Glacial Erosion II: Processes, Rates & Landforms

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Housekeeping for the day

Friday Discussion Section
• Holiday Friday – no discussion session

Monday Discussion Section
• 12:30-1:20 CDH 601C
• Erosion/deposition questions and readings
• Mid-term discussion

Homework on Glacial Erosion
• Posted online, due next Thursday, November 17

Tuesday
• Bernard Hallet on Permafrost and Periglacial Processes
Checking aspects of theory
Clean Ice Sliding over Clean Bedrock
Ice sliding over bed bump under 150-200m of ice at Bondhusbreen, Norway
Forces on Rock Tools

Force Balance

\[ F_{\text{contact}} - F_{\text{flow}} = \text{Friction} \]

Velocities

\[ v_e = U \]

\[ v_h \]

\[ v_r \]

\[ v_c \]

\[ v_{\text{rel}} \]

Force Inducing Motion =

Force Resisting Motion

\[ F_{\text{flow}} = F_{\text{friction}} = \mu F_{\text{contact}} \]

\[ \delta v_{\text{rel}} = \mu \delta v_h \] (Viscous Forces dominate)

\[ \alpha(R,N) \] but \( \delta \) cancels out making the result independent of clast size and effective viscosity.

\[ \therefore \cos \theta = \frac{v_h}{v_{\text{rel}}} = \frac{1}{\mu} \Rightarrow \theta \approx 50^\circ \]

Also,

\[ U - v_e = \mu v_h \Rightarrow v_e = U - \mu v_h \]

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

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 $n = 0.1 \text{ MPa a}$. 

From N. Iverson
Chatter marks, arcuate cracks & lunate fractures
Lunate Fractures
Striations up close

10 mm
Laser profile of striation in stainless steel
Chatter marks, arcuate cracks & lunate fractures: Sliding indentors

From B. Johnson dissertation, 1975

Rotating blocks
Glaciated Landscape with Cirques and Horns
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).
Speed in a Glacier Cross Section

C.F. Raymond
Development of a U-Shaped Valley

J. Harbor
Erosion into Strong Homogeneous Bedrock
Erosion into a Fault

J. Harbor
Alaska: an ideal glacier laboratory

Coastal mountains in Alaska's active margins offer an exceptional and largely untapped opportunity to measure and to understand rates of erosion from both glaciated and non-glaciated terrains

—rates are high (relief and precipitation are both high and bedrock is damaged)
—fjords are nearly perfect sediment traps for both suspended sediment and bedload.
—seismic profiles together with retreat history can be used to infer sediment yield history for ~100 years
—sediment sources are close to sinks and storage is minimal
Singular transition between major transform fault (Fairweather) & thrusting under most massive glaciers in N.America: coincidence?
Mt. St. Elias to Sea Level
Both transitions between major transform fault (Fairweather-Denali) & thrusting occur under most massive glaciers in N.America: coincidence?

Image © 2005 EarthSat
Could rapid glacial erosion localize thrusting?
  • a type of tectonic (crustal) aneurysm (a la Koons & Zeilter)?
  • Or are glaciers just rapidly eroding fault-shattered rocks?
Extreme rates of erosion & uplift expected here of Malaspina Glacier.
Massive sediment plumes reflect rapid sediment evacuation from coastal mountains to the Pacific.
Holocene Sediment in Gulf of Alaska

Figure 4 - Jaeger et al.
Important to select glaciers carefully in assessing basin-wide erosion rates

**Requirements:**

- **good sediment sink** (fjords with sills that define deep basins, and proglacial lakes are ideal)

- glacier must be in retreat otherwise they would be over-riding and entraining their own sediments; sediment yields would not reflect bedrock erosion (this is easy because, with few notable exceptions, all glaciers have been in retreat since the early 1900s, the end of the Little Ice Age)

- Glacier must be fast moving and highly erosive to produce easily measured sediment volumes (seeking large signal-to-noise ratio)
But, this leads to systematic bias

Glacial erosion rates from Alaskan tide-water glaciers are exceptionally large (cm’s/yr) for the last century

