ESS 203 - Glaciers and Global Change

Monday February 8, 2021

Outline for today

- Volunteer for today's highlights on Wednesday
  - Caroline Wills
- Highlights of last Friday's class
  - Madelyn Ulvin

Highlight reporters

- Remember to turn in your ~100-word reports

- Glacier flow, sliding, and fracturing
- Historic Blue Glacier video
- Kinematic and dynamic views of Earth systems

HW 15 – Ice Cores

For Wednesday:

Please read "Ice Cores and Climate Change"

https://canvas.uw.edu/courses/1434502/files/folder/HomeWork?preview=73332058

Scientists often say that climate records from ice cores provide *context* for modern and future climate change.

- According to this article, what do ice cores tell us about how current climate change compares to past climate change?
- What can't ice cores tell us?

Please write up your answer in a paragraph (~200 words).

There are 2 ways that a glacier can move

Internal or Viscous Deformation

- Ice can deform (change its shape) and flow, like honey or molasses.

(Start Greenland Ice Sheet.)

A glacier can slide along its substrate

- Bedrock
- Glacial till
- Lake or ocean mud

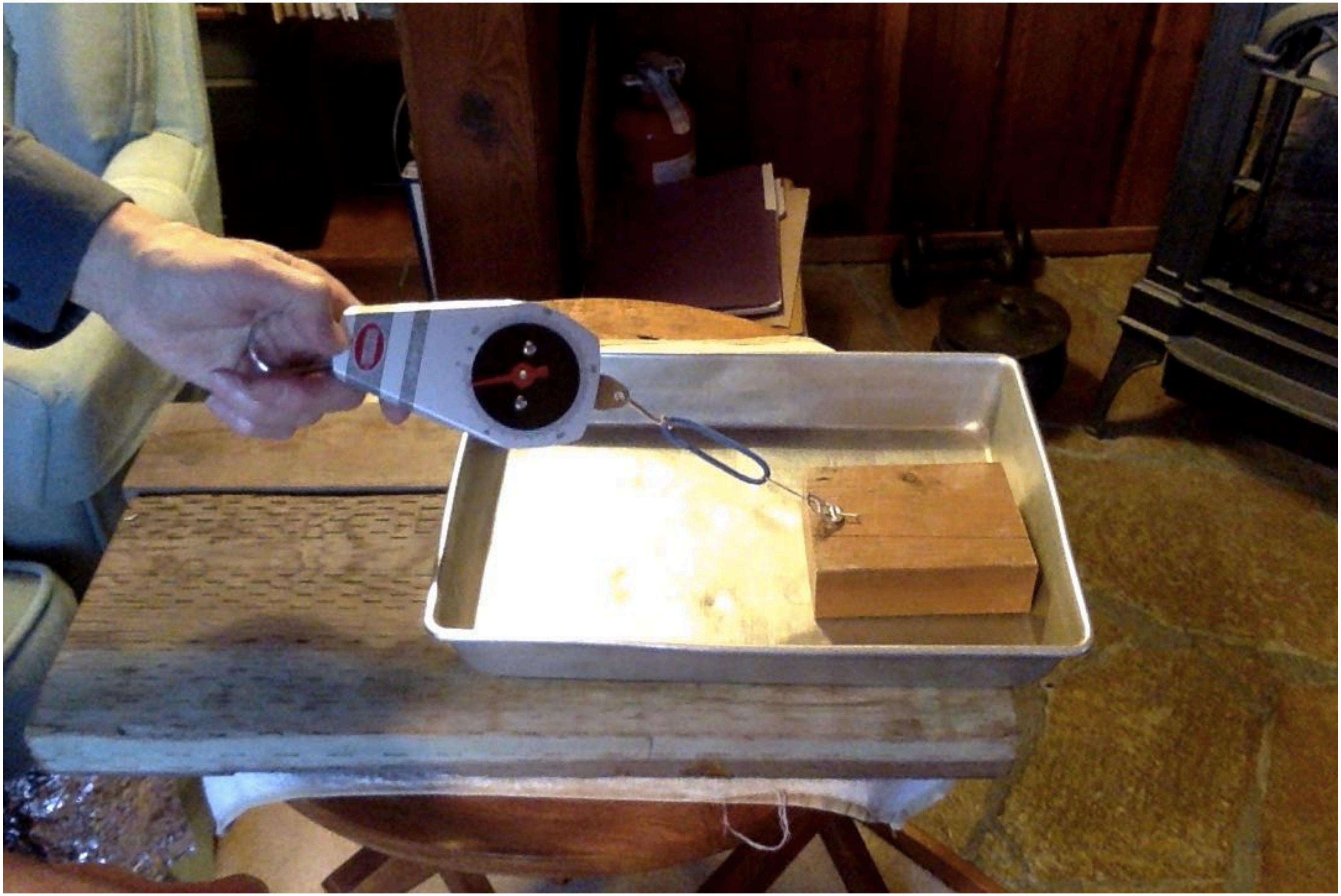
Basal water pressure and Sliding Speed

Frictional resistance is proportional to the contact force.
Or in common language,

- It's harder to make something slide when you push down on it harder.

Demo: change in force needed to make a block slide as water pressure increases.

