

Midterm #3 Format

- The format is the same as the previous two midterms. (multiple choice and short answers)
- The material covers the lectures since since Midterm #2 and includes today's lecture on glaciers.
- There will be calculations but the math is very simple. A formula sheet is provided
- Do the practice questions!
- Ask questions & talk to your TAs or to me.

Question from the Lecture 14 - Groundwater

- How do you use dimensional analysis?
- Can you explain Darcy's Law again?
- Can you do some more practice questions in class

How do you use dimensional analysis?

Example: Calculate Unit Discharge in units of m/a

Information: Discharge in m^3/s and Area km^2

Calculation: Unit Discharge = Discharge / Area

Dimensional analysis: $\text{m/a} \neq \text{m}^3/\text{s} / \text{km}^2$

Dimensional analysis: $\text{m/a} = \text{m}^3/\text{s} * \text{s/a} * 1/\text{km}^2 * \text{km}^2/\text{m}^2$

Groundwater movement

Darcy's Law –, the velocity of groundwater will increase as the slope of the water table (hydraulic gradient) increases.

$$v = -\frac{K}{\eta} i$$

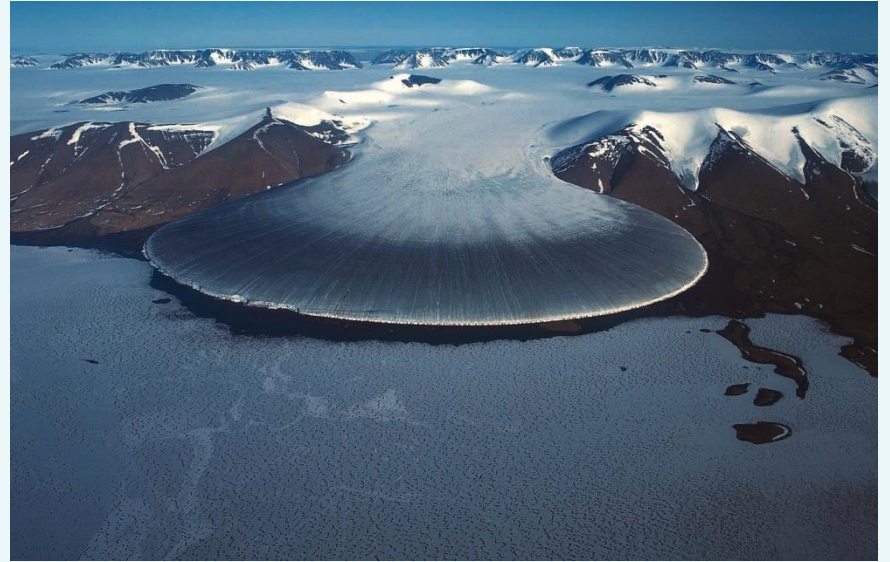
v = groundwater velocity

K = hydraulic conductivity (related to permeability)

η = porosity

i = hydraulic gradient = driving force

GLACIERS



GLACIERS – Pre-lecture questions

- What is a glacier?

- Are they important?



How do glaciers move?

- Is glacial ice a rock or fluid?



Outline

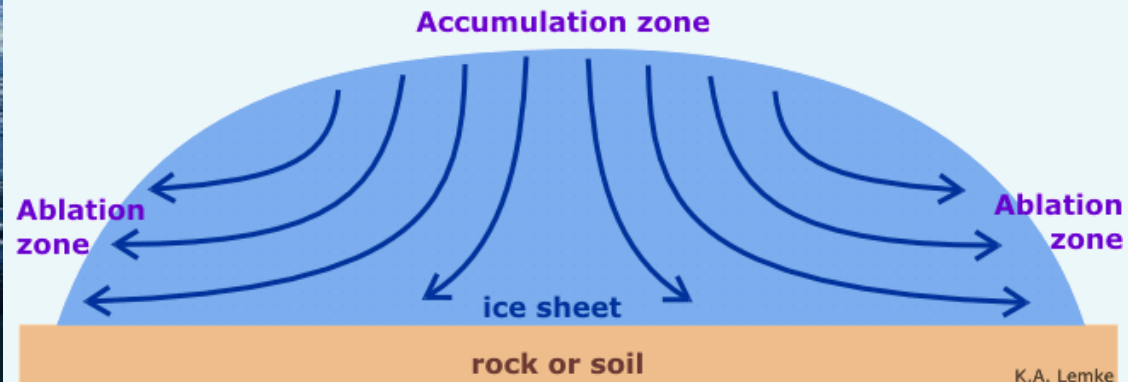
1. What is a glacier?
2. Why are glaciers important?
3. What is ice (rock, fluid)?
4. How do glaciers form and move?
5. How do glaciers move?
6. Are there different types of glaciers?
7. What geologic landforms and deposits are formed by glaciers?
8. Glaciations in Earth's history



Definition

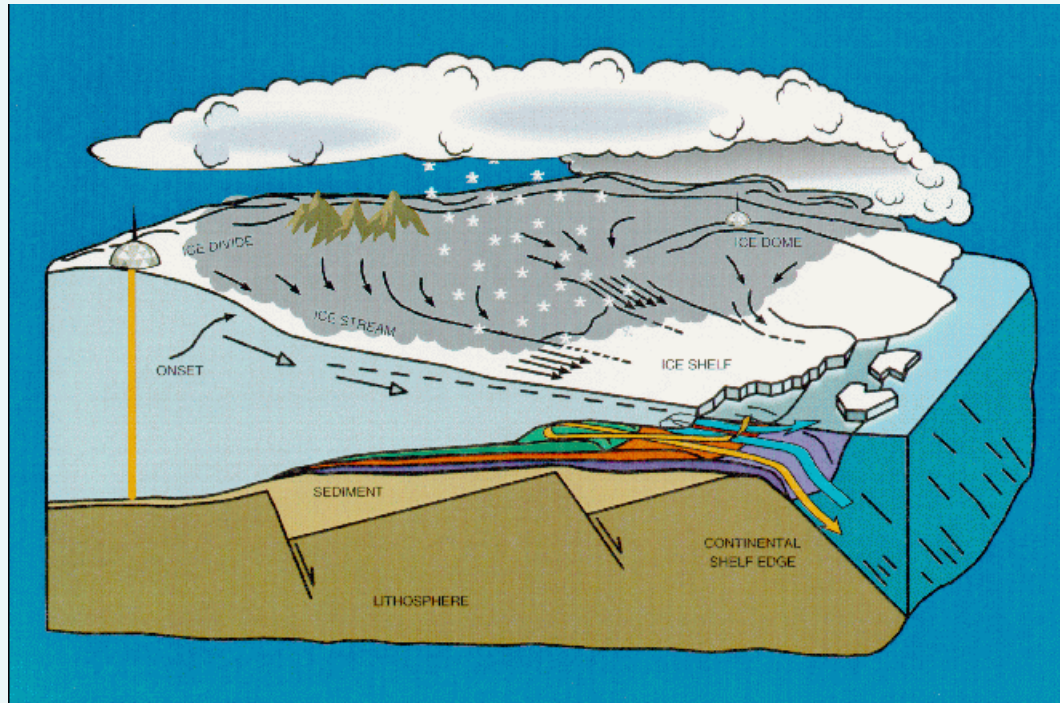
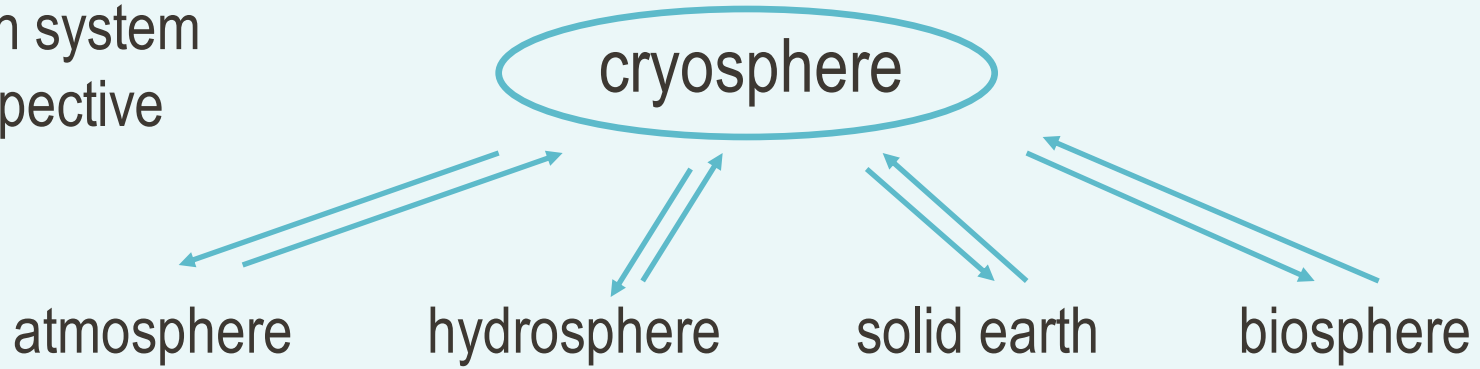
What is a **GLACIER**?

- a thick, naturally accumulated ice mass that forms over hundreds or thousands of years, and deforms (flows) under the force of its own weight.



Importance

Earth system
perspective



Hydrologic cycle (review)

