abrasion ($\mathring{A} = \alpha F_c v_p C$) is proportional to the rate at which work is being done on rock/rock friction, and to the square of the velocity.

A model of glacial erosion (Hallet, unpublished)



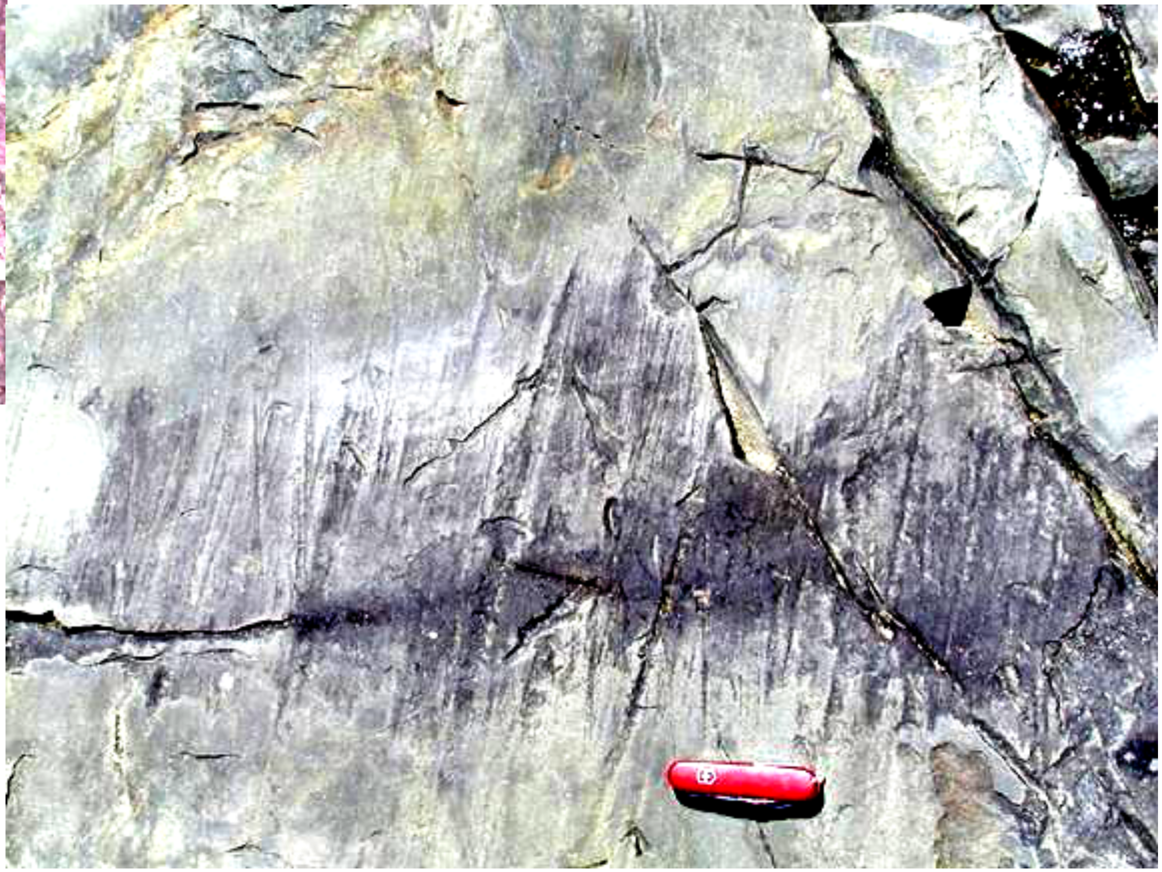


Note interesting result that total erosion, which includes quarrying, operates ~10 times faster than abrasion.



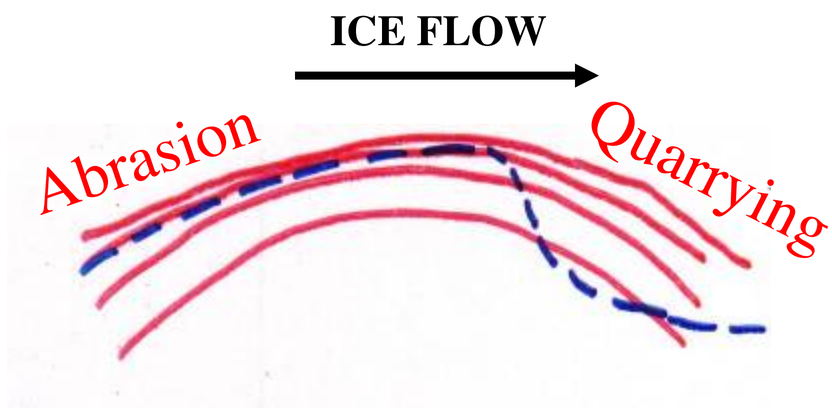
Abrasion is slow

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.



