

Glaciers I: Intro, Geology and Mass Balance

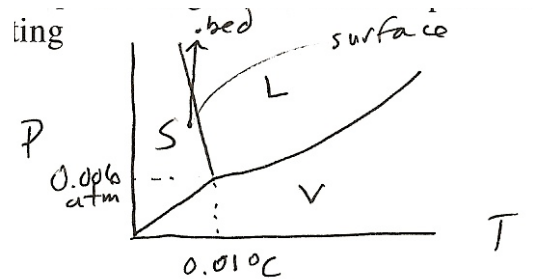
I. Why study glaciers?

- Role in freshwater budget
 - Fraction of earth's water that is fresh (non-saline): 3%
 - Fraction of earth's freshwater that is ice: $\sim 2/3$
 - Fraction of earth's surface covered by ice: $\sim 8\%$
- Climate records, climate effects & feedbacks: more in climate lecture
- Postglacial rebound helps constrain mantle viscosity
- Major driver of erosion, sediment transport, and landscape evolution
- But how important have glaciers been over Earth's history?
 - Over very long timescales, there seems to be a rhythm to glaciations
 - From geologic evidence: 950 Ma, 750, 650, 450, 350-250, 4-?
 - Proposed to reflect arrangement of continents (supercontinents promote accumulation of continental ice). But we don't even have a very good record of this beyond a few hundred Myr, let alone precise climate records
 - We have better records for more recent intervals
 - Antarctic glaciation began 25 Ma, Greenland 20Ma, Alaska 7Ma. Major Northern hemisphere glaciations began ~ 4 Myr. And this has been the typical climate state since!
 - Again, more in climate lecture. For now, suffice to say that glacial periods have dominated recent climate history.
 - We're in an interglacial, the first major one since ~ 125 ka. And our interglacial is an anomalously warm one. We must remind ourselves of this when examining landforms today.
 - What was North America like during glacial conditions? During LGM, we know there were
 - Extensive ice sheets [PPT]
 - Alpine glaciers in mountains beyond the ice margin
 - Large glacially-dammed lakes (Missoula, Bonneville) [PPT]
 - Huge floods from these lakes (formed Channeled Scablands in WA, Snake River gorge in ID)

- Pleistocene megafauna! [PPT]
- Glaciers change drainage networks [PPT: North America]

II. Glacial features & terminology

- Definition of glacier: perennial ice that has moved
- Ways to classify glaciers
 - Morphologic [PPT: Cirque, valley, ice sheet]
 - Confined by topography: valley glacier, cirque glacier
 - Unconfined: ice sheet/cap, ice shelf, ice stream
 - Thermal
 - Temperate (melting @ base due to high T_s + basal pressure).
 - Base of glacier is usually warmer than surface due to conductive temp gradient
 - Recall phase diagram of water & pressure melting



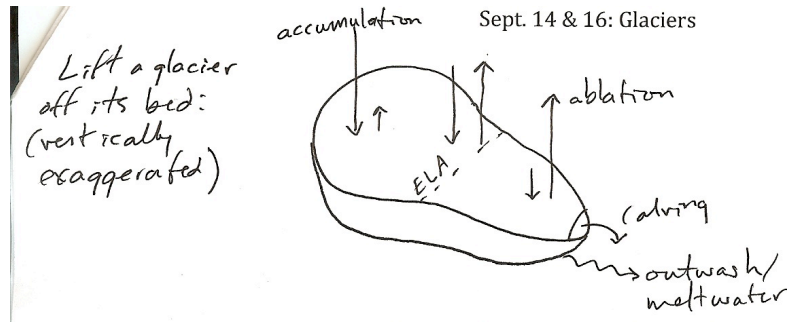
- Cold-based/polar (no basal melting; frozen to bedrock)
- Dynamic
 - Steady flow
 - Unsteady (surging – e.g., Pacific NW)
- Glacial features
 - Depositional
 - “Drift” = all deposits of glaciation
 - Nonstratified drift = Till: unsorted, often angular debris
 - Ablation till = debris concentrated as a lag on surface losing mass
 - Lodgement till = basal deposition