Distribution of Earth's water

1. Oceans: 97.2%

2. Freshwater: 2.8%

2a. glaciers: 2.15% → Today's lecture

2b. groundwater: 0.62%

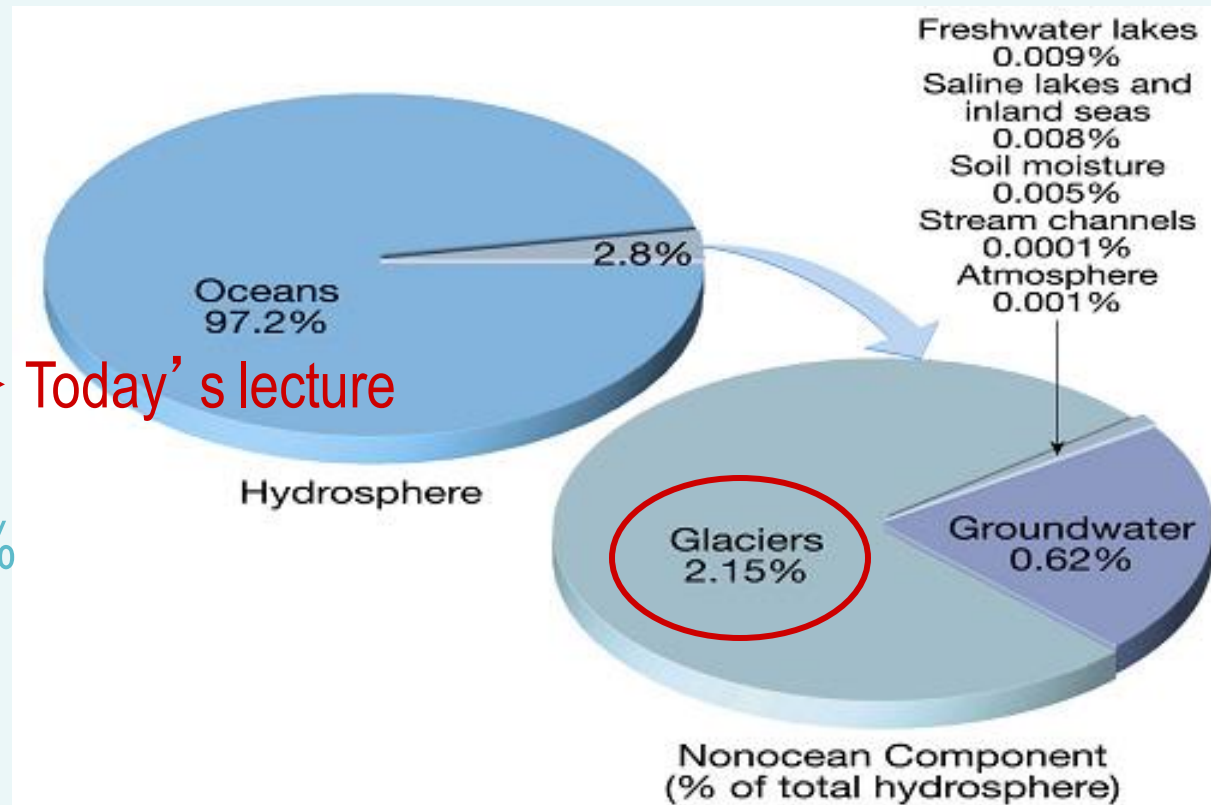
2c. other

lakes: 0.009%

soil moisture: 0.005%

atmosphere: 0.001%

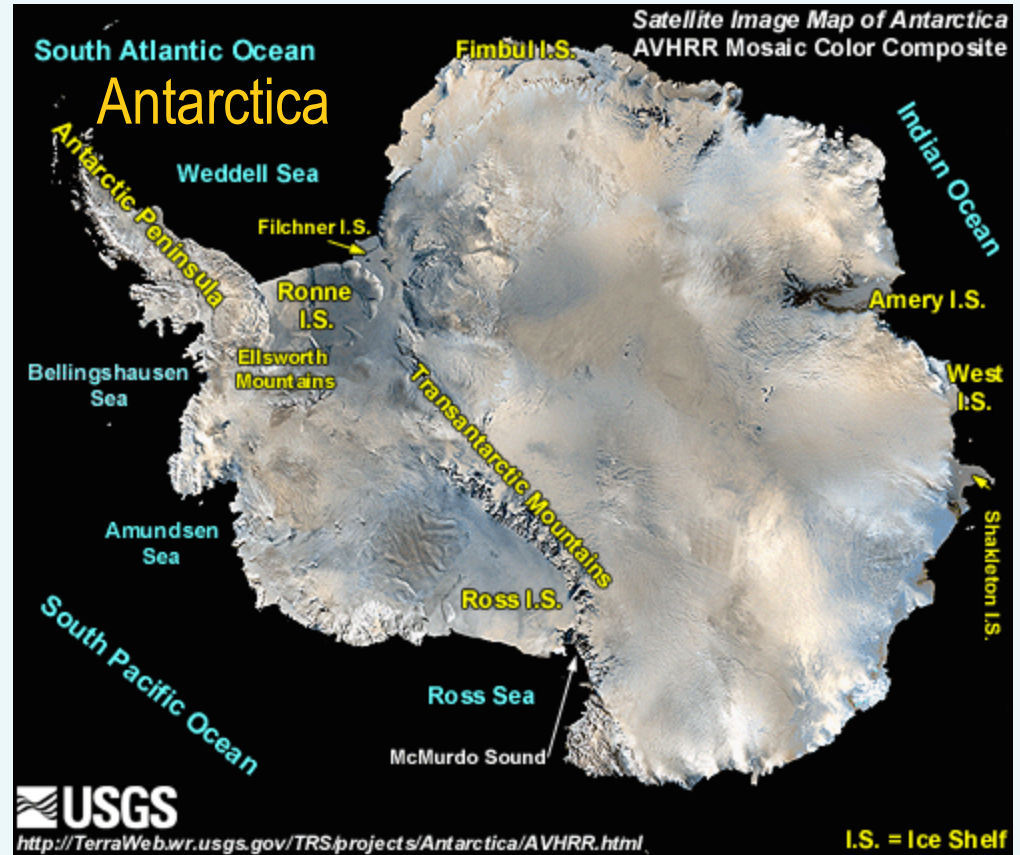
streams: 0.0001%



Importance – Water Storage

~2% of hydrosphere, ~ 80% Earth's freshwater

Greenland



Glaciers cover ~10% of land surface (95% shown in the two figures above)

Importance -

- Release of all stored water would flood coastal areas
- Storage / delay tank for runoff water in mountain systems that is used for agriculture and irrigation
- Weather control in local areas and broader climate influence of continental scale glaciers
- Process responsible for geologic deposits of, gravel, sand etc.
- Climatic archives to understand history of earth

Importance

- glaciers shaped landscape Canada and N. USA
- glacial deposits → aggregate, groundwater reservoirs



Glacier formation

Ice is also a good preservation agent!

Inca mummy
from Peruvian
Andes

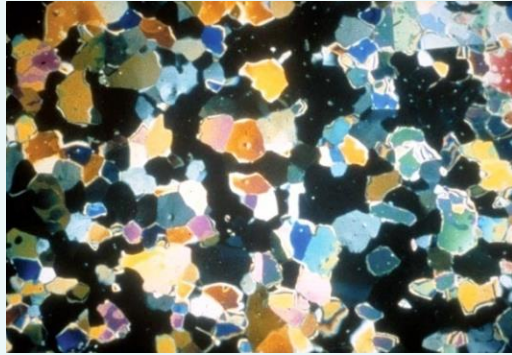


What is ice?

1) Is ice a rock?

Solid coherent substance
made up of many ice crystals
(why is ice a mineral?)

*ice under the
microscope*



Ice is like:

an igneous rock – Why?

a sedimentary rock – Why?

a metamorphic rock – Why?



What is ice?

2) Is ice a fluid ?

Fluids:

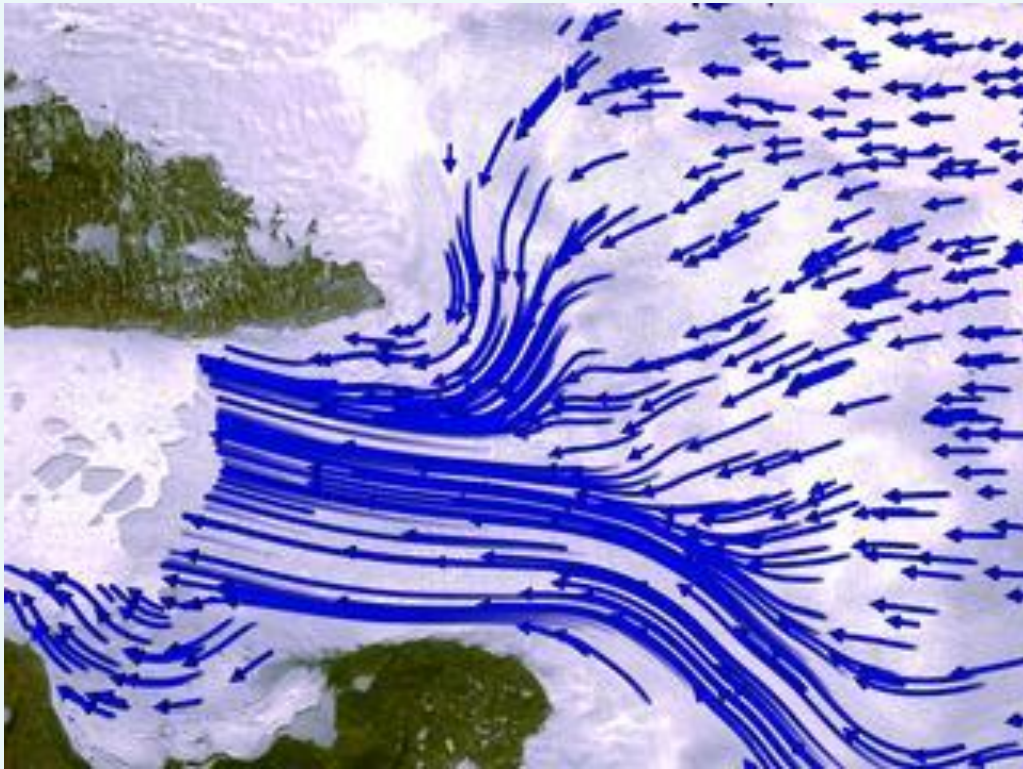
- deform under ...
- have the ability to ...



What is ice?

Velocity vectors showing glacier flow

Jakobshavn, Greenland



Nasa / Goddard space flight center

Kalstenius Ice field, Ellesmere Is.

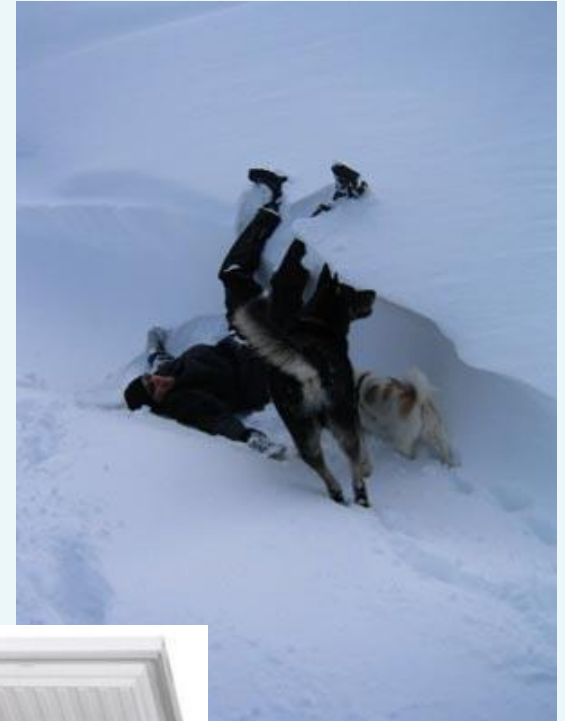


How are glaciers formed?

Glacier recipe:

1. ...

2. ...