Sliding friction and water pressure



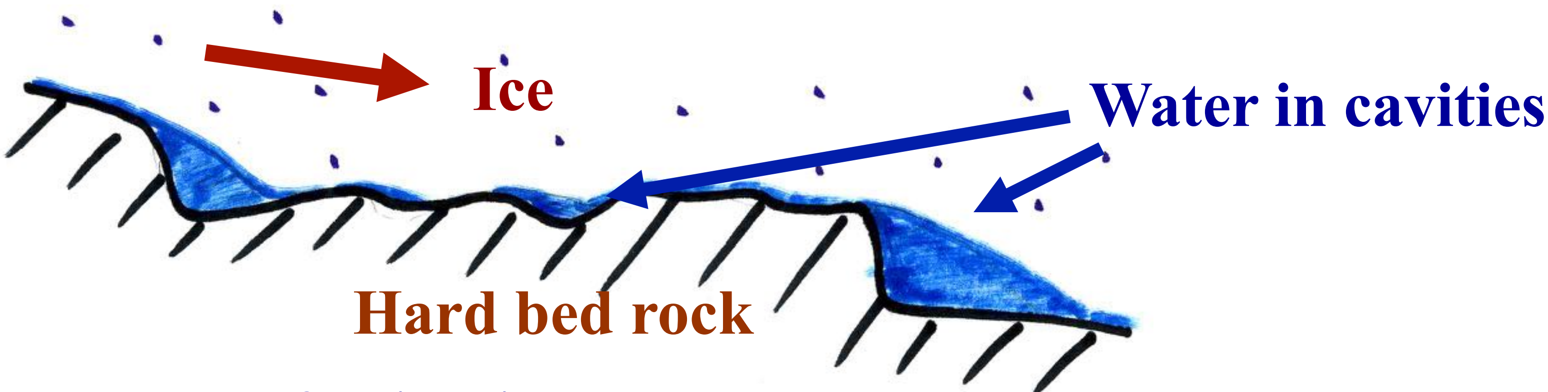
Factors that Influence Glacier Sliding

- Ice thickness
- Surface slope
- Basal temperature (must be at melting temperature).
- Regelation – melt-freeze around small bedrock bumps.
- Viscous drag in deforming subglacial sediment.
- Frictional resistance on rough bedrock (like sand paper).
  - basal water pressure is proportional to water depth.
  - Water pressure tends to lift up a block (or a glacier), reducing the amount it presses down on its bed.
  - Just as a floating boat is supported totally by water pressure. It exerts no force on the seabed, and feels no frictional resistance to motion from the sea bed.

Sliding Speed and Basal Water Pressure

On a rocky bed:

- Higher pressure "floats" ice.
- Higher pressure reduces friction with the bedrock.
- If bed is "rough", higher pressure also reduces contact area where sliding friction can occur.



On a "soft" bed:

- High water pressure softens basal mud.
- Softer mud deforms and flows faster.
- Carries glacier along with it faster.

Examples of Sliding Speeds

Where	**When**	**Sliding Speed**	**Deformation Speed (surface)**
Nisqually Glacier Mt Rainier	Summer/fall	70 m a^{-1}	15 m a^{-1}
Nisqually Glacier	Winter/spring	35 m a^{-1}	20 m a^{-1}
Blue Glacier (lower reach)	summer	10 m a^{-1}	40 m a^{-1}
Variegated Glacier	Surging	10,000 m a^{-1}	40 m a^{-1}
Jakobshavn Isbrae (Greenland)	All the time	8-12 km a^{-1}	5 km a^{-1}
Ice Stream Whillans (West Antarctica)	All the time	500 m a^{-1}	5 m a^{-1}

