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

C. F. Raymond
Development of a U-Shaped Valley, assuming erosion rate scales with ice speed (and that the rock is uniform and erodible)

J. Harbor
Erosion into Strong Homogeneous Bedrock (under constant ice flux & without hillslope processes)
Geiranger, 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.
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.
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 $\geq 100$ m/yr)
- nearly float ($Pe \sim Pi/100$, $Pe$ & $Pi$ are effective and ice pressures);
- small $Pe \sim 0.2$ 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 NOT 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
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**
Factors affecting contact force

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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 \( \eta \) 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 \((3 \times 10^{12} \text{ Pa-s})\), 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:

\[
6 \pi \times 1 \text{ bar-yr} \times 0.5 \text{ m} \times 1 \text{ m/yr} = 10^6 \text{ N} = 100 \text{ tons.}
\]

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:

\[ \dot{A} = \alpha \ F_c \ v_p \ C \]  

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

Hans Carol
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
Bondhusbreen, S. Norway

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

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


Hypothesis: decreasing water pressure promotes crack growth

Slow or no crack growth

Enhanced crack growth
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.

Briner and Swanson, 1998

Abrasion rate

\[
< \frac{0.3 \text{m}}{2 \times 10^3 \text{yrs}} = 0.15 \frac{\text{mm}}{\text{yr}}
\]

Quarrying rate

\[
> \frac{3 \text{m}}{2 \times 10^3 \text{yrs}} = 1.5 \frac{\text{mm}}{\text{yr}}
\]

Cl-36 concentration

Depth

\(~ 1 \text{m}~

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.)