- during rapid retreat, glacier surfaces were lowered 100’s of meters basin-wide.
- for tide-water glaciers in Alaska, most of the ice is lost by calving, not ablation, hence the drawdown results from greater ice loss by calving than is added as snow. This requires an acceleration of ice transfer to lower elevations.
- research at Columbia glacier shows that ice speeds increase with calving and retreat rates

∴ erosion rates are expected to increase with the more rapid basal ice motion during the retreat
Columbia Glacier, 2005
Calving glaciers: surprising relation between calving rate and ice speed

\[ U_C = U_i - \dot{R} \]

\[ U_C = kH_W \]

\[ Q_S = k\bar{U}_i \]
Erosion History at Tyndall Glacier, Alaska

From M. Koppes
**Glacial & Non-Glacial Denudation Rates**
Rates from Alaskan Tide-water glacier reduced 5-fold

Denudation rates
Alaska Glacier Erosion Are High
but are they representative and robust?

Peak rates of glacial erosion, inferred from sediment yields of tidewater glaciers, surpass those of fluvial erosion by up to an order of magnitude. They have recently come into question, however, because

- Biases inherent in the approach (effect of rapid retreat; sediments sloughing off fjord walls)
- Essentially nothing is known about characteristics of the glaciers or of the drainage basins that cause these high sediment yields.
- Little is known about whether peak erosion rates, found in southern Alaska, are representative of other glacial-tectonic settings.
Needs

• To improve our understanding of controls of erosion rates (sliding power, basal T)

• To determine erosion rates by dynamic glaciers outside Alaska: Patagonia

• To improve estimates of glacial erosion rates
  – Longer time scales
  – Better modeling of spatial and temporal patterns of erosion through the large glacial-interglacial climatic oscillations
Seek better understanding of how glacial erosion influences orogenic processes and reflects climate variability

• Need to identify controls on glacial erosion rates, as has been done for fluvial erosion for which precipitation rates and basin relief and size exert first-order controls. Similar quantitative relationships between glacial sediment yields and hydrologic or other basin characteristics have not yet been established.

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Glacial Buzzsaw

From J. Tomkin
Torres del Paine, Patagonia
Crossing Drake Passage

Figure 5. Map of mean annual atmospheric isotherms, Antarctic Peninsula region
Figure 6. Location DEM of Antarctic Peninsula study areas.
Figure 7. Map of mean annual precipitation in Patagonia (mm/yr), HPN = Northern Patagonia Icefield, HPS = Southern Patagonia Icefield, CDW = Cordillera Darwin Icefield.
We propose to examine explicitly the role of glacier dynamics in determining glacial sediment yields through a combination of techniques from glaciology and marine geology.

• Hypothesis: rates of glacial erosion are a function of sliding speed, and are therefore expected to diminish sharply as basal temperatures drop below the melting point.

• To test this hypothesis, we will measure both sediment accumulation rates in fjords and dynamic characteristics of the glaciers producing the sediments, for six tidewater glaciers ranging from fast-moving temperate glaciers in Patagonia to slow-moving polar glaciers on the Antarctic Peninsula.
Patagonia & the Antarctic Peninsula: ideal natural laboratories for our purposes

• Large latitudinal range provides for a large range of precipitation and glacier thermal regimes over relatively homogeneous lithologies and tectonic settings

• Prior studies of the region have noted a significant decrease in glaciomarine sediment accumulation in the fjords along a southward transect but they have not assessed sediment yields or erosion rates, and

• Fjords constitute accessible and nearly perfect natural sediment traps that can be readily surveyed by research vessel, the Nathaniel Palmer.
For each glacier system, we aim to

• assess sediment yields and, by inference, erosion rates by determining sediment accumulation rates within the fjords using seismic profiles and core data

• measure dynamic properties and basin characteristics of each of the glaciers, which have distinctly different ice fluxes and basal thermal regimes.

• We will seek to define an empirical relationship between glacial erosion rates and ice dynamics.