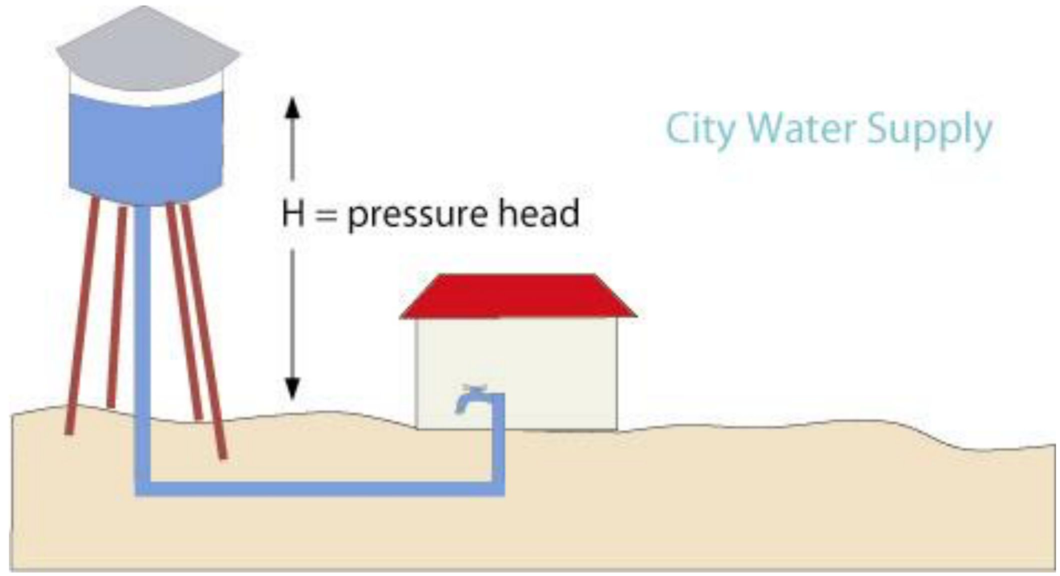
Rapid Changes in Speed

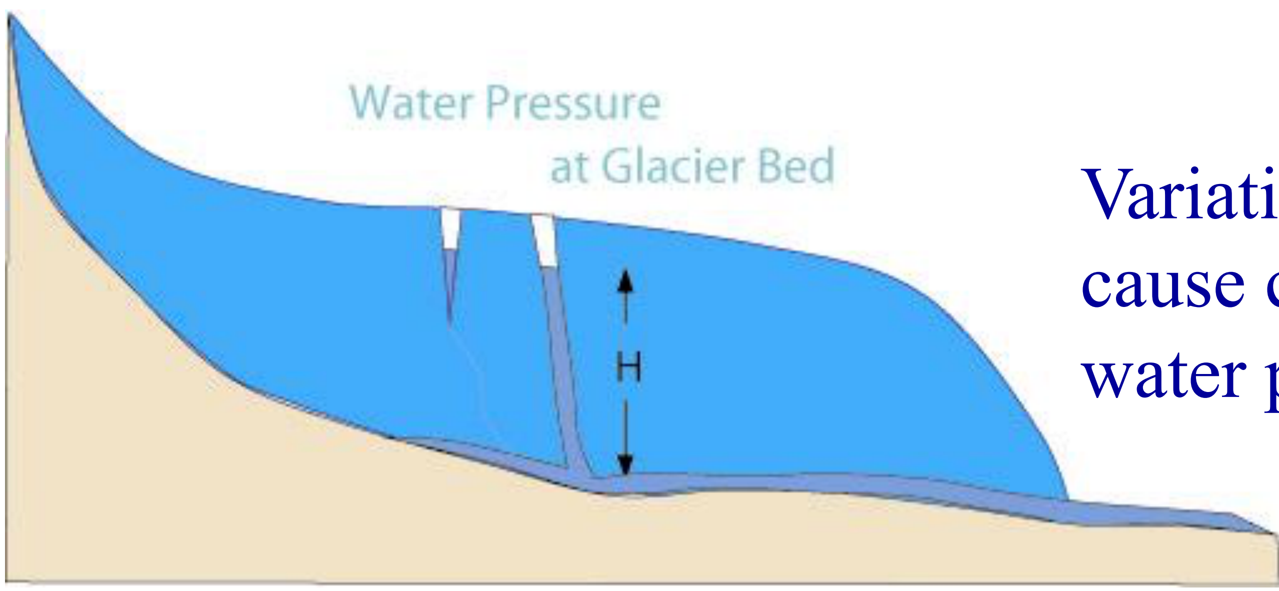
When a glacier changes its motion quickly (e.g. daily or weekly), the cause ***must*** be a change in the ***sliding speed***.

- The internal deformation (quasi-viscous flow) cannot be radically altered until the thickness, or slope, or temperature of the glacier change significantly.
- All of these take a much longer time to change.

Why does Water Pressure Change?

Height of water in water tower controls water pressure in faucets.





Variations in water level cause changes in basal water pressure.

Water Flow in Glaciers

Origin of water

- Melting of ice and snow at the surface
- Rain
- Frictional melting from ice sliding over bedrock.

Result

- Large supply of water on hot summer days and after rain storms.