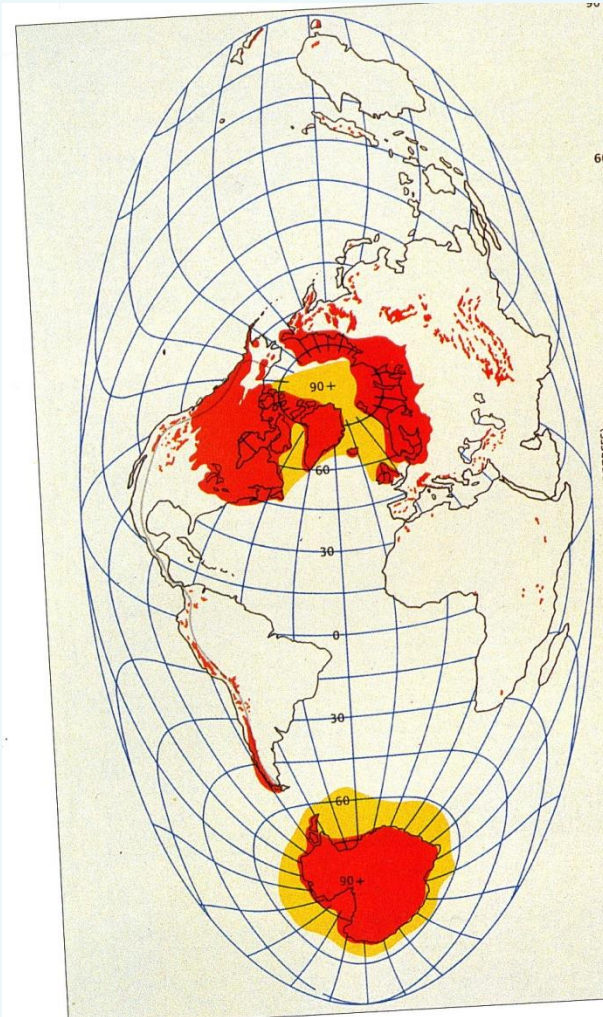


Matt Stone / Boston Herald via Polaris



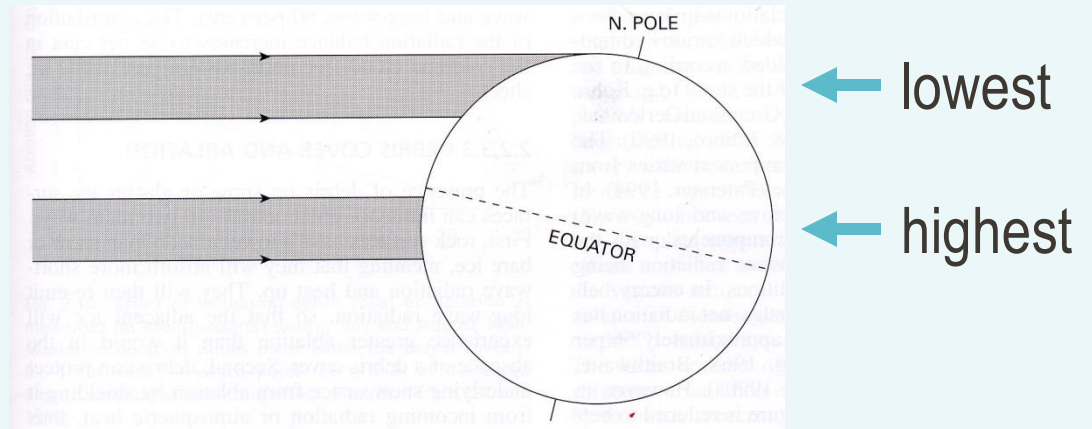
Glacier formation

Where do we get snow with good preservation potential?



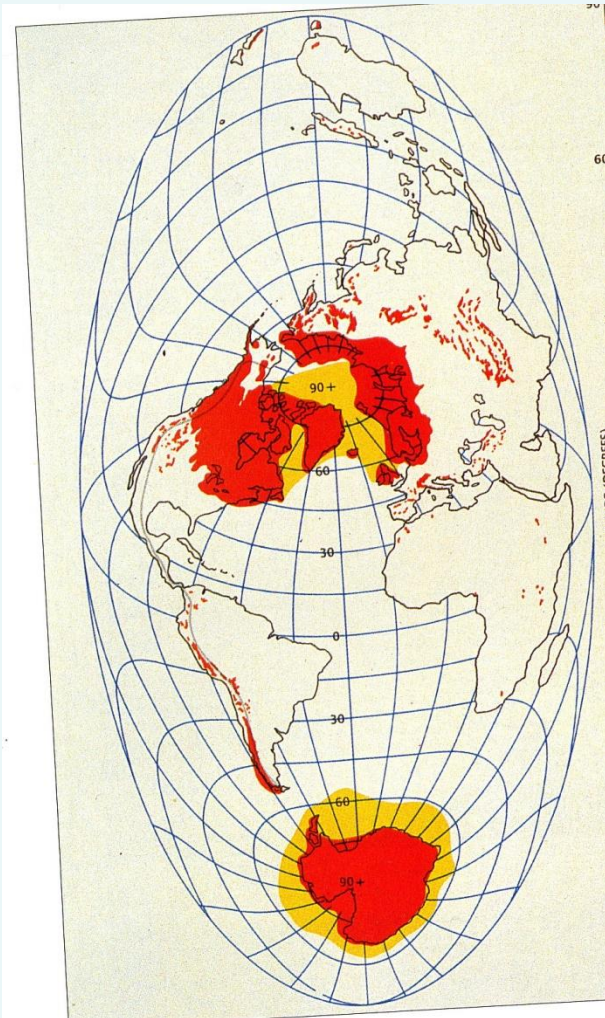
High ...

Solar radiation / m^2



Glacier formation

Where do we get snow with good preservation potential?

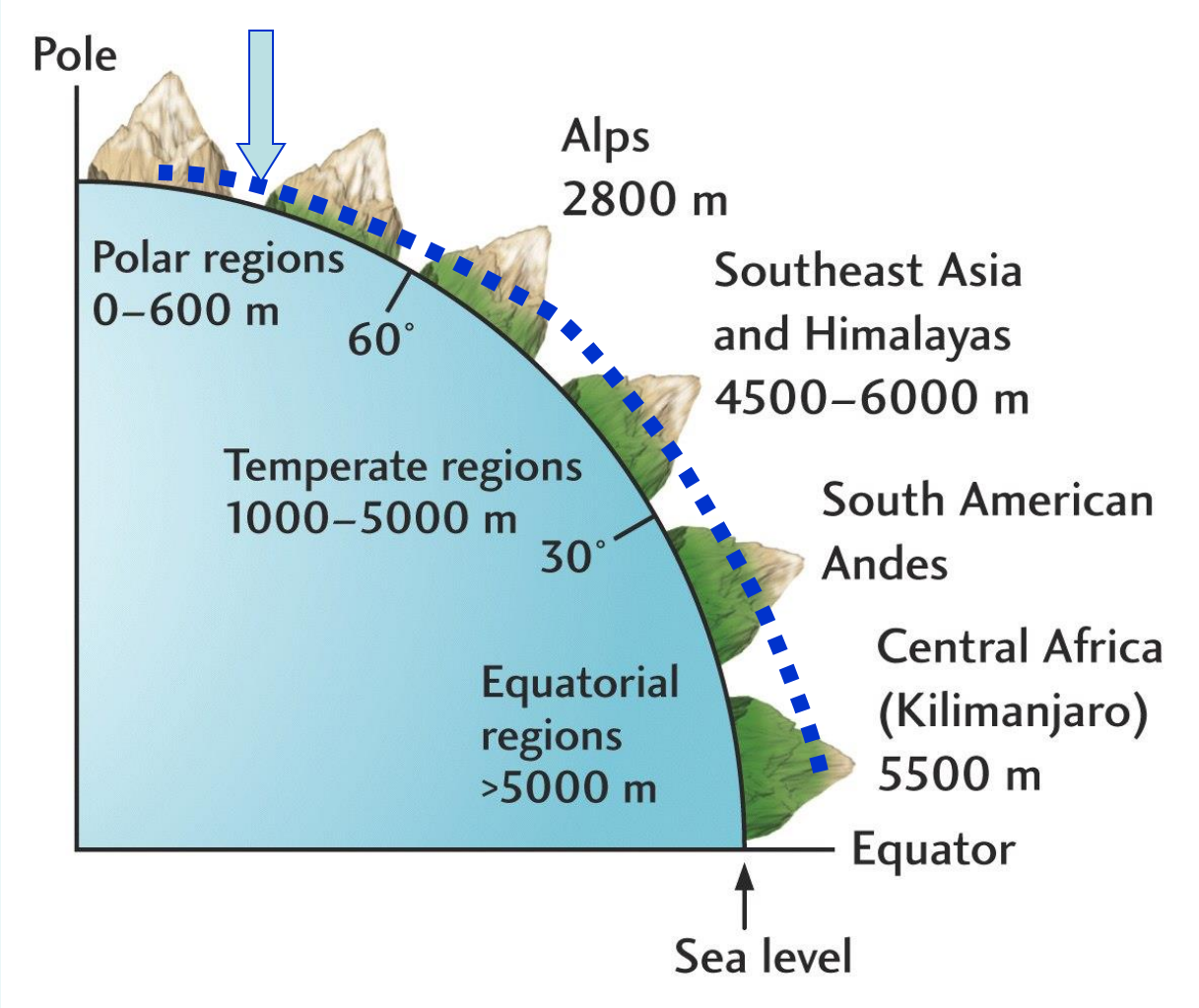


High ...



Glacier formation

Snow line: elevation above which snow doesn't completely melt in summer



Key Point

Glaciers grow with more snow fall
and or
less melting of the snow fall

Glacier formation

How do we go from snow to ice?

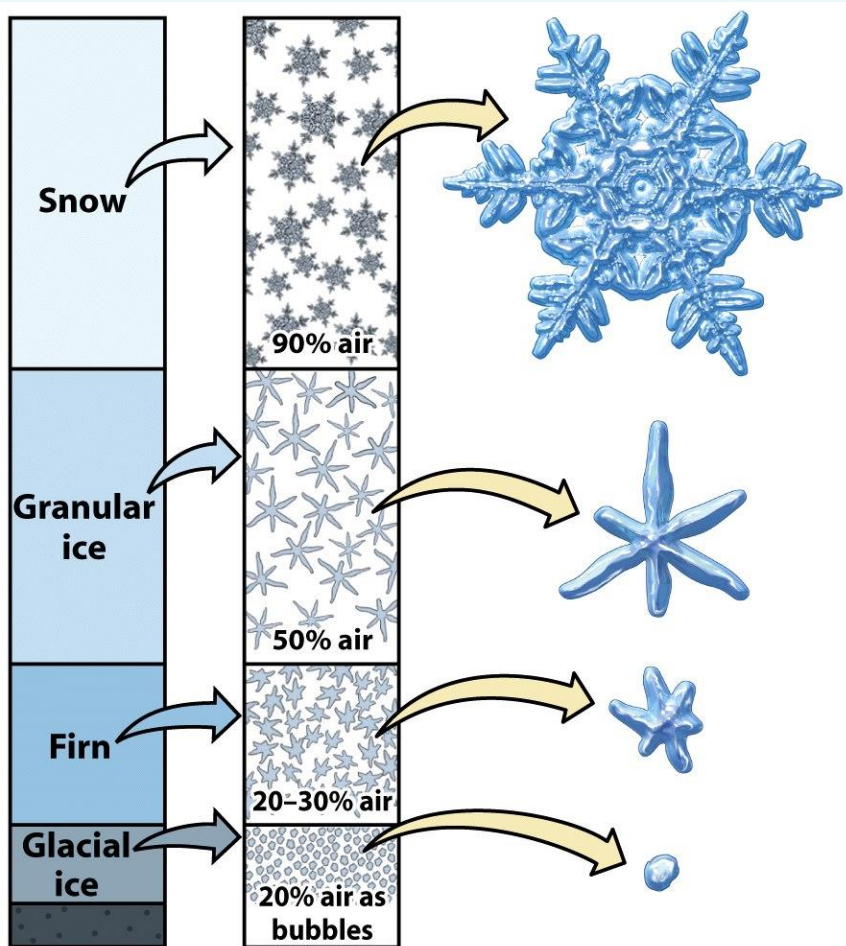


Figure 21-7
Understanding Earth, Fifth Edition
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Burial metamorphism