- Stratified/sorted drift = Outwash: fluvioglacial sediments deposited by meltwater
- Moraines [PPT]
 - Marginal: lateral, terminal, recessional
 - Interior: ground, medial
- Other
 - Drumlin: streamlined hill, often in groups of many. Origin not well understood. [PPT]
 - Kame: mounds (hills) of layered sand & gravel up to 50m high [PPT]
 - Kettle: depression formed by melting of ice block (many New England ponds) [PPT]
 - Esker: sinuous deposits from subglacial river [PPT]
- Erosional
 - Negative relief
 - Small scale: chattermarks, crescentic gouges, striations [PPT]
 - Groove (up to many km long, 100s of m wide)
 - Cirque: [PPT]
 - Deep erosional recess with steep walls & amphitheater shape, usually located at head of valley
 - Signature of a small alpine glacier
 - Positive relief
 - Whaleback: 10s to 100s of m, all sides smooth
 - Roche moutonnee: 1m to 100s of m, smoothed on one side and steep on the other. Flow direction indicator [PPT]

III. Glacier mass balance

- Ice forms from compression and sintering of snow: starts at $\sim 0.5 \text{ g/cm}^3$, ice forms at $\sim 0.85 \text{ g/cm}^3$
- Accumulation and ablation zones
 - Accumulation: snow
 - Ablation: sublimation, melting, calving

- Both can occur over entire glacier
- Boundary between net accumulation and net ablation typically defined by elevation → equilibrium line altitude (ELA)
- Why is ELA defined by altitude? The temperature lapse rate influences the fraction of annual precip that falls as snow, and the fraction of each year when melting or sublimation can occur.



- Thus, ELA is a climate signature. Has been used as a paleo-temp proxy
- How can glacier accumulate in one area and lose mass in another, and maintain constant form? It flows.
- How do glaciers flow up and over mountain ranges? For example, how did the Cordilleran ice sheet flow from western Canada over the Cascades to Seattle?

Glaciers II: Flow and Erosion

IV. Glacier motion

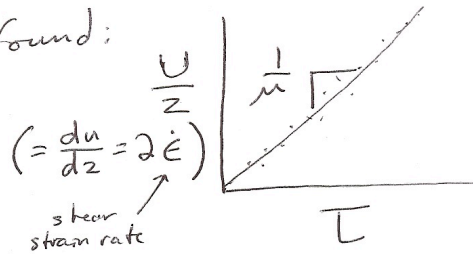
- How fast do glaciers move? Some representative surface velocities:

Site	Surface velocity (m/yr)
S. Cascades	20
Antarctica	32
Greenland	50
Alps	100
Saskatchewan, Canadian Rockies	120
SE Alaska	500
Ansterdalsbreen, Norway (icefall)	2000

- 2 main mechanisms:
 - 1. Basal sliding. Why does it occur?
 - Increased fluid pressure → decreased effective normal stress → decreased friction
 - Where sliding is accommodated by shearing of subglacial sediments, elevated fluid pressure will decrease effective viscosity
 - Moderate-sized bumps favor regelation: pressure melting and refreezing allows flow around objects. Recall phase diagram of water, and that bed of temperate glaciers is commonly at melting point.
 - Increased P on up-flow side → melting
 - Refreezing at lower P on leeward side releases latent heat → diffuses back upslope and further enhances melting
 - Note that regelation promotes quarrying of blocks from leeward side → roches moutonnees
 - 2. Internal deformation
 - Why does ice deform?
 - A bowl of ice will not flow. Why not?
 - What about a block on a slope? Yes.