Rivers on the Greenland Ice Sheet

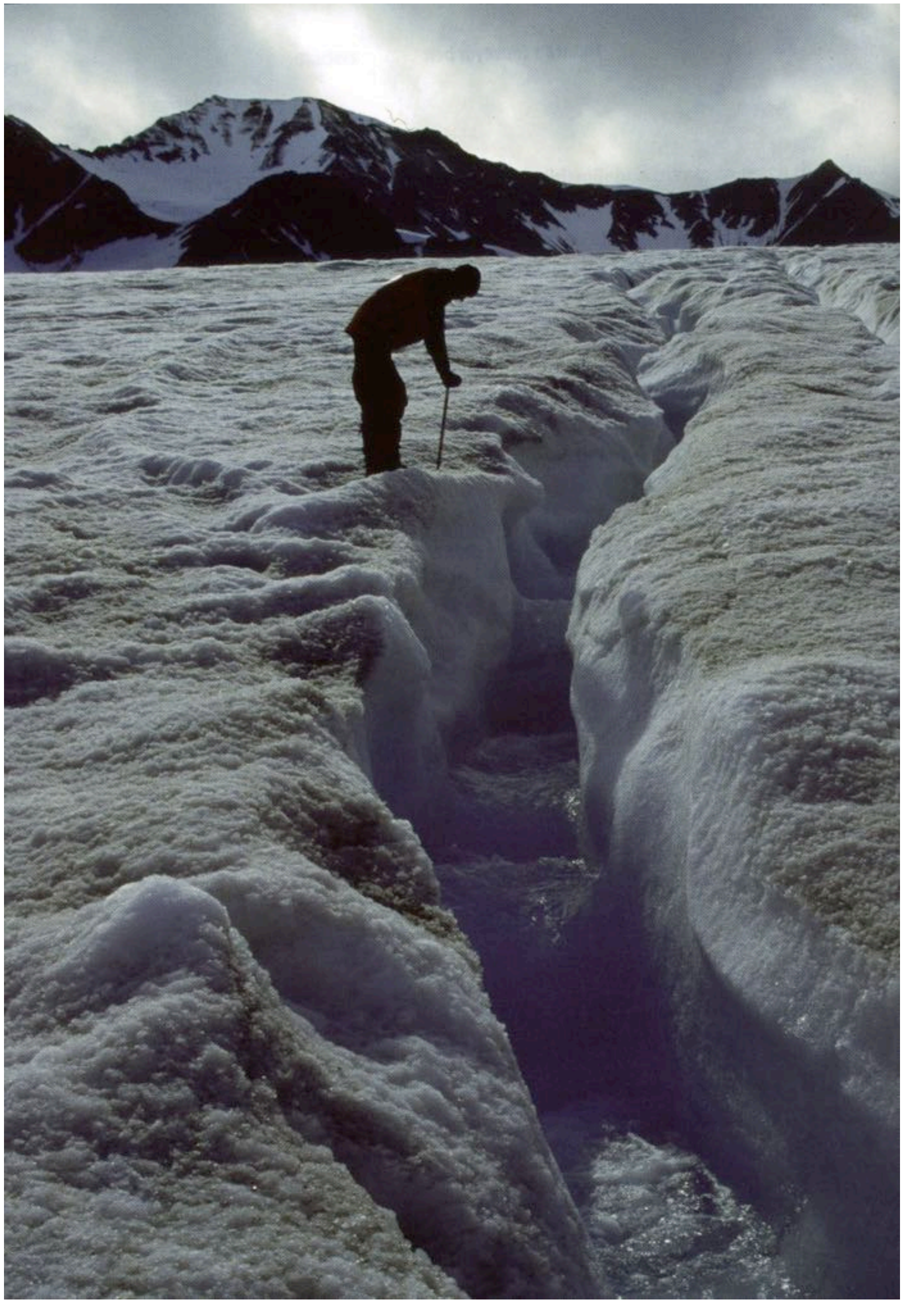
Vibeke Gletscher,
East Greenland

An opportunity to go rafting?

Probably not a good idea…

~300 m

Hambrey and Alean, ***Glaciers***.



Austre Lovenbreen, Spitsbergen. Hambrey and Alean. ***Glaciers***.

Streams on Glaciers

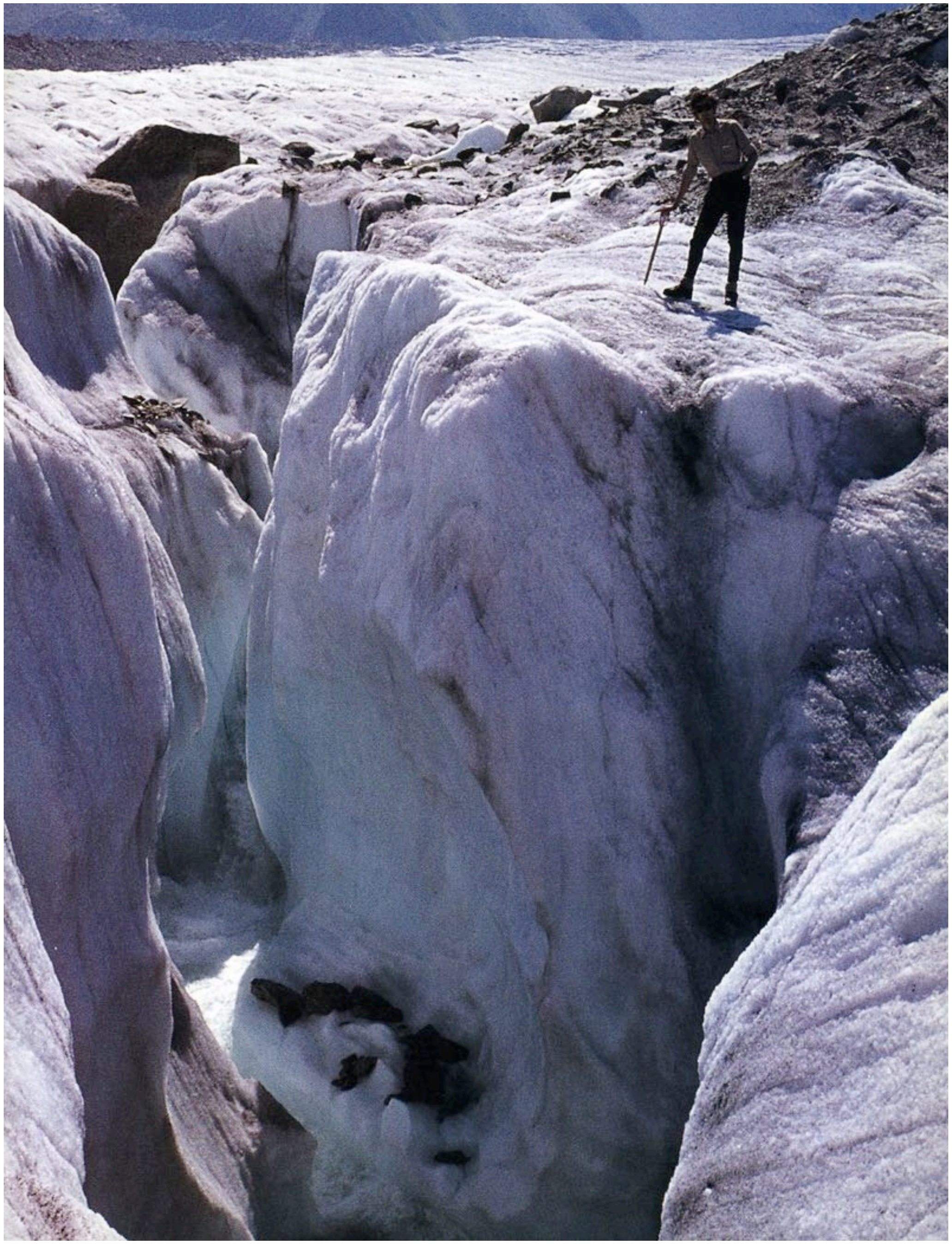
Water can melt channels into glacier ice.

- Water has lower albedo (darker) than ice, so water absorbs more sunlight than ice does.
- Water dissipates potential energy as it loses elevation.
- Water in contact with ice stays at 0°C.
- So what happens to that energy?