SNOW $\rho \sim 0.05 \text{ g/cm}^3$
porosity $\sim 90\%$



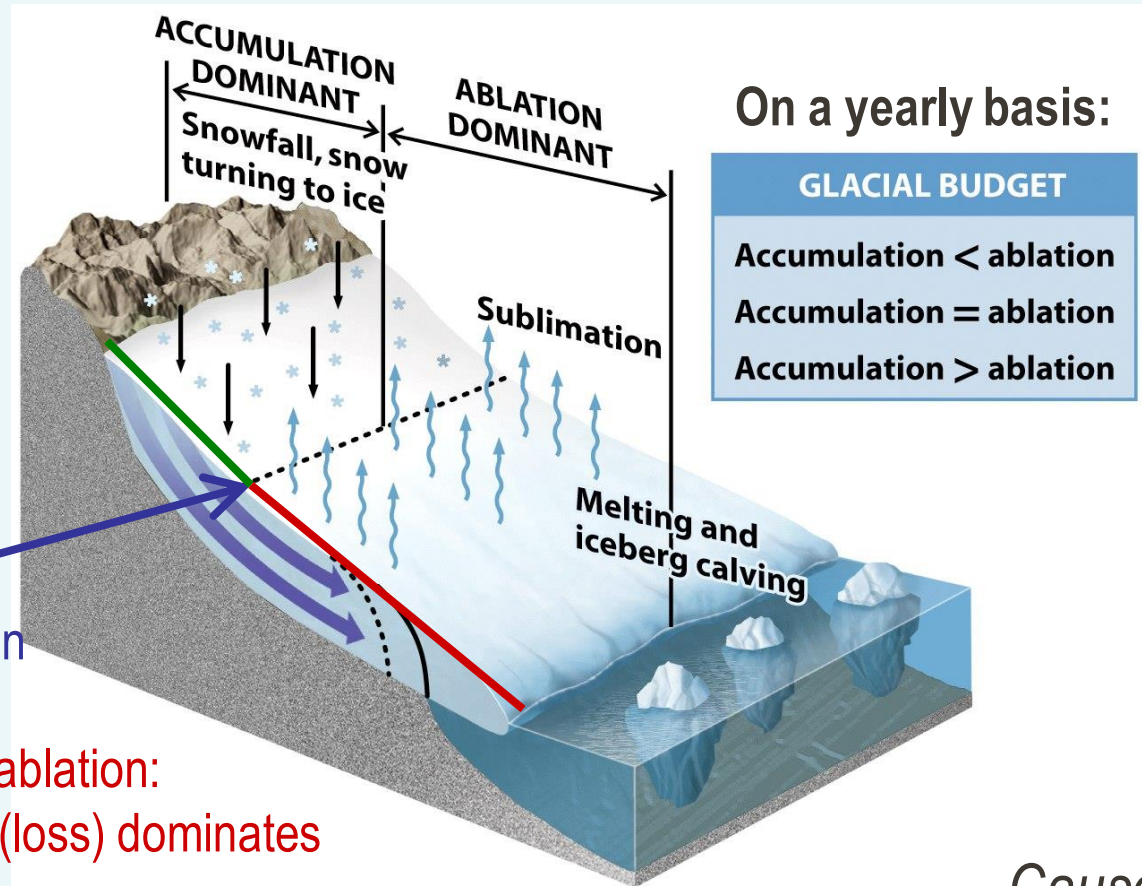
FIRN $\rho = 0.4 \text{ to } 0.83 \text{ g/cm}^3$
porosity = 20-30%



ICE $\rho = 0.83 \text{ to } 0.9 \text{ g/cm}^3$
porosity $< 20\%$

e.g. sidewalks in winter

The Ice Mass Balance of a Glacier



Zone of accumulation:
accumulation dominates

Equilibrium line:
accumulation = ablation

Zone of ablation:
ablation (loss) dominates

On a yearly basis:

GLACIAL BUDGET	
Accumulation < ablation	-
Accumulation = ablation	'0'
Accumulation > ablation	+

Budget

Figure 21-9
Understanding Earth, Fifth Edition
© 2007 W. H. Freeman and Company

Causes?

- + budget (accumulation > ablation) = glacier **advance** → add snow
- budget (accumulation < ablation) = glacier **retreat** → melting, calving, sublimation

Mass balance

Calving: large pieces of glacier ice break off into water



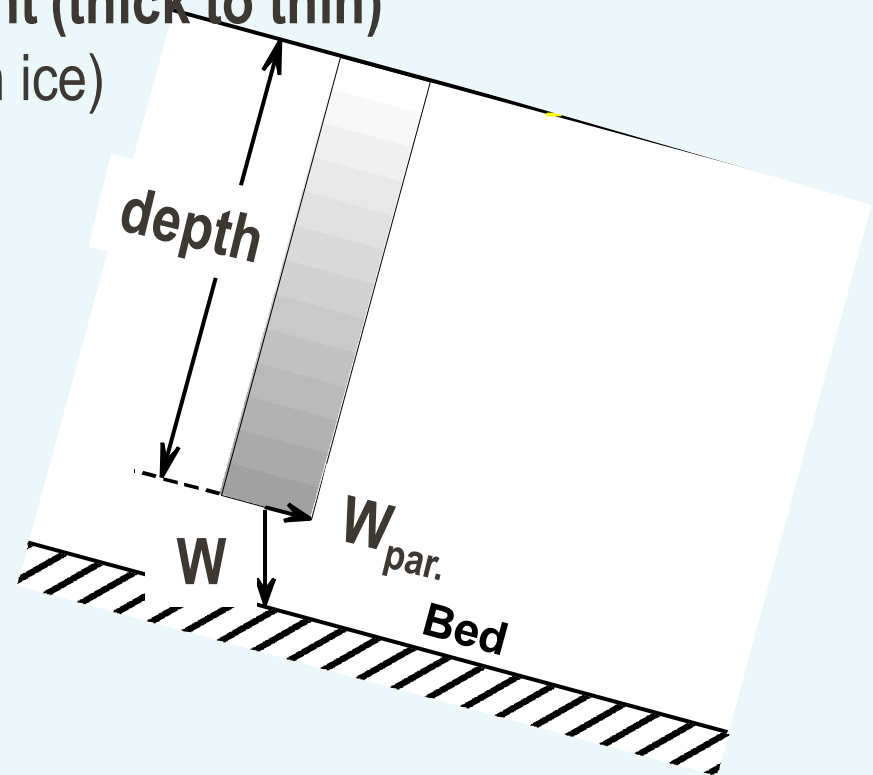
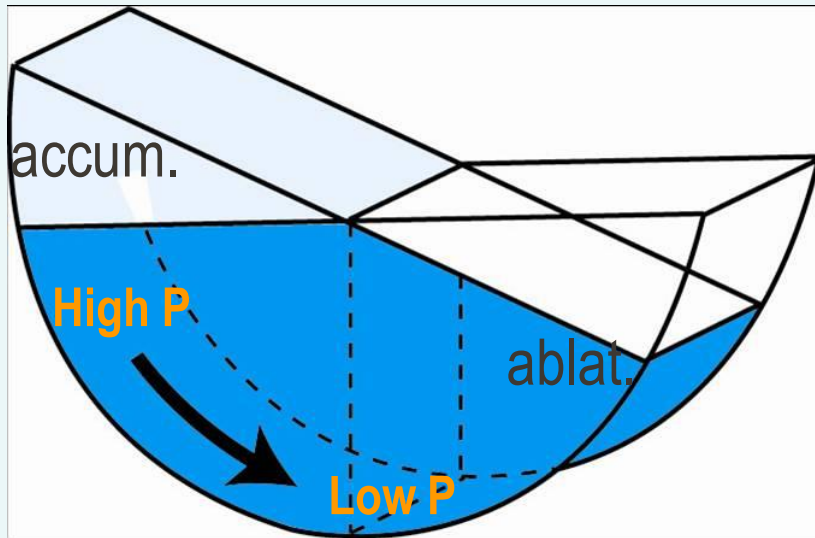
* *video*

How do glaciers move?

Force that cause glaciers to move = **Gravity** → $W = \rho g \cdot \text{depth}$

Direction of mvt =

- **Pressure gradient (thick to thin)**
- **Topography (thin ice)**

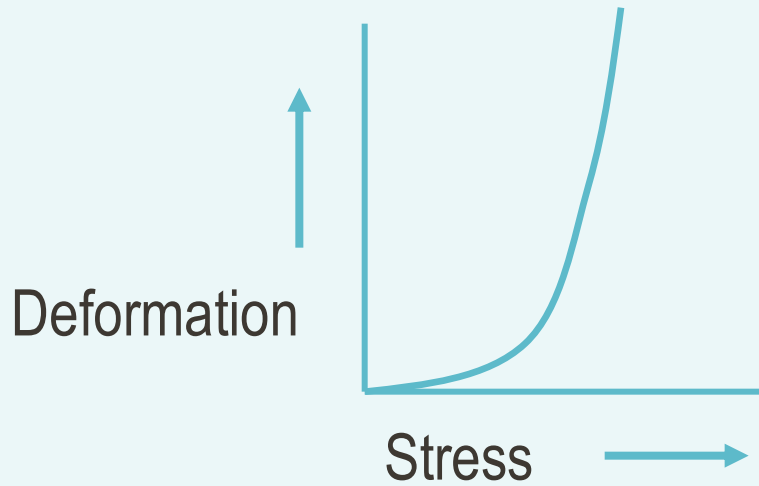


Resisting forces = **Friction**
(substrate)

How do glaciers move?

Type of deformation

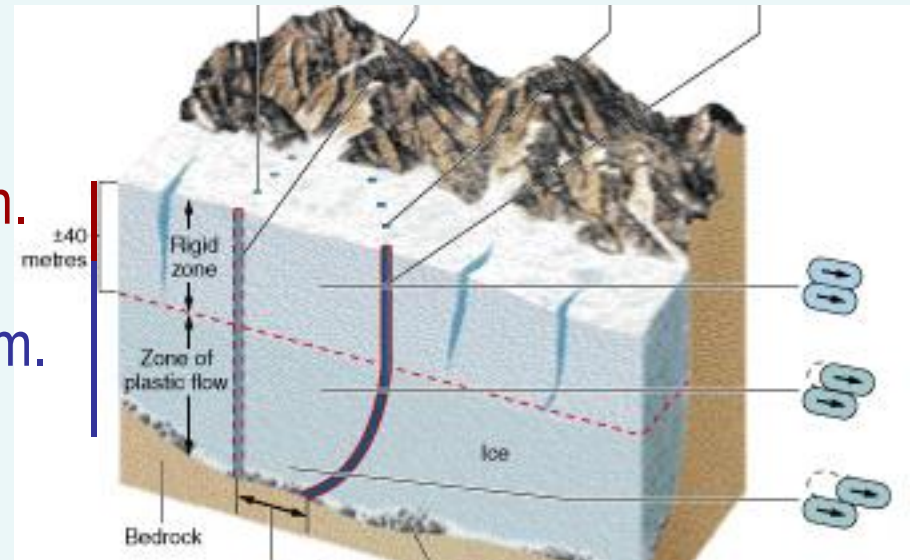
Ice will deform under stress (just like rocks!) and display:



- elastic
 - plastic
 - brittle
- deformation

Brittle deform.
(~ top 40 m)

Plastic deform.



How do glaciers move?