- What about a block with a horizontal bed and sloping surface? Yes.
- What about an ice sheet with a sloping surface over a bed that slopes in opposite direction? Which wins?
- What drives flow? Pressure gradient.
- Once we subtract out basal sliding, how does ice deform?
 - No-slip condition at bed
 - Ice with a free surface must flow by shearing
 - Recall stress-strain rate relationship for a viscous (Newtonian) fluid

He found:



"Newtonian fluid"

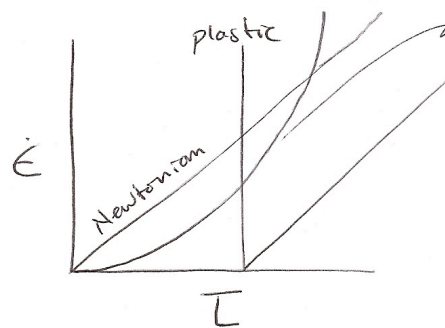
$$\frac{du}{dz} = \frac{1}{\mu} \tau$$

← "viscosity"
(dynamic)

units: $\frac{L}{T} \cdot \frac{1}{L} = \frac{1}{T} \cdot \left(\frac{M}{LT^2}\right) = Pa$

$$\mu = Pa \cdot s \equiv \frac{M}{LT}$$

Other stress-strain rate rheologies:



Nonlinear viscous:

$$\dot{\epsilon} = K \tau^n$$

(I have drawn $n > 1$)

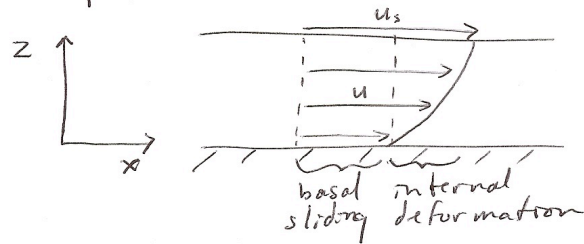
For ice, $1.5 < n < 4.2$

$n = 3$ Glen's Law

$$K = f(T, \dots)$$

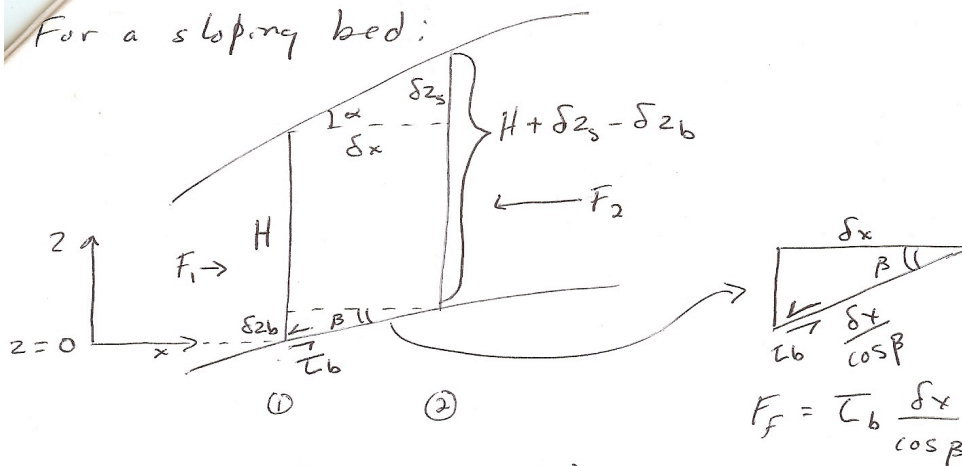
- This gives us the local velocity gradient, which we can integrate to get the velocity profile
- Ice, like many natural fluids, has a more complicated rheology, but the shear stress is still the key
- Glen's flow law: shear strain rate = $k\tau^3$
- Need at least ~50m of ice to deform viscously. At shallower depths, brittle deformation → crevasses
- Sketch typical velocity profile: basal sliding + viscous flow

Velocity gradient over a horizontal bed:

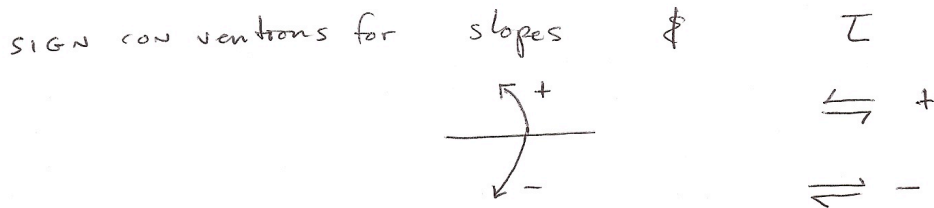


- Basal shear stress for sloping surface and sloping bed
 - Expression (explain how derived)
 - Illustrate how sign depends only on surface slope