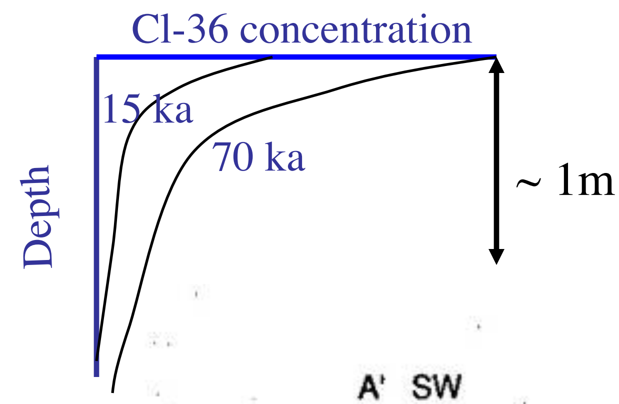
They suggest that abrasion is very slow, since earlier striations are not removed. Abrasion is limited to mms in 10^2-10^3 yrs.

Relative importance of abrasion and quarrying



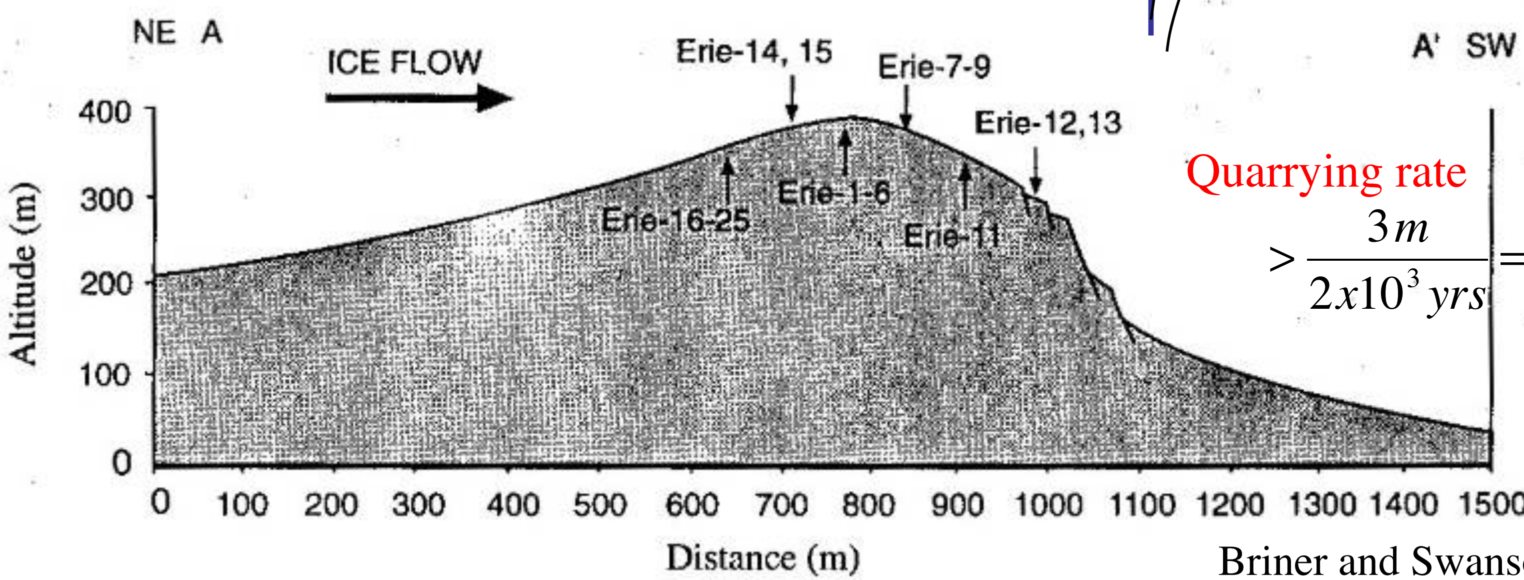
Asymmetry of exfoliating granite domes

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



Abrasion rate

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



Quarrying rate

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

Briner and Swanson, 1998