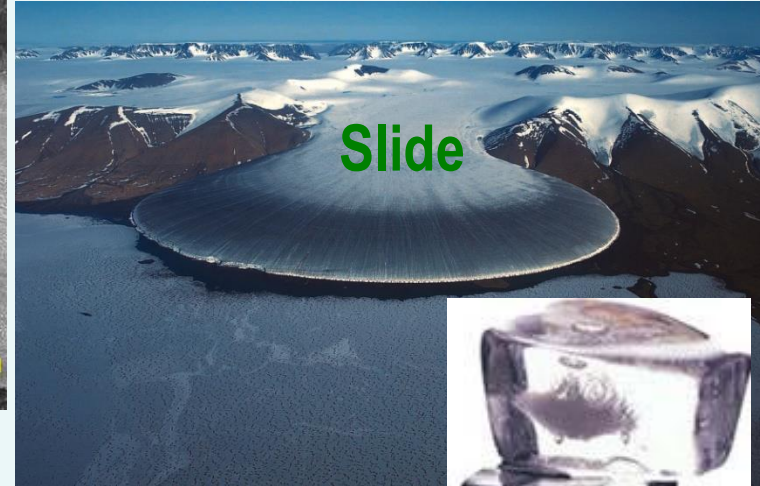
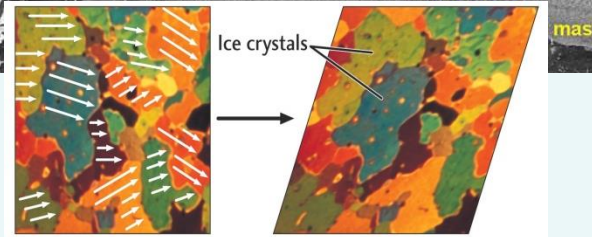
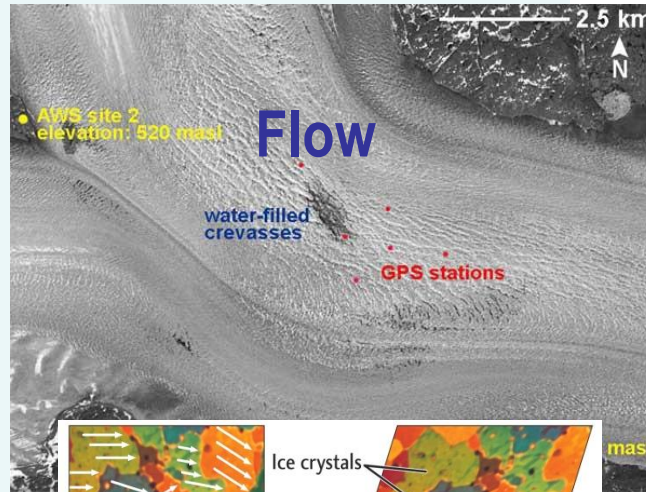
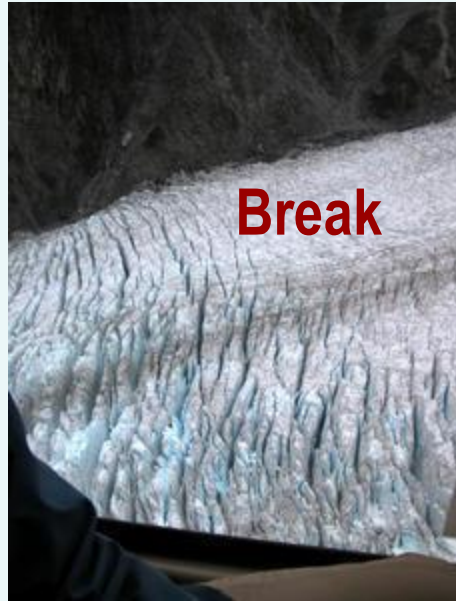
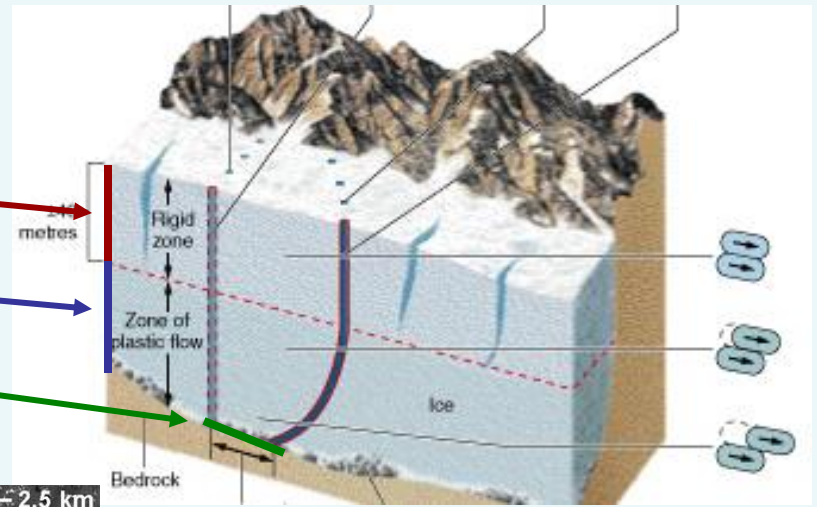
Mechanisms of ice movement

Glaciers

1. Break (brittle)

2. Flow (plastic)

3. Slide (basal slip)

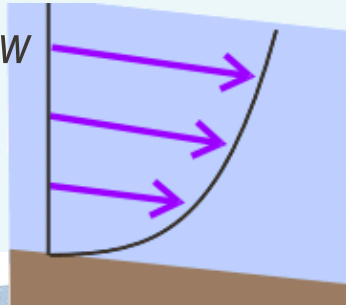


How do glaciers move?

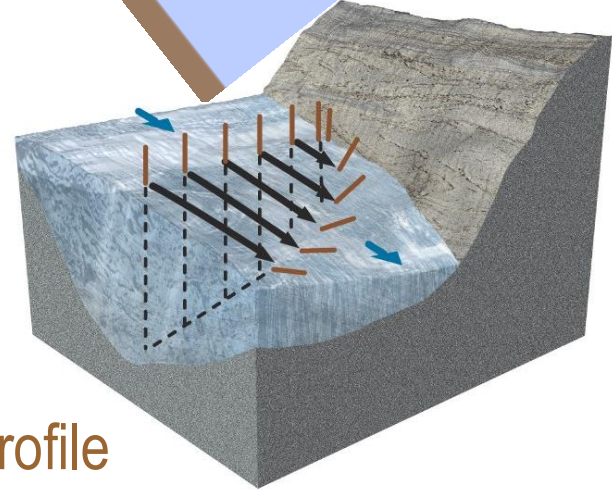
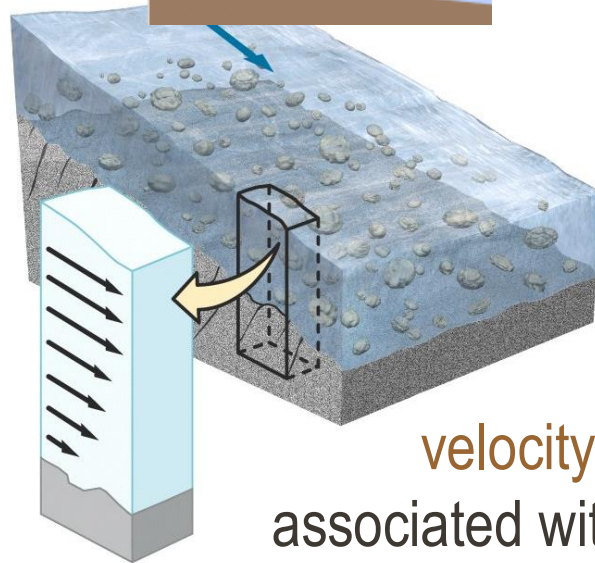
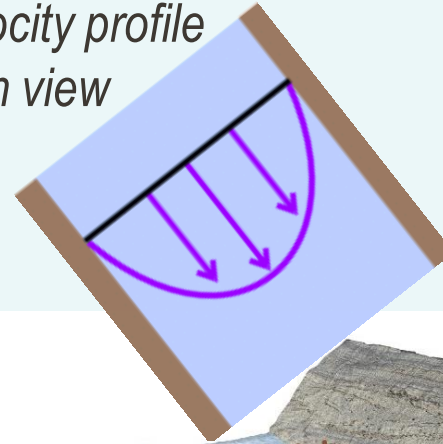
Plastic Flow

Dominant mech. → **dry-based glacier** (no meltwater); colder climates or insufficient ice thickness to cause melting

*velocity profile
cross-sectional view*



*velocity profile
plan view*



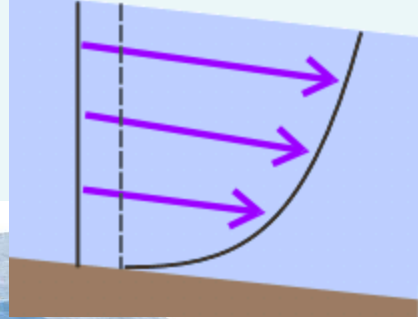
**velocity profile
associated with plastic flow**

How do glaciers move?

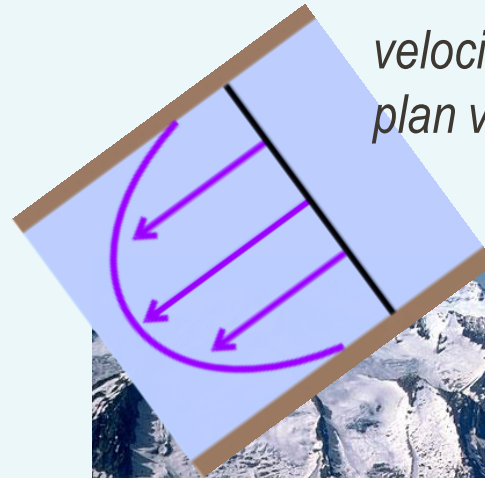
Basal Slip

Dominant mech. → **wet-based glacier** (meltwater); temperate climates or sufficient ice thickness ($\uparrow P$) to cause melting

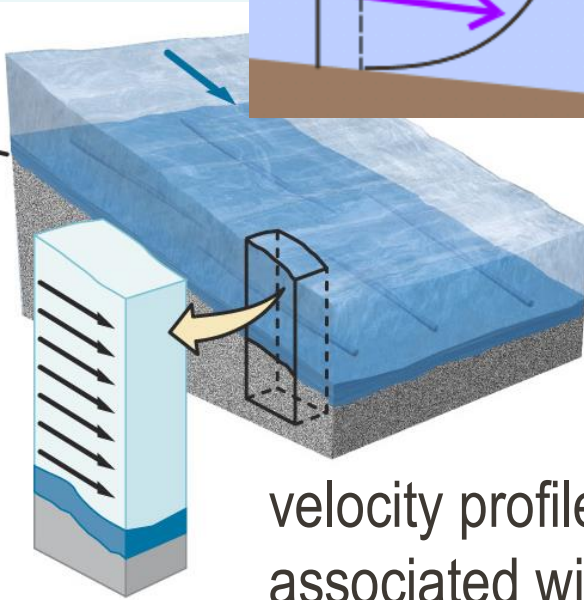
*velocity profile
cross-sectional view*



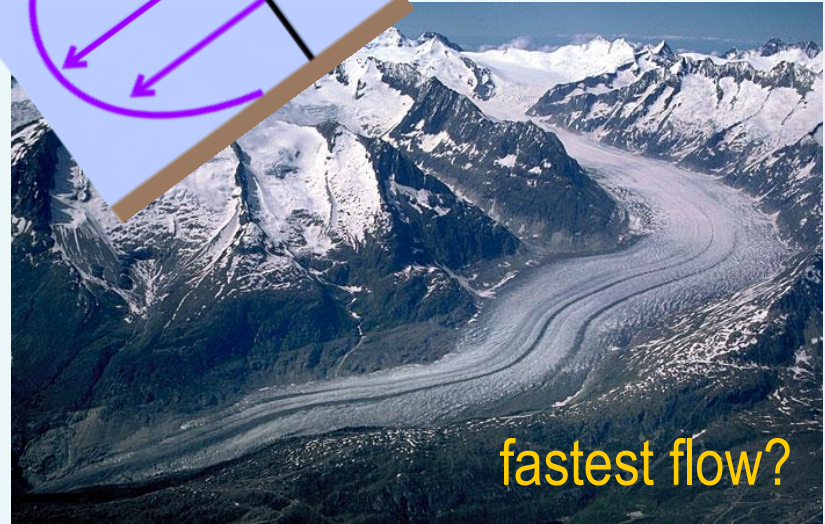
*velocity profile
plan view*



Liquid water



velocity profile
associated with basal slip



fastest flow?