Moulins

Water will find a way somehow to move down into a glacier.

• a supraglacial stream will typically flow into a crevasse.



Mer de Glace, France

Hambrey and Alean. ***Glaciers***.

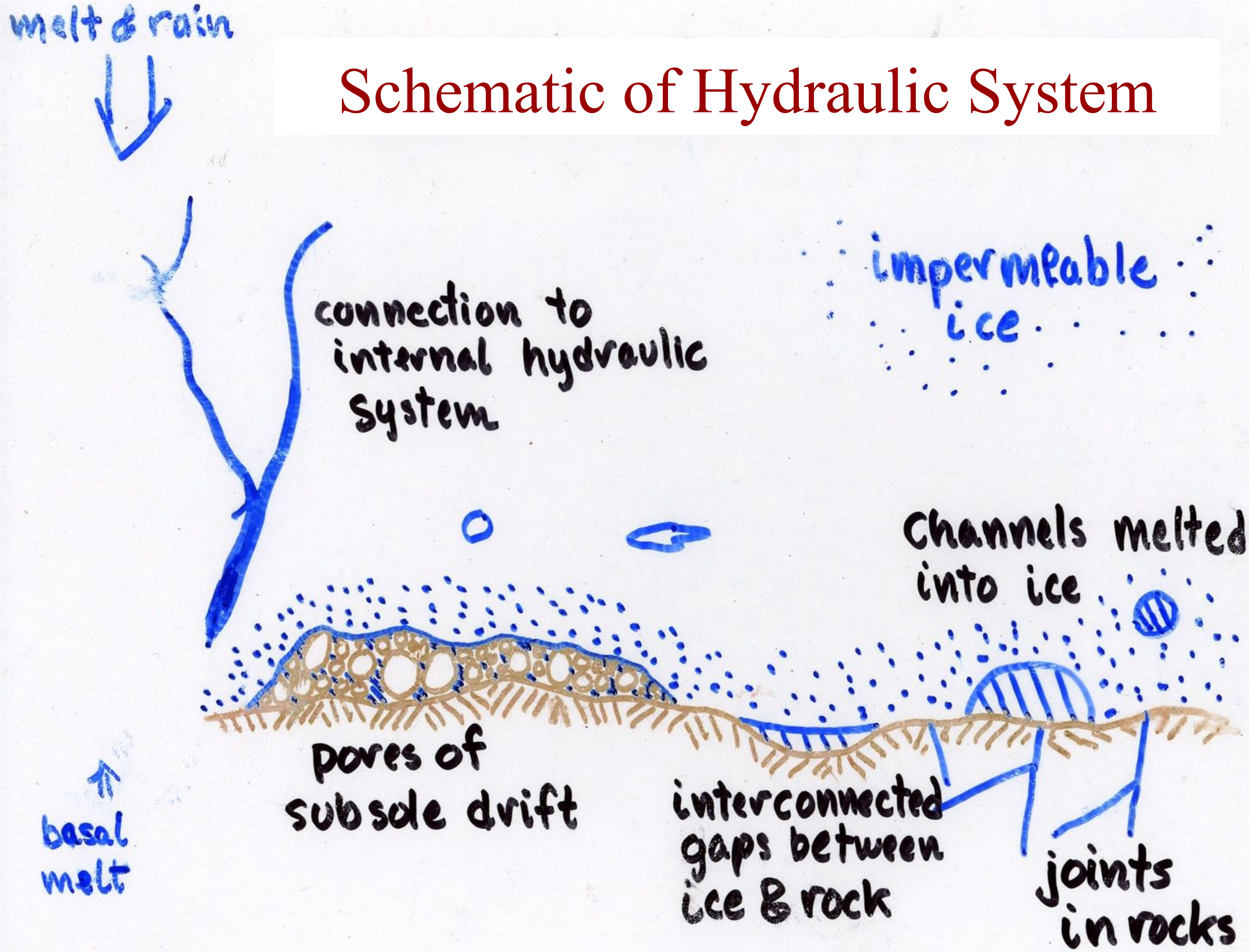
Tunnels

We can see the water coming out at a glacier terminus

- But where has it been?

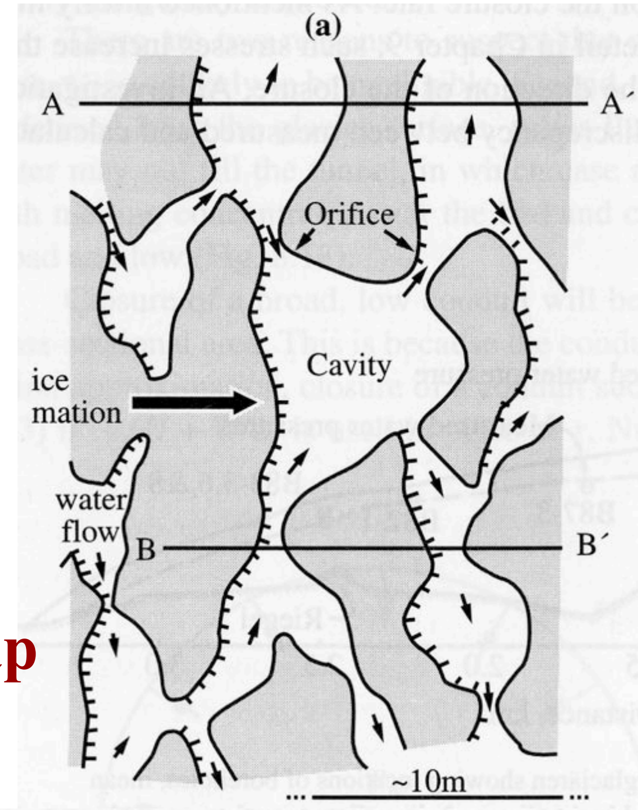
Fox Glacier, NZ.
Hambrey and Alean. ***Glaciers***.

