

# Groundwater and Ice Sheets

November 17, 2006

## Groundwater

Two important measures: (1) Porosity & (2) Permeability

Water Table: “Aquifers”, *Cone of depression*, “*saltwater intrusion*” & *subsidence*

## Groundwater erosion

*Sinkholes, Karst topography, Caves, & Speleothems*

Formation of glacial ice—Snow, Firn, Ice, air pockets and recrystallization

## Controls on glacier formation

Snowline

Mass balance of ablation and accumulation

## Glacier morphology

Flow mechanisms—shearing and crystal deformation, basal melting

Erosion

Rock falls, plucking, moraines (terminal, lateral and medial)

Sediment characteristics—till, rock flour, glacial-marine, lacustrine and stream

## deposits

Flow in ice streams, crevasses

Mountain Glacier landforms—u-shaped valleys, hanging valley, cirques, horns

## Ice sheets

Climate effects—“cold monsoons”

Loess

Flow Velocities along ice margins

Ice sheet landforms

Erratics, drumlins, eskers, and kettles, dropstones

## Pleistocene ice sheets

Isostatic effects and rebound

Drainage re-organization

Ice-dammed lakes

Sea-level effects—base-level and potential sea level rise

Pluvial lakes

Number of glacial cycles—oxygen isotopes from marine sediment cores

## Past Glacial Periods

Feedbacks to formation of ice caps



### Groundwater

Rocks can absorb considerable amounts of water--25-45% of total volume in gravel, even granite can have 1.5% pore space and can have much higher water storage capacity in fractures and joints

Two important measures:

**Porosity**—the amount of void space in a rock—

1. influenced by grain size (increases with grain-size),
2. sorting (higher with higher sorting),
3. texture (more uniform rocks typically have more uniform joints (a source of significant porosity),
4. composition—solution cavities, and
5. mode of formation—vessicles in volcanic rocks

**Permeability**—the degree of interconnections between pore spaces—key to allowing fluids to move through rocks

1. highest permeability in sandstones and conglomerates, also fractured granites and solution cavities in limestone
2. lowest in shales and quartzite

**Water Table:** zone of saturation (lies below the aerated zone where water does not fill the pore spaces but may exist mostly at grain contacts. Fluids at grain junctions can be very difficult to extract—on reason why it is hard to pump all the oil out of a saturated formation.

1. Permeable rocks below the Water Table are “*Aquifers*” that are recharged from surface waters seeping into soils and the subsoil.
2. Changes in elevation can modify the pressure head or *hydraulic head* causing groundwater to flow to lower pressure regions
3. Where hydraulic head is high and there are breaks in the confining seals (for example, impermeable clay layers) on an aquifer, can get “*Artesian Springs*”
4. ***Cone of depression:*** Drilling into an aquifer and pumping the ground water will lower the water table near the well since fluid flow may not be as fast through the formation as it is in the well.
5. Can get a reverse cone of depression in areas where freshwater lies on salt water in subsurface aquifers; in this case, pumping can cause “*saltwater intrusion*” by reducing the amount of freshwater allowing salt water to flow into formerly fresh aquifers.
6. Excessive pumping an aquifer can also cause *subsidence* when the pore space in an aquifer collapses. Once subsidence has occurred recharge is reduced—the aquifer is, in effect, destroyed.

### Groundwater erosion

Dissolution can be significant in limestones and evaporates

1. creates *sinkholes* where cavities have been eroded by ground water causing the overlying land surface to collapse. Called *Karst topography* where sinkholes merge creating steep-sided ridges.
2. *Caves* are enlarged when groundwater is flowing through rock. As the cavities enlarge, the water table may drop (because more space has been made for water deeper in the limestone) leaving the caves relatively dry (other than seeping groundwater from the surface)
3. Cave formations (*Speleothems*) formed by ground water seepage into open caves—carbonate deposited as water releases CO<sub>2</sub> when it enters the open air (and lower pressure) of a cave.

### **What if you were lost in the desert?**

If you were lost in the desert, what kind of rock formation would you be most likely to find good springs?

1. Don't try limestones—dissolution and cave formation tend to keep streams underground
2. Don't try shales—shales are “tight” and tend to prevent water from flowing out—act as impermeable layers.
3. Do try granites that have been fractured by wide-set joints—these joints can store a great deal of water and direct the water out in specific places [springs].