How fast do glaciers move?

Examples of annual distances covered by glaciers:

- Min. ~ **2 m/yr**
(Meserve Glacier, Antarctica)

Which is a wet-based glacier?

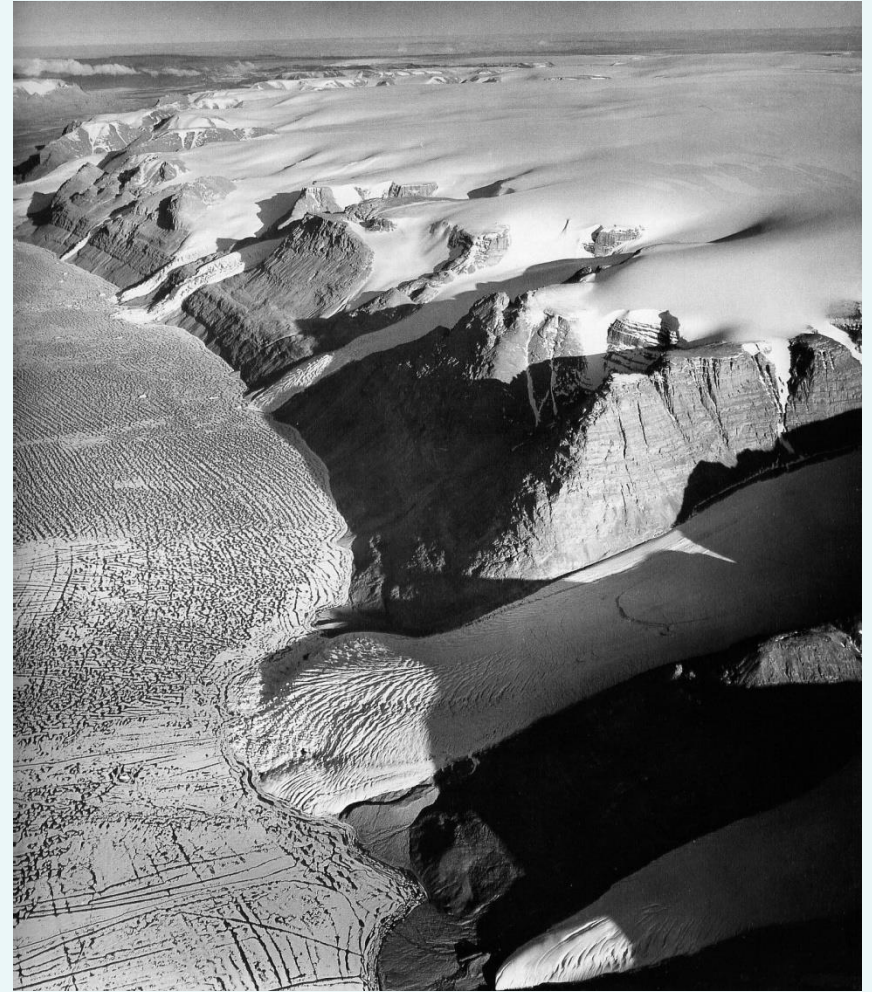
- Max. ~ **8400 m/yr**
(Jacobshavns Isbrae, Greenland)

→ length of Rideau Canal!



What types of glaciers exist?

Glacier classification mostly based on size and *morphology*

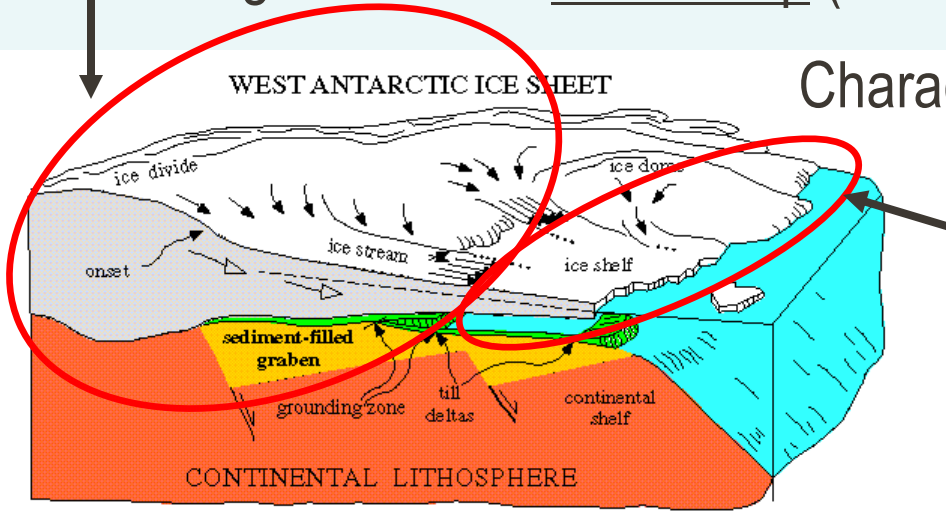


Continental - Largest and thickest glaciers (~ 95% of present-day ice volume)

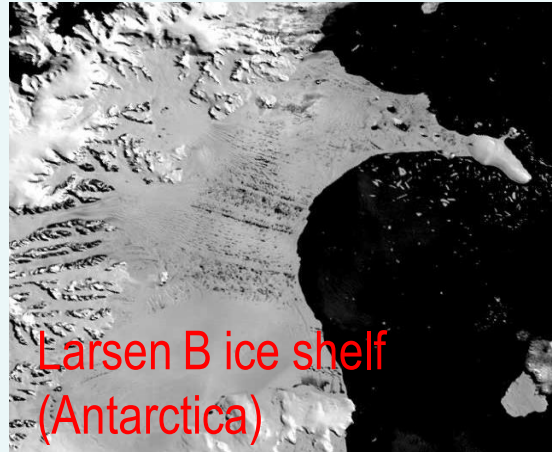
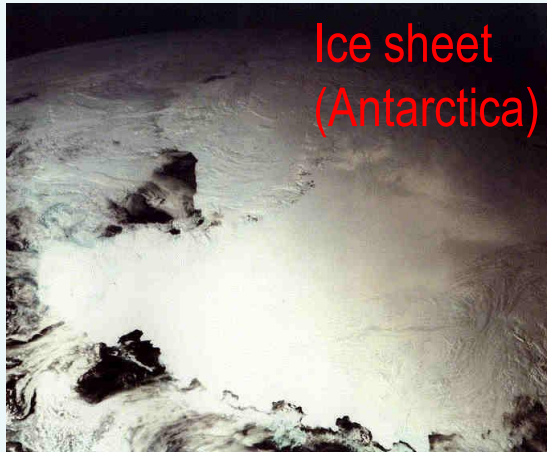
Continental-scale glaciers:

- 1a. Ice sheet (> 50 000 km²), e.g.: Antarctica, Greenland
- 1b. Ice cap (< 50 000 km²), e.g.: Baffin Island, Iceland

Characteristics: thick, flow radially from center



2. Ice shelves:
portion of the glacier that extends over the ocean

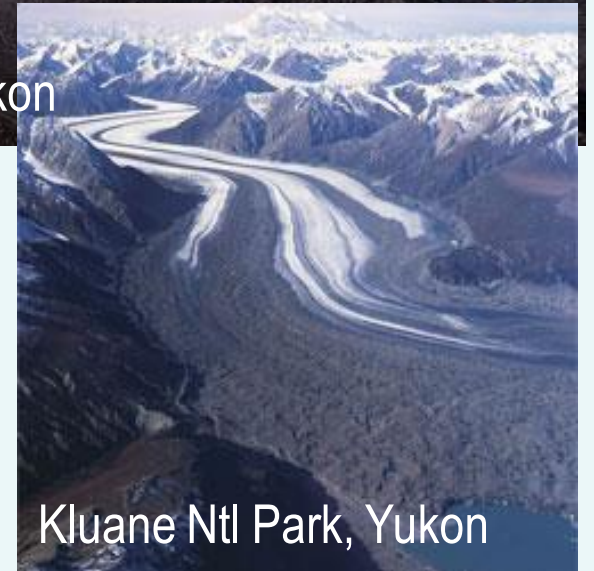


Valley – smaller and thinner (~ 5% of present-day ice volume)

3. Valley glacier: discharge of ice into deep bedrock valleys (high altitude)



Kluane Ntl Park, Yukon



Kluane Ntl Park, Yukon

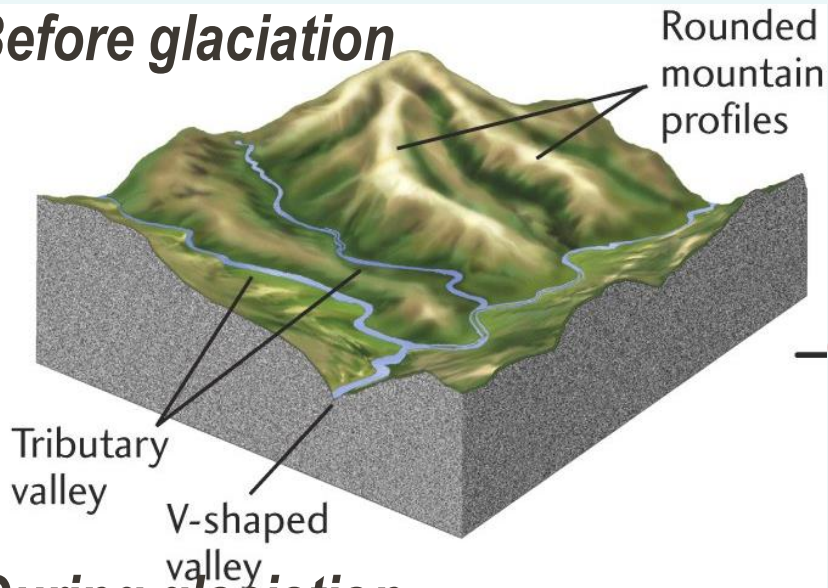
Like streams smaller tributaries feed into a main channel.

What landforms, erosional features and deposits are formed by glaciers?