Schematic of Hydraulic System



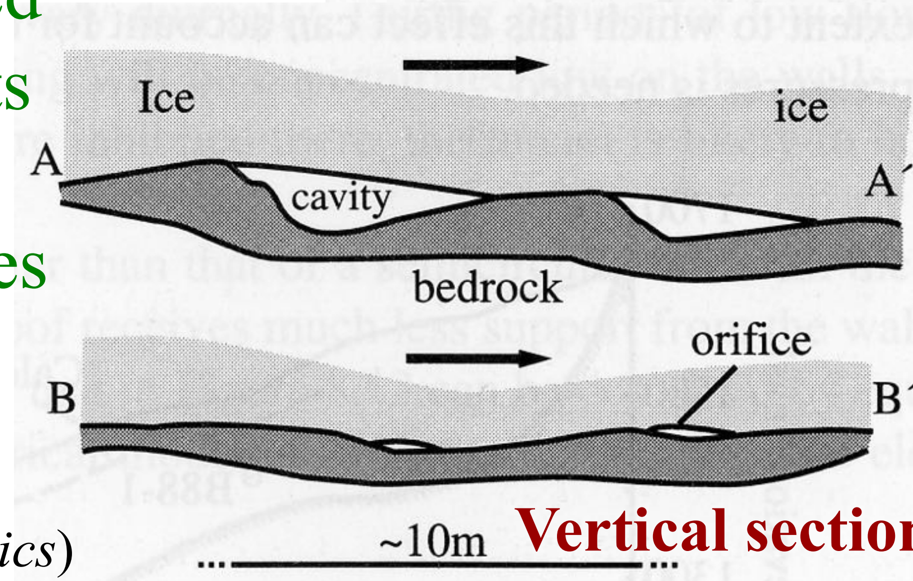
Linked Cavities

In absence of subglacial tunnels, water flows through a ***linked-cavity system*** of interconnected basal cavities and narrow passage-ways.



Map

- Drainage is inefficient.
- High water pressure is needed to carry even limited amounts of water.
- Water will collect in crevasses and cavities until high pressures are reached.



Vertical section

(Hooke, *Fundamentals of Glacier Mechanics*)

Linked Cavities in Central Park

Glaciated bedrock with ledges, cracks, and hollows

(http://www.swisseduc.ch/glaciers/)

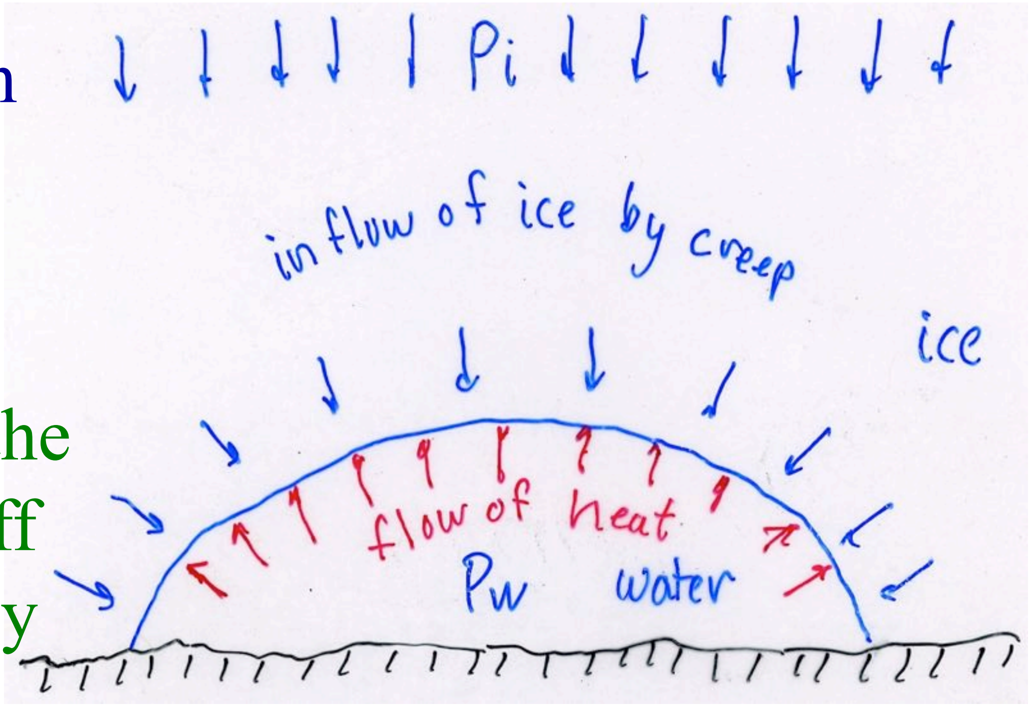
Tunnels

Arborescent networks of tunnels can carry large volumes of water at relatively low pressure compared to the pressure due to the weight of the overlying ice.

- Water flows from high pressure to low pressure.
- Water will flow from linked cavities into tunnels.

Ice also flows from high to low pressure.

- Ice also flows into the tunnels.
- Energy dissipated by the flowing water melts off the walls as fast as they can close in.



Seasonal Water Cycle

Early winter: little melt-water, low water pressure.

- Tunnels close, linked cavities survive.

Late winter: seepage, basal melt.