**Glaciers—permanent bodies of ice**, formed from compacted and recrystallized snow.

### **Formation of glacial ice:**

Snowfall produces air filled snow layers that can be re-arranged by wind to form denser snow. Hence summer snowfall is often less dense than that formed during the winter winds; both types of snow are compacted to form “old snow” or **firn**.

After ~200 years, the firn recrystallizes enough to seal off the air pockets from the atmosphere and form ice; the ice retains layers richer in air bubbles (formed in summer) and these preserve the composition and chemistry of the ancient atmosphere. During recrystallization to form ice, snow is compacted about 2/3rds (3 feet of snow = 1 foot of ice)

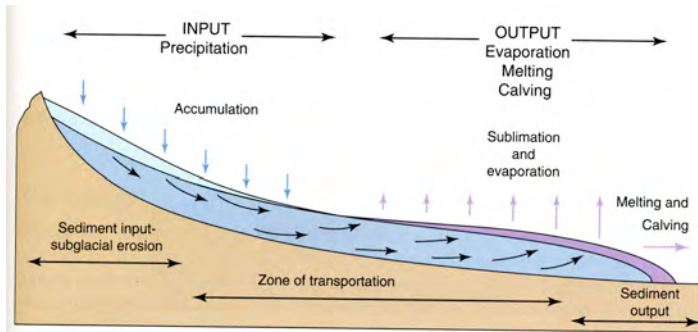
After compaction by 2000 feet of ice, the air bubbles are under high pressure—such ice will snap and pop when brought to the surface (polar hands enjoy a fizzy, noisy drink made with such old ice!).

### **Controls on glacier formation and stability**

**Snowline**—lowest elevation at which snow can survive all year (lower limit of year-round snow pack); snowline varies from the tropics (where it may be at an altitude of 5000-6000 m) to the poles (altitude 0 m)

**Mass-balance**—between **accumulation** (by snowfall) and **ablation** (melting or evaporation). The balance of these two varies seasonally and with altitude

In a stable glacier, excess ablation at the down hill end of a glacier is made up by accumulation at the uphill end and flow to replace lost ice.

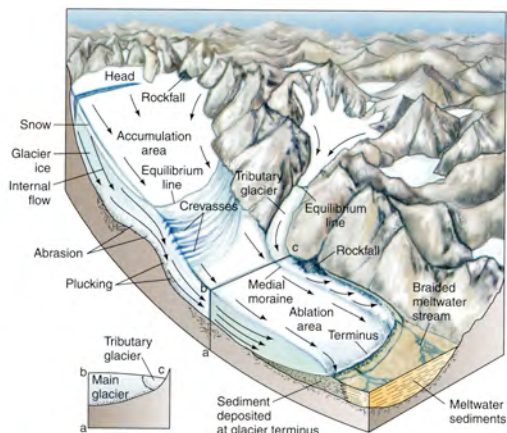


### Major parts of a glacier:

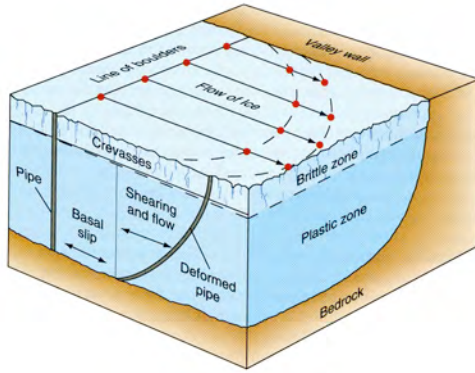
Glacial ice flows under pressure by (1) **shearing and deformation** of ice crystals along weak planes in the crystal lattice and (2) **by melting** along the underside of the glacier (due to trapping geothermal heat)

**Erosion occurs by rock fall** onto the ice surface (creating **lateral moraines**) and by **ice plucking** of the bed of the glacier.