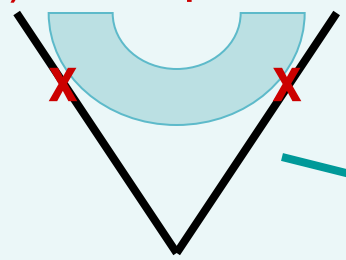


Glacial landscapes

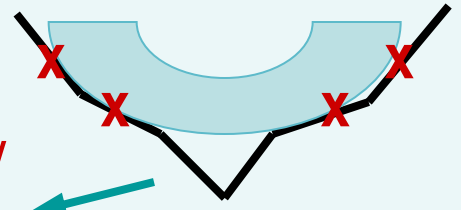
Before glaciation



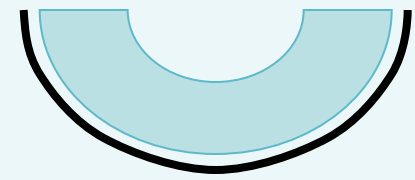
(1) V-shaped valley



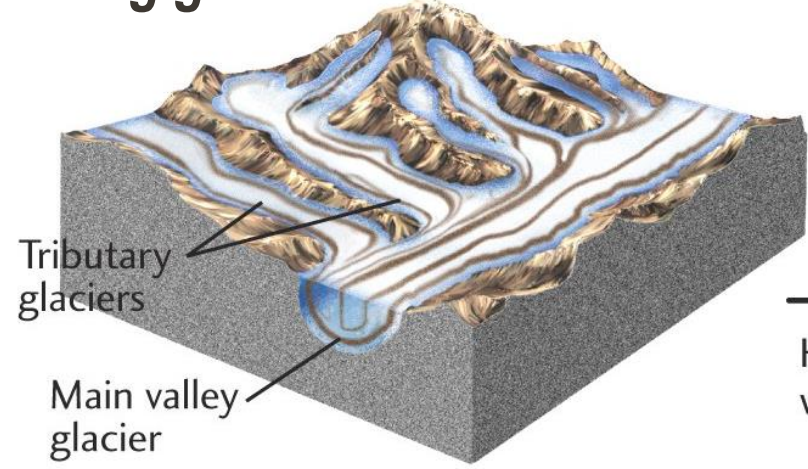
(2) Intermediate stage



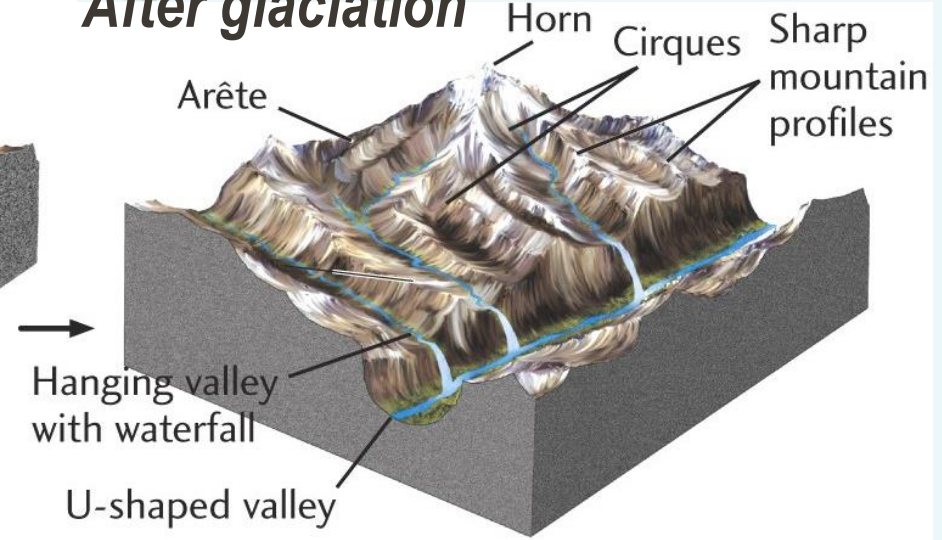
(3) U-shaped valley



During glaciation



After glaciation



Glacial landscapes – photos gallery

Cirque: forms at the head of a glacial valley



Arête: forms by erosion on opposite sides



U-shaped valley: forms by valley glacier's erosion



Fjord: a drowned glacial valley

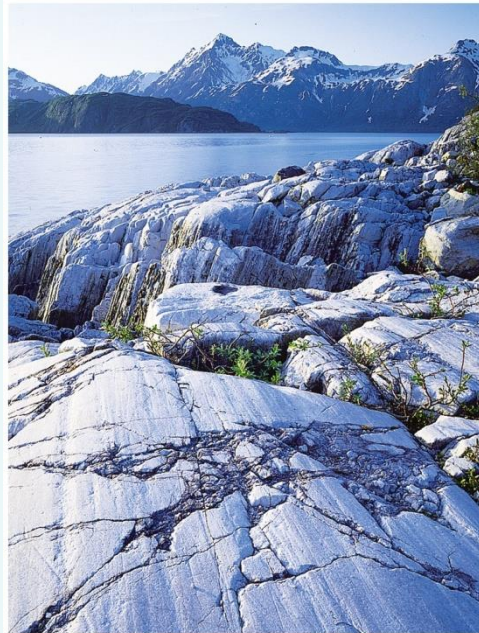


Erosional features – smaller scale

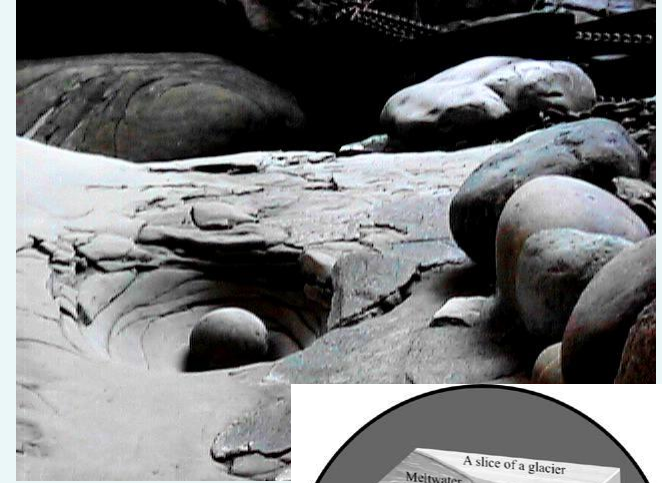
Examples of smaller-scale erosional features



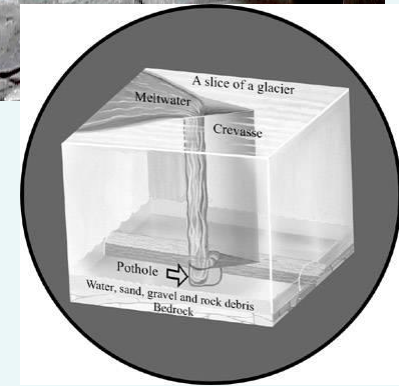
grooves



striations



potholes



Formed by → drag of hard object against substrate
→ sediment-laden turbulent flows (like sandblasting)

Glacial deposits

Drift: all glacial deposits; can be either **OR** unstratified (deposited by ice)
OR stratified (reworked by water)

- **Till:** unsorted, unstratified drift
unorganized mix of sediment
(clay, silt, sand, gravel, boulders)

*Deposited by **ICE***



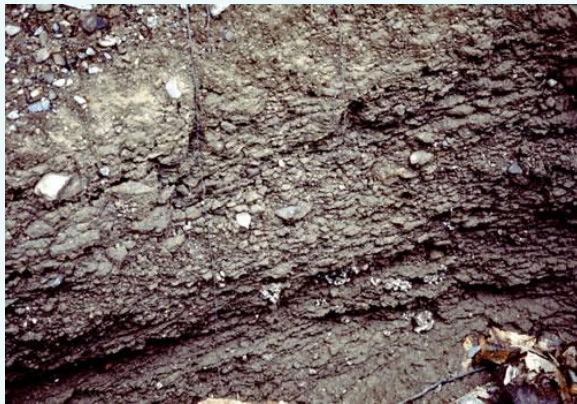
- **Stratified drift:** sorted, stratified sediment

*Deposited by **MELTWATER***



Glacial deposits

Associate these deposits with the right transport agent



1. transport agent:

2. transport agent:

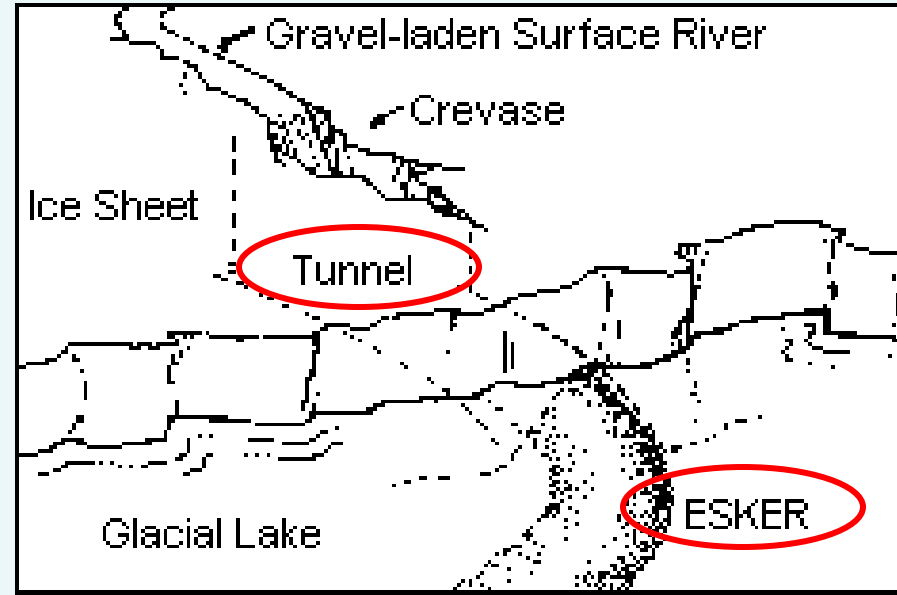


Glacial deposits – stratified drift

Stratified drift with distinctive morphology

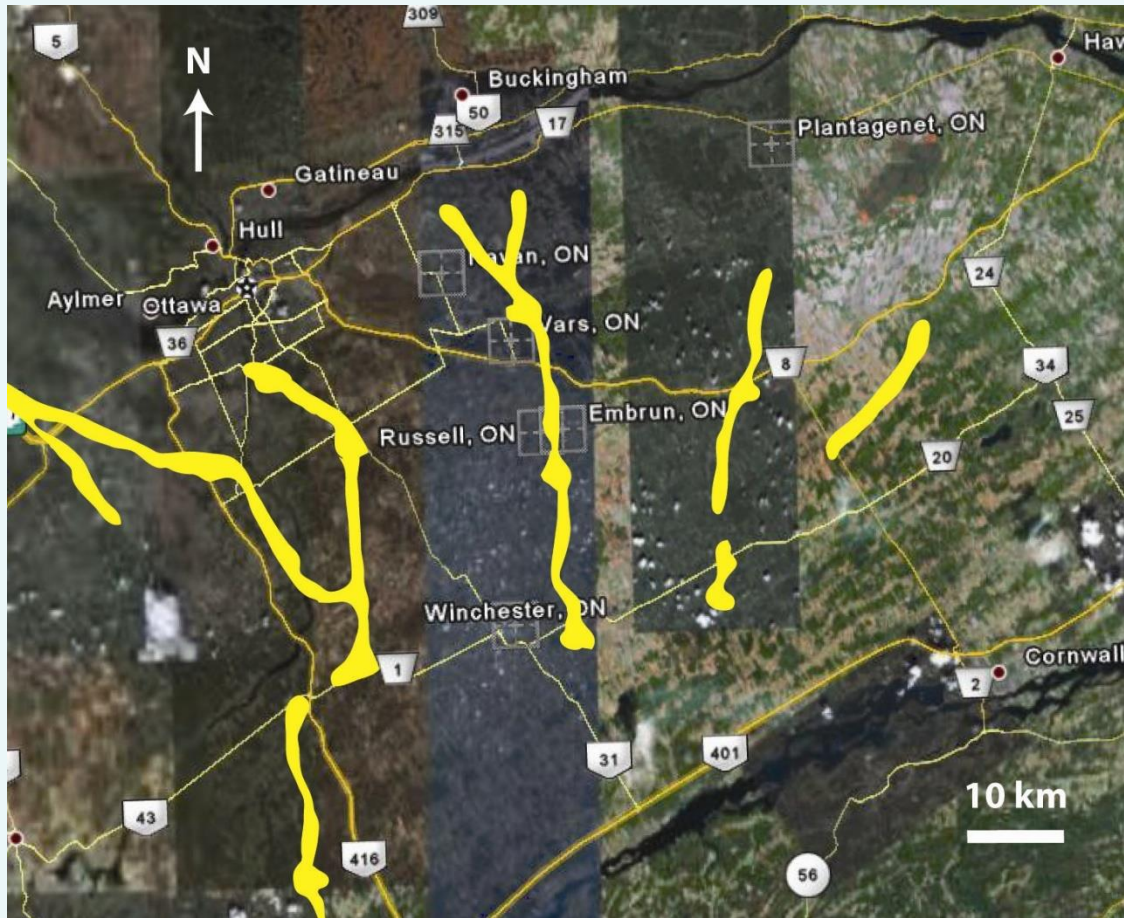
1. eskers

- elongated, sinuous ridges
 - A few to 10's of m high
 - (wider than high)
 - few to 500 km long
- stratified sand and gravel
- deposited in englacial tunnels



Glacial deposits – stratified drift

Esker deposits southeast of Ottawa (yellow lines)



as mapped by Gorrell (1991)

Why are geologists interested in mapping these features?