- water pressure rises slowly, sliding increases slowly.

Spring: high melt-water flux enters linked cavities.

- Water pressure rises, sliding increases slowly.

Early summer: too much water overloads cavities.

- Sliding hits its peak.
- Surface rises, cavities join, tunnels start to form.

Late summer: water flows in low-pressure tunnels.

- Basal water drains, sliding slows down.

Flow of Nisqually Glacier

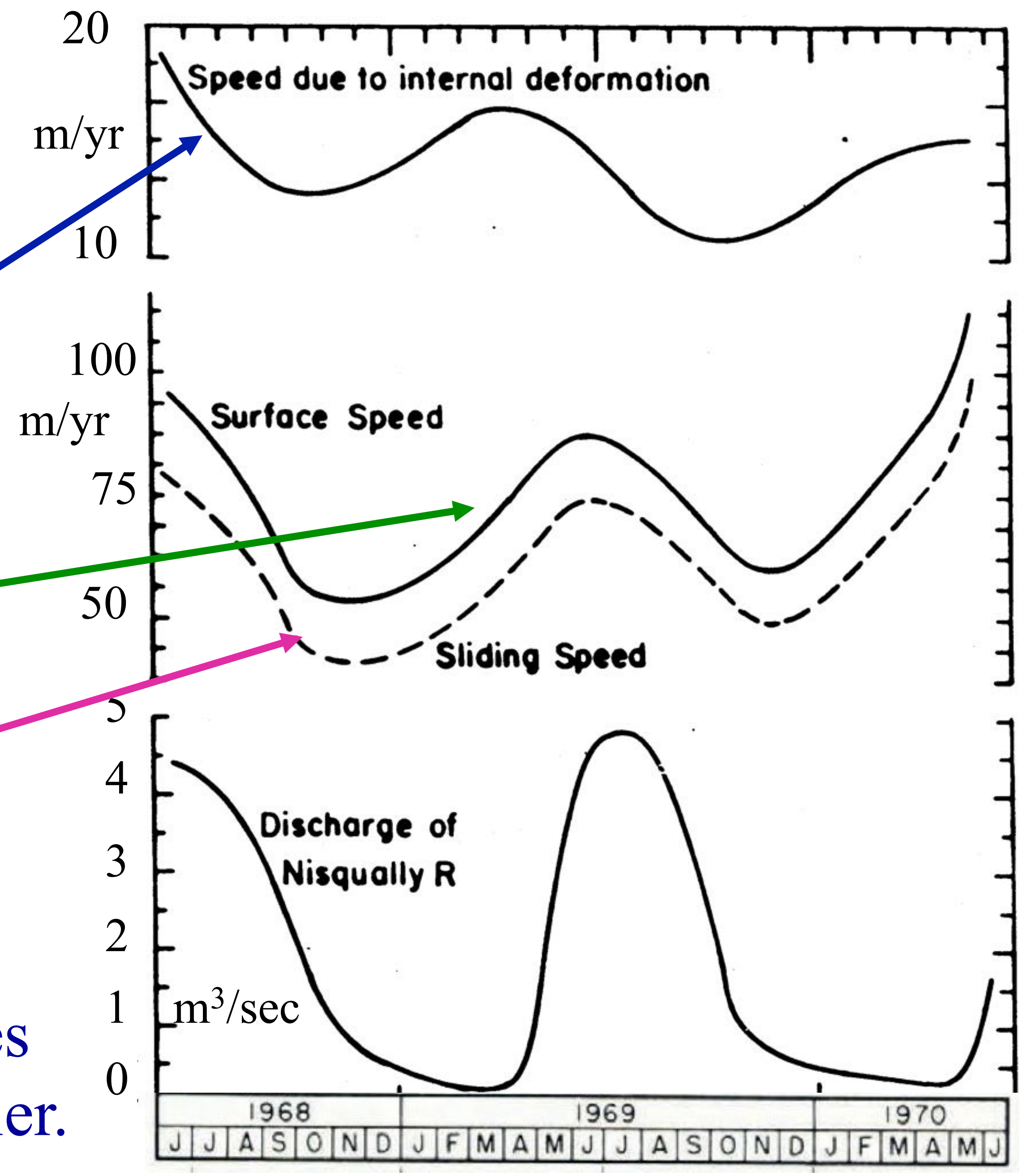
Speed due to viscous flow (deforming ice).
- Calculated from ice thickness and slope.

Surface speed
- Measured

Sliding speed
- Calculated as their difference.

Nisqually River comes from under the glacier.

(Hodge, S., 1974. *J.Glaciol.*)