**Sediment (till)** is transported **in the ice** and by **under-ice streams** in the lower parts of a glacier. Develops **glacial striations** by grinding against rocks imbedded in moving ice. Poorly sorted and mixed with **rock flour**—ground up rock; **Un-stratified till mixed with braided stream deposits, and glacial lake/pond deposits**



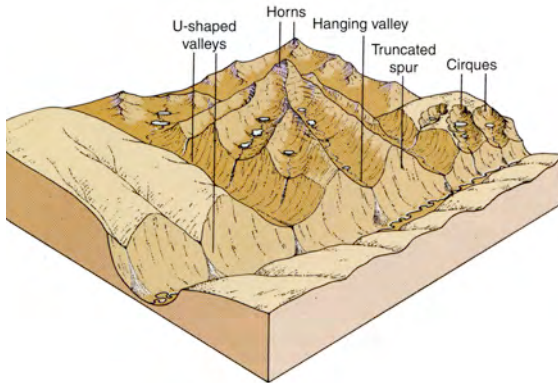
Like a river, glacial ice **moves fastest** in the **center of the flow and top** of the flow. There is a **brittle and ductile layer** as in the crust. **Crevasses** form when the ice undergoes extension across bedrock highs



## Glacial landforms

Separate ice streams can create **medial and terminal moraines**

Also form **U-shaped valleys**, **hanging valleys** (site of tributary glaciers), **cirques** (accumulation basins for glacial ice and snow), and **horns**. U-shaped valleys form because ice erodes along the sides of the valley as well as along its bed.

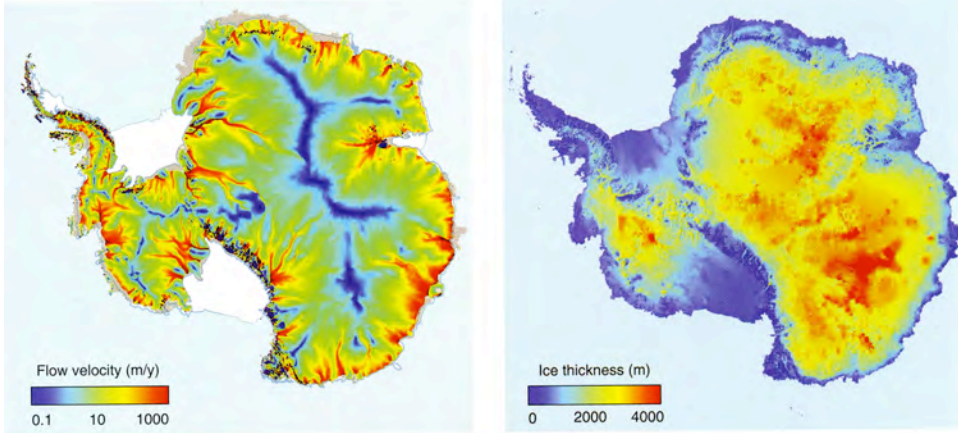


## Icesheets (ice caps)

These are **large scale** features with elevations of **>3000 m** (ie ~1.5 miles thick & rivaling the elevation of the Tibetan Plateau). The great elevation sets up '**cold monsoons**'—cold, dry winds that flow off the ice to surrounding areas; Ice sheet also draws in moisture like the effects of the Tibetan Plateau on the monsoon; have climate effects far beyond the ice itself. Wind also carried **loess**—silt and clay—**from glacial rock flour**—extensive deposits in China, central Europe and Missouri River Valley.

Ice cap surfaces arch gently because there is a zone of ablation along the margin (e.g Barnes Ice cap and Iceland ice cap)

**Flow velocity fastest along ice sheet margins** (e.g. Antarctica). All glaciers need a supply of snow which requires a supply of moisture. Glacial growth will be inhibited under arid conditions or if ice shelves choke off moisture supply.



### Ice cap landforms

**Erratics**—large blocks of rock deposited by retreating glacier

**Drumlins**—elongate hills with blunt end up stream

**Eskers**—sediment deposited in sinuous ridges by confined streams flowing under the ice

**Kettles**-depression (often occupied by a pond) left by a melting block of ice

**Varves**—annual layers of sediment deposited in alternately ice-covered and ice free lakes

**Dropstones**—rocks deposited in water by melting icebergs (ice-rafted debris)—reflect distribution of ice bergs caved off glaciers that reach the sea.