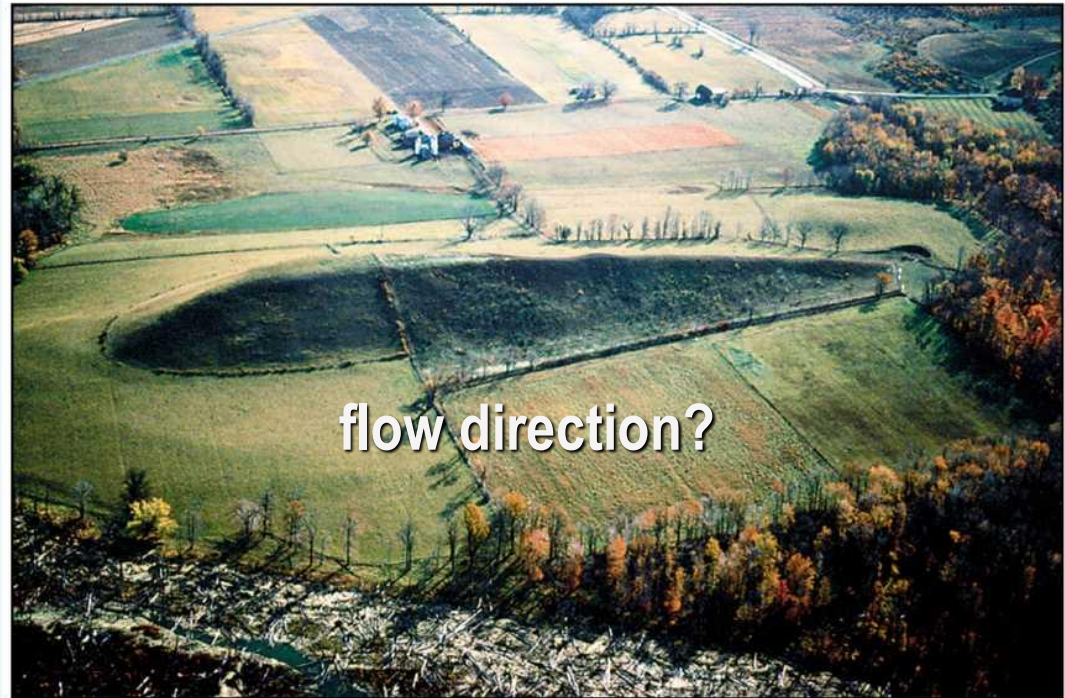
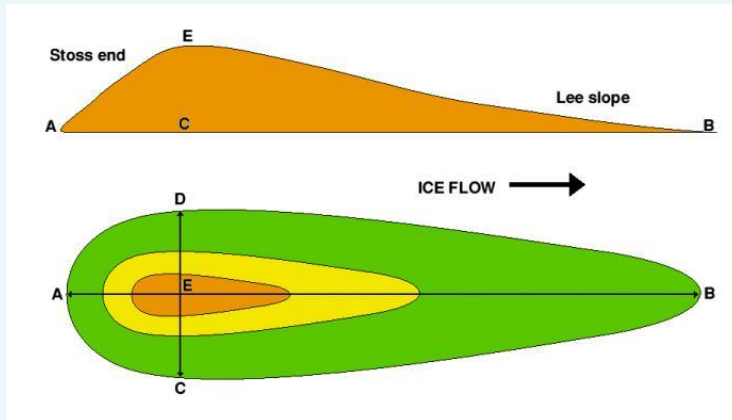
90 000 domestic wells
in Eastern Ontario

Glacial deposits – stratified drift

Stratified drift with distinctive morphology

2. *drumlins*

- assymmetric, tear-drop, stratified sand and gravel ridge
- narrower downflow (flow of ...?)
- 15-40 m high
- length to width 1:3



Ice ages through Earth's history

Numerous intervals of global refrigeration –
 Glaciers and ice sheets more extensive than today

Subdivisions		Ice ages
Phanerozoic	Late Quaternary	—
	Carboniferous-Permian	██████████
	Late Devonian	—
	Late Ordovician	—
Precambrian	Neo-Proterozoic 1,000	██████████ ?
	Meso-Proterozoic 1,600	██████████
	Paleo-Proterozoic 2,500	██████████
	Archean 3,800	██████████
Hadean		

◆ Figure 12.C Major glacial episodes in Earth history as indicated by horizontal bars.

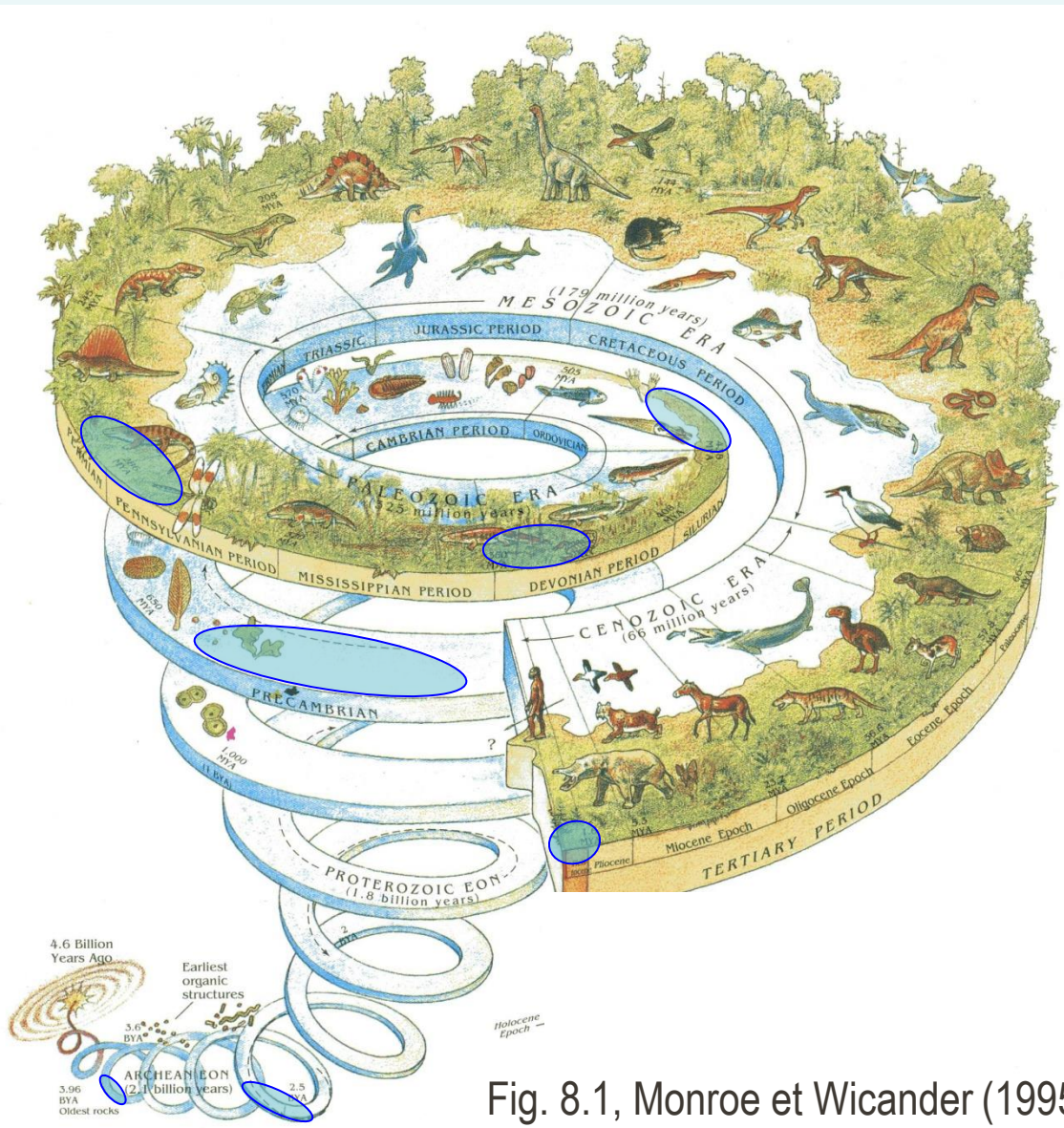


Fig. 8.1, Monroe et Wicander (1995)

A few Interesting Videos

- The fastest moving glacier

www.youtube.com/watch?v=roWl-R2mey4

- Glacial Erosion

<http://www.youtube.com/watch?v=AG3luuhc-5Y>

- Inside a glacier

http://www.youtube.com/watch?v=Gbfu2-Z_iDI

Summary

1. Glacier is ice moving under its own weight.
2. Glaciers store water and produce economic geologic deposits.
3. Glaciers form when snow accumulation is greater than loss from melting & sublimation.
4. Ice is a deformable solid.
5. Glaciers flow under their own weight.
6. Mountain glaciers and polar ice fields.
7. Eskers, drumlins and morrains formed by glaciers.
8. Earth has been extensively glaciated many times. Currently in an interglacial period.

Another Darcy's Law Example

A farmer says the local business is contaminating his well. You are the investigator. What would you do to see if his claim is legitimate?

Measurements in the Groundwater Flow System

- Height of farmer's well= 30m
- Height of water table at business =40m
- Distance is 500 meters between the two wells
- Gradient is the difference in height of the water table divided by distance between the two points (e.g. 40m vs 30m 500 meters apart)
- Porosity of a sandy material is about 0.3 (30%)
- Hydraulic Conductivity of a sand is $\sim 10^{-5}$ m/s
- Velocity (m/s) = $10^{-5} * 0.3 * (40-30)/500 = 6 * 10^{-8}$ m/s
- Time to Travel 500 meters = distance /velocity = $500/ 6 * 10^{-8}$ m/s
- Time is about 264 years

Can the water flow to the well since the business was established?

- **Conclusion:** NO!! Flow is too slow and travel time too long to move the contaminant to the farm