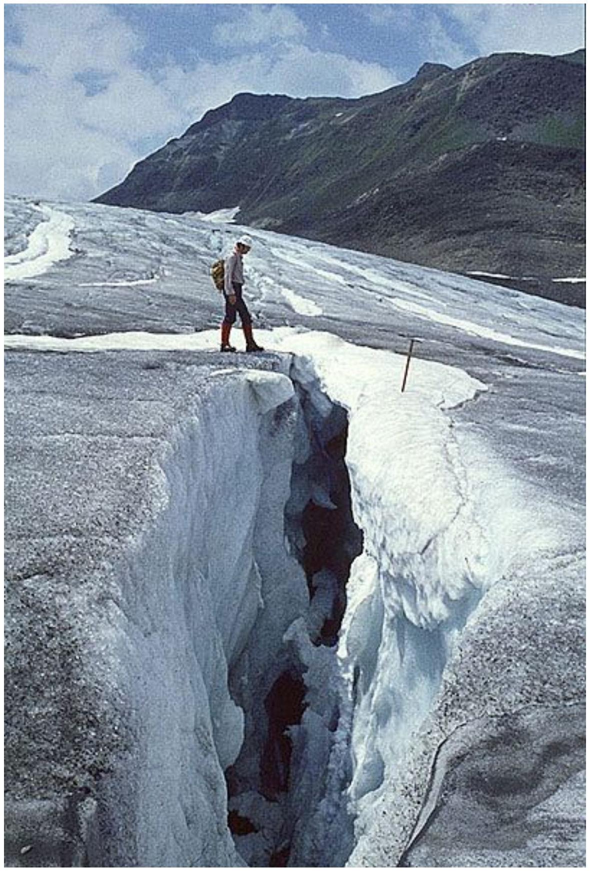


Brittle Behavior in Glaciers

Crevasses can form in the upper "skin" (about 30 meters, or 100 ft) of flowing glacier ice, when the ice tries to *stretch* rapidly.

- At greater depths, the ice continually flows back in to close up the cracks.
- Crevasses almost always form at right angles to the direction of the maximum stretching.

Demo: silly putty



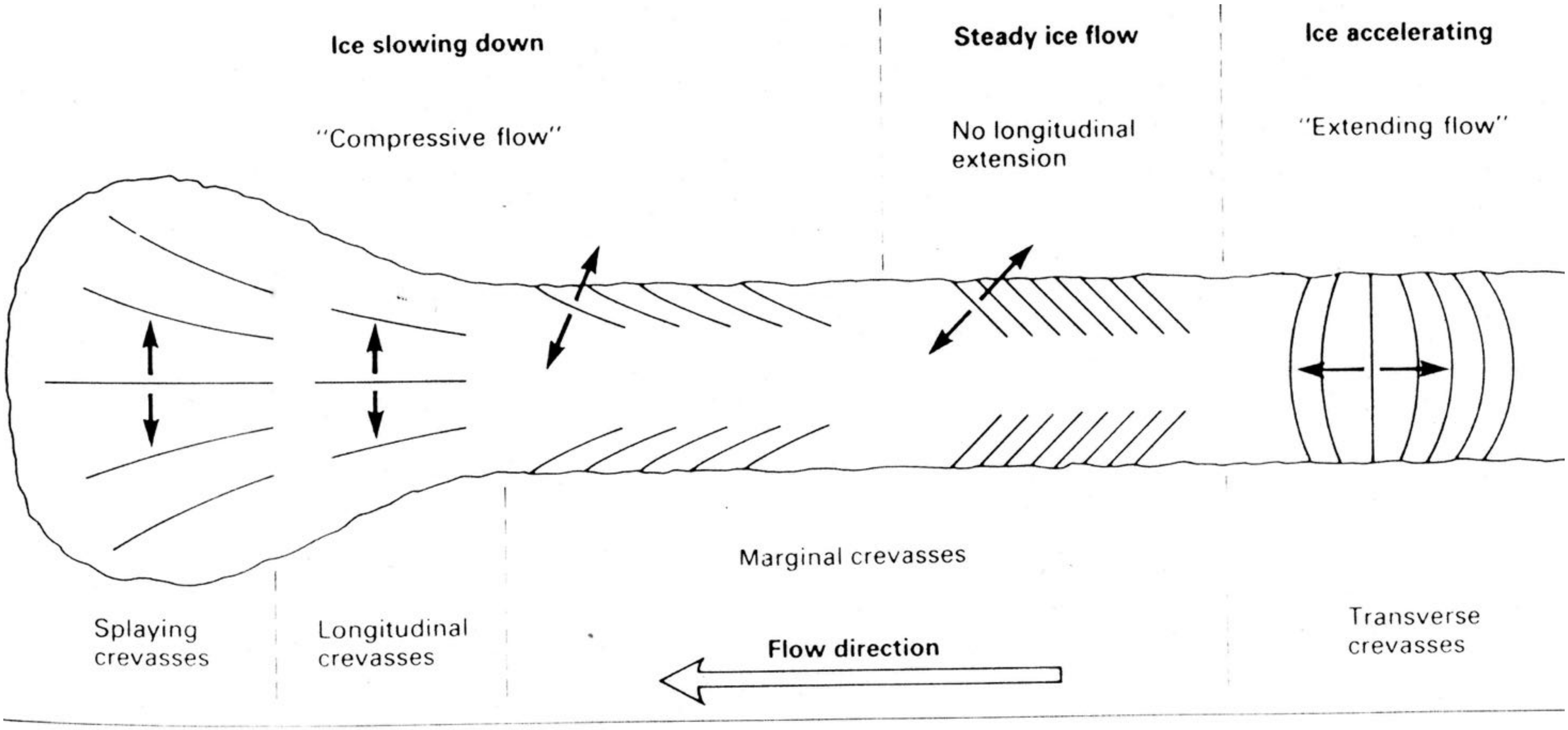
Hambrey and Alean, 2005. *Glaciers.*

HELP!COFFEE*

Hawley
Extremely
Lightweight
Portable **!**
Crevasse
Orientation
Freehand
Failure
Estimation
Equipment

[*Designed by former ESS 203 TA Bob Hawley]

Where Crevasses tend to Form



Hambrey and Alean, 2005. *Glaciers*.

Crevasse on Griesgletscher Switzerland

- Why might this crevasse have formed?

- Since this is summer, you can see it easily.
- In winter it might be hidden by a thin snow bridge (falling through is bad for your health!).

Crevasses on Fox Glacier, New Zealand

Crevasses on Arctic Piedmont Glaciers

- Why did these crevasses form?

