

## Glaciers

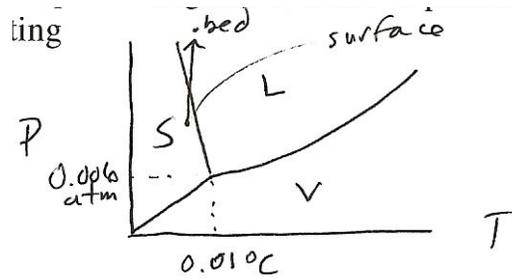
### I. Why study glaciers? [PPT: Perito Moreno glacier, Argentina]

- 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
- Major driver of erosion, sediment transport, and landscape evolution. Ice sheets can change entire river networks [PPT: North America]
- Major role in Earth's history
  - Recall the “snowball Earth” hypothesis: there may have been multiple episodes when glaciation was nearly global in extent
  - Glaciation has been the typical climate state for all of human history
    - Major northern hemisphere glaciations began  $\sim 4\text{Myr}$
    - For the past  $\sim 1\text{Myr}$ , climate dominated by  $\sim 100\text{kyr}$  glacial cycles
    - We're in an interglacial, the first major one since  $\sim 125\text{ ka}$ . 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]
    - Large glacially-dammed lakes (Missoula, Bonneville) [PPT]
    - Huge floods from these lakes (formed Channeled Scablands in Washington, Snake River gorge in Idaho)
    - Pleistocene megafauna [PPT]

### II. Definition and types

- Definition of glacier: perennial ice that has moved
- Major distinctions among glaciers are based on form and thermal state
  - Morphologic [PPT: Cirque, valley, ice sheet]
    - Confined by topography: valley glacier, cirque glacier

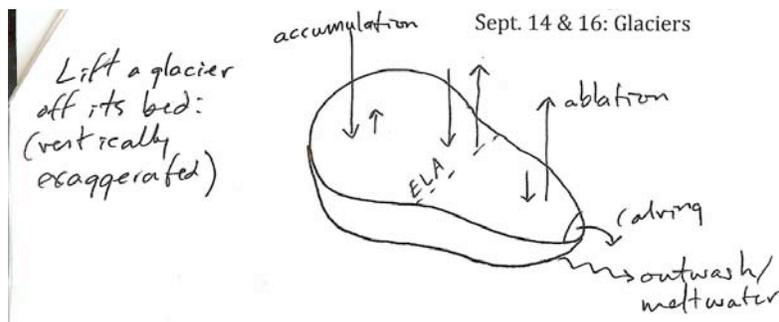
- Unconfined: ice sheet/cap, ice shelf, ice stream
- Thermal
  - Temperate (melting @ base due to high  $T_s$  + basal pressure).
    - Base of glacier is usually warmer than surface due to conductive temp gradient
    - Recall phase diagram of water & pressure melting



- Cold-based/polar (no basal melting; frozen to bedrock)

### III. Glacier mass balance

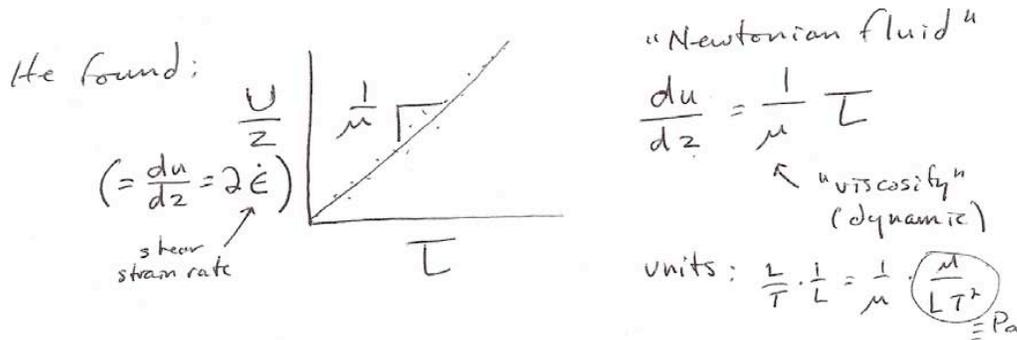
- Why do glaciers form? How can the Fox and Franz Josef glaciers in New Zealand extend down to sea level, right next to temperate rainforest? [PPT]
- Sketch of glacier mass balance
  - Accumulation: snow at high elevations, which then sinters  $\rightarrow$  ice
  - Ablation: sublimation, melting, calving
  - Both can occur over entire glacier
  - Boundary between net accumulation and net ablation typically defined by elevation  $\rightarrow$  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.



- How can a glacier accumulate in one area and lose mass in another, and maintain constant form? It flows.

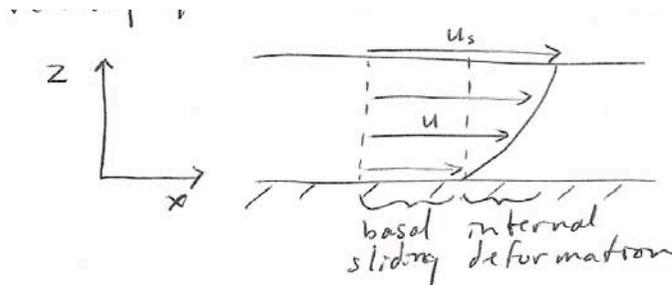
#### IV. Glacier motion

- How fast do glaciers move? [PPT: some representative surface velocities]
- 2 main mechanisms:
  - 1. Basal sliding
    - Increased fluid pressure → reduced friction (recall landslides)
    - Shearing of subglacial sediments
  - 2. Internal deformation
    - Why does ice deform?
      - Flow driven by pressure gradient, like any fluid
      - Surface slope – not bed slope – drives direction of pressure gradient (thought experiment if time permits)
      - This is why the Cordilleran ice sheet could flow from western Canada over the Cascades to Seattle [PPT]
    - 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:  $du/dz = \tau/\mu$



- This gives us the local velocity gradient, which we can integrate to get the velocity profile. Stress increases with depth (z) due to the weight of the overlying ice, so the velocity gradient gets smaller at shallower depths, so the velocity profile is curved (parabolic).

- Ice, like many natural fluids, actually 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 [PPT]
- Sketch typical velocity profiles:
  - XS: basal sliding + viscous flow. Make surface and bed inclined and parallel.



- Map view: cross-valley velocity profile with sliding + curved profile at sides

## V. Glacial erosion

- Main mechanisms, in probable order of importance
  - Plucking: ice frozen to rock, pulls it off (rocks weaker in tension than in compression)
  - Abrasion: rocks in ice scrape bedrock → can often see striations
  - Subglacial fluvial processes
- How important is glacial erosion?
  - We see the clear imprint of glaciers in many landscapes. Must be important! [PPT: several slides of glacial landscapes]
  - The “buzzsaw” hypothesis
    - Compelling [PPT: Apparent correspondence of ELA and peak elevation in Andes]
    - But controversial:
      - Doesn't work everywhere
      - High inland elevations can be dry and unglaciated
      - Cold-based glaciers can *armor* bedrock

- Geologic features produced by glacial erosion & deposition (time permitting; see textbook)
  - Depositional
    - “Drift” = all deposits of glaciation
      - Nonstratified drift = Till: unsorted, often angular debris
      - Stratified/sorted drift = Outwash: fluvio-glacial sediments deposited by meltwater
    - Moraines [PPT: Alaska, New England islands]
      - 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: chatter marks, crescentic gouges, striations [PPT]
      - Large scale: Groove (kms 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]

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