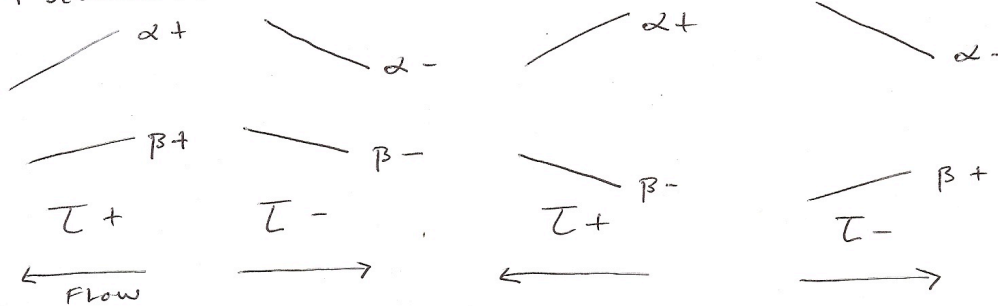
For a sloping bed:



$$\rho g H \tan \alpha \cos^2 \beta = \tau_b$$



4 scenarios:



Flow direction is controlled only by the surface slope.

- This is why the Cordilleran ice sheet could flow from western Canada over the Cascades to Seattle [PPT]
- Empirical observation: τ_b is typically ~ 1 bar
 - Maintained by surface-slope feedback: if surface slope is low, ice shears slowly, and accumulation & ablation will build up surface gradient. If slope is high, ice will shear rapidly, lowering surface gradient faster than mass fluxes can build it up.
 - Surface and basal slopes are typically small, so we can estimate depth from surface slope
 - $\cos^2 \beta \sim 1, \tan \alpha \sim \alpha \rightarrow \tau_b \sim \rho g H \alpha$
 - So $H \sim (10^5 \text{ Pa}) / (10^3 \text{ kg m}^{-3} * 10 \text{ m s}^{-2} * \alpha) = 10 / \alpha$
 - We can compare the thickness predicted by this rule of thumb with some endmember cases:

	α	H_{pred}	H_{actual}
Lyell Glacier, Yosemite (valley glacier)	0.1 rad	100 m	50 m
Greenland Ice Sheet	0.01 rad	1000 m	2000 m

V. Glacial erosion

- How important is glacial erosion?
 - The “buzzsaw” hypothesis. Controversial (doesn’t work everywhere), but compelling. [PPT: Apparent correspondence of ELA and peak elevation in Andes]
 - We see the clear imprint of glaciers in many landscapes. Must be important! [PPT: several slides of glacial landscapes]
- Mechanisms
 - Abrasion: rocks in ice scrape bedrock
 - Plucking/Quarrying: ice frozen to rock, pulls it off (rocks weaker in tension than in compression)
 - Subglacial fluvial processes
 - Dissolution by subglacial drainage

- Abrasion and plucking are most important. Generally thought that quarrying dominates.
- What controls rate of glacial erosion? [PPT: Striations]
 - Ice thickness (recall expression for shear stress)
 - Ice slope
 - Velocity: Faster abrasion where constrictions (horizontal or vertical) lead to higher velocity
 - Temperature: if melting is more rapid, abrasion will be more rapid b/c bed-normal sediment velocity will be higher. This might also apply to plucking since more rapid melting could enhance velocity and regelation
 - Sediment concentration: Higher concentration → more rapid erosion
 - Rock strength
 - Lack of a well-tested glacial erosion law is a major unknown in geomorphology, especially given the evidence supporting the importance of glaciers (buzzsaw, U-shaped valleys, etc.). Most widely used is an expression in which erosion rate is a power function of sliding velocity