### Pleistocene Ice caps

**Laurentide** and **Eurasian** Ice caps in the Northern Hemisphere and more extensive sea ice than today on both poles.



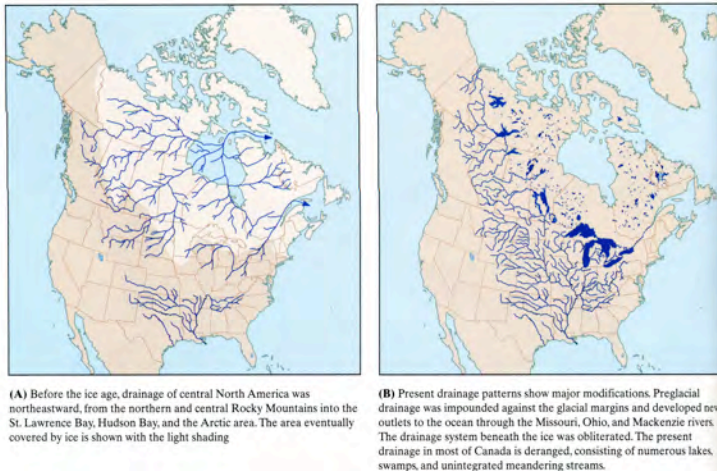
Laurentide extended south of the Great Lakes, over New England & N. Oregon

### Isostatic adjustment

ice sheet melting has caused large uplifts of formerly glaciated areas—**Hudson Bay: 300 m (with 80 m to go), ~400 m in Great Lakes region** (tilting old lake shorelines);

Adjustment still accounts for **2-3 cm/year local sea-level fall** in Norway and eastern Canada.

### Reorganizes drainages



Weight of ice depresses continent causing rivers to flow toward the ice sheet and develop glacial lakes; since water is forced to flow along the ice margin.

### Ice-dammed glacial lakes

Developed extensive system along Laurentide Ice sheet—e.g. Lake Missoula (on Idaho) and Agassiz (on N. Dakota, Minnesota and Manitoba) as well as in New England.

Created multiple large floods when the ice dams gave way

### Effects on Sea-level

N. hemisphere ice sheets **stored enough water** to account for **~137 m of sea level** change (in contrast, melting Greenland yields **~7 m** of sea level change; modern Antarctica stores enough water for **~70 m** of sea level rise)

Lower Glacial sea level allows people to walk from SE Asia almost to Australia and England, turns the Sea of Japan into a lake, and isolates the Black Sea. The **changes in base-level** caused many rivers to down cut during glacial times creating submarine canyons.

### Pluvial Lakes

Increased winds and moisture supply caused by elevated ice sheets lead to increased precipitation over western N. America—creates an extensive series of lakes in many of the valleys of the Basin and Range. Lake Bonneville was 300 m deep and about the size of Lake Michigan (covered 500,000 km<sup>2</sup>); overflowed into the Snake River



### Number of Glacial Cycles

Counting moraines difficult because ice advances can scour old deposits; use marine sediment cores instead.

Trick is use of oxygen isotopes— $^{16}\text{O}$  evaporates more easily than  $^{18}\text{O}$  so rain and snow is enriched in  $^{16}\text{O}$ ; remaining seawater is therefore enriched in  $^{18}\text{O}$  when there are large ice sheets around; can measure the  $^{18}\text{O}/^{16}\text{O}$  ratio (called  $\delta^{18}\text{O}$ ) in marine microfossils which can be precisely dated.

Results show that there have been **~28 glacial advances in past 2 my**. N. Hemisphere ice cap starts to grow ~2.5-2.7 Ma, Antarctic ice sheet starts to grow ~33 Ma.

### Past Glacial Periods:

Major glacial stages in the early Proterozoic ~2.1-2.2 by, Late Proterozoic (1200-600 Ma), Ordovician (445 Ma), Carboniferous (300 Ma) and past 33 Ma. Causes are not always known but cooling in the Carboniferous probably related to evolution of woody trees—store  $\text{CO}_2$  as coal drawing down greenhouse gas content and cooling the earth.

Modern (past 700-800 Kyr) Glacial-interglacial cycles have 100 kyr beat—similar to the orbital eccentricity cycle that regulates amount of solar radiation the earth receives. Possible pre-conditioning by closure of the Panama Isthmus diverting more moisture to N. Hemisphere.

Other factors, regular beat of  $\text{CO}_2$  and methane (important greenhouse gases) and glaciations as seen in ice core air bubbles. Not clear whether this is a reflection of ice growth or a cause.

**Numerous feed back loops**—ice reflects solar energy cooling the planet allowing ice to grow more—eventually reaches a steady state between ablation and surging and further ice addition; bed melting causes surges and ice sheet collapse. Colder climates may lock up  $\text{CO}_2$  in permafrost further reducing Earth temperatures.

