Glacial Geology – Erosional and Depositional Features
How do glaciers modify the landscape?

Evidence of glaciated regions: polished bedrock, smooth bumps, u-shaped valleys, etc.

Aim to be more specific in our description of these features beyond the statement: "produced by glacial processes".
Some scraps of glaciers remain in the lower 48
Glacial vs. Fluvial Erosion/Evacuation Rates

1. Glaciers erode more effectively than rivers
2. Glacial erosion increases with basin size

How and why?

(after Hallet et al., 1996)
Process #1: Glacial Scour – Abrasion

Regelation only gets water around the bumps in the bed – not rock particles.

What sets the abrasion rate?
Abrasion – a “smoothing” agent

Concentration \( (c) \) is simple: more particles equals more abrasion (up to a point)

\( U_c \) is sliding velocity of clast, equal to or less than, the sliding velocity of glacier

\( A_s \) is a bit more involved…
Abrasion – function of sliding speed (squared!)

As controls gouging depth, i.e. the cross-sectional area of the striation, controlled by:

1. eroding bedrock susceptibility

2. the force with which the clast is pushed into bedrock (related to the drag force).

\[
F_d = \frac{1}{2} A_s \rho_f C_d v_{rel}^2
\]

\[
(Re=v_{rel} D \rho_f / \mu)
\]

for low Re, \( C_d = 24/Re \),

\[
F_d = 3\pi D \mu v_{rel}
\]

\[
\dot{e} = c A_s U_c
\]

\[
\dot{e} = \gamma U_{rel}^2
\]
Abrasion: Effect of Relative Clast Sliding Speed

Tradeoff between absolute clast velocity and clast velocity relative to the ice:

If clast flows at ice velocity, no abrasion because $F_d \rightarrow 0$

If clast stops completely, drag force is high but the clast isn’t moving across the rock, and so can’t scrape it.

Where do you think the maximum (abrasional) erosion rate should be occurring?
Process #2: Glacial Quarrying – a.k.a. Plucking

Abra sáng depends upon availability of tools. Besides those that exist prior to glaciation or those that fall into the marginal crevasses (potentially many), the only other source of tools is quarrying.

The evidence for quarrying is clear: meter+ scale depressions in bedrock with characteristically steep lee sides.

Glaciers can easily entrain rocks once they've broken free. The challenge for the glacier is detaching the rocks in the first place.
Quarrying Mechanics

Begin with a bedrock step with a water-filled cavity on its lee side, observable in the field.

Ignoring the water, we imagine that high pressure is concentrated on the edge of this step. A large column of ice is bearing down upon this edge, supported by very little rock, concentrating the force per unit area.

However, a high uniform stress on the rock, alone, is not sufficient to precipitate cracking. Rock is strong in compression. It is the stress gradient which causes formation and extension of cracks.

Note that the stress contours are oriented parallel to the vertical step face, and that they are closest together (highest stress gradient) near the edge. That means fracturing should occur and propagate in such a way as to maintain the step.

When water pressure in the cavity drops, the stress gradient rises.

But, as soon as that water pressure drops, ice starts to sag by internal deformation, contacting the bed over a greater area and hence reducing the stress gradients at the bump edge.

It would eventually close the gap entirely if it weren’t for basal sliding. More rapid sliding will keep the ice launching over the lip, increasing pressures and enhancing quarrying.
Sub-glacial water pressure variability

Upshot: glacial quarrying is proportional to sliding speed, and ice thickness, but inversely proportional to water pressure at the glacier bed.

So, the optimal scenario (for quarrying) is a thick glacier sliding rapidly over its bed with generally high basal water pressures that occasionally crater.

There’s good evidence that the sudden release of basal water pressure when newly formed conduits reach cavities is a common phenomenon in mid-summer, exactly at the time when sliding is a maximum. During this time, significant quarrying likely occurs.

Subglacial water pressure fluctuations are high and rapid over the crest of a bedrock rise, but low over at the overdeepenings.

Figure 7.35. Topographic profiles of ice surface and bed (a), and water pressure records (b) from Storglaciären, Sweden. Profile shows several overdeepenings of the bed and major crevasse zones in regions of extension. Borehole locations in major overdeepening and at crest of bedrock bump are shown, along with spot measurements of the water pressure in the middle of the overdeepening. These measurements are all close to the level expected for flotation of the ice: 90% of the ice thickness, shown in gray line. Pressure records are very different for two sites, that in the middle of the overdeepening showing little variation around 90-100% of flotation, that at the crests of the bump showing major diurnal fluctuations between 70-90% flotation and that pressure associated with the depth of the transducer (gray line). Similar pressure fluctuations are inferred to promote enhanced quarrying of the bed at sites shown in (a). (after Hooke et al., 19xx, figures 2&3).
Play Subglacial Flow Movie from Grinnell Glacier, Montana

/Users/pna/Work/Teaching/Animations/grinnel_cd.mov
Glacial Geology –
Large Scale Erosional Landforms
U-Shaped Valley

Grinnell Glacier, Montana
Cross Valley Glacial Profile Evolution

Figure 7.38 Numerical simulation of cross-valley profile evolution during steady occupation of the valley by a glacier. Initial fluvial v-shaped profile evolves to u-shaped profile characteristic of glacial valleys in roughly 100 ka, given the sliding and erosion rules used. Bottom graph shows initial distribution of sliding speed and corresponding erosion rate. Low erosion rates in valley center allow faster rates along the walls to catch up. Final erosion rate is roughly uniform, causing simple downwearing of the u-shaped form. (after Harbor et al. Nature, 19xx)
Figure 7.40. Longitudinal profiles of two glaciated valleys, showing steps and overdeepenings. (after MacGregor et al., 2000, Fig. 1)
Numerical Modeling of Glacial Long Profile Evolution

Play Kelly MacGregor’s Matlab Simulations

/Users/pna/Work/Teaching/Animations/glacdeepen.mov

/Users/pna/Work/Teaching/Animations/glactrib.mov

Figure 7.41. Modeled evolution of the long profile of a valley with one tributary subjected to repeated glaciation. Steps develop in the valley profile, and the tributary valley is hung. The height of the step and the height of the hang depend upon the position of the tributary, and the long-term ice discharge. (after MacGregor et al., 2000, figure 3)
Proglacial Stream Discharge Fluctuation

Fig. 3-1. Comparison of predicted (potential) and actual (measured) meltwater discharge from Mikkaglaciaren, Sweden, 1957. Note that early in melt season (breakup period), potential discharge (total meltwater generated) is much higher than measured discharge due to storage on and within the glacier. Release of stored water contributes to higher-than-predicted discharges during the nival flood period. Closer correspondence between actual and potential discharge characterize late summer flows when drainage patterns are integrated and snowpack has disappeared from much of the glacier surface. From Stenborg (1970) with modification by Church and Gilbert (1975).

Fig. 3-2. Diurnal water-stage fluctuations in the small meltwater stream of Hilda Glacier, Alberta, for two sets of four successive fair-weather days. Note early season flow variations are more subdued than later in summer. From Hammer and Smith (1983).
Figure 7.39 Numerical models of long valley profile evolution of a glaciated valley in the face of a) steady climate, over 30 ky, and b) climate in which the ELA lowers at 4 m per thousand years, for 90 ky. Initial profile is a linear (uniform slope) valley. Top diagram shows all time slices in the respective simulation as light lines. (after Oerlemans, 1984)
Observations of downvalley surface motion, uplift, and proglacial discharge.
Glacial Landscape Evolution Model Schematic
Grewink Glacier, Southcentral Alaska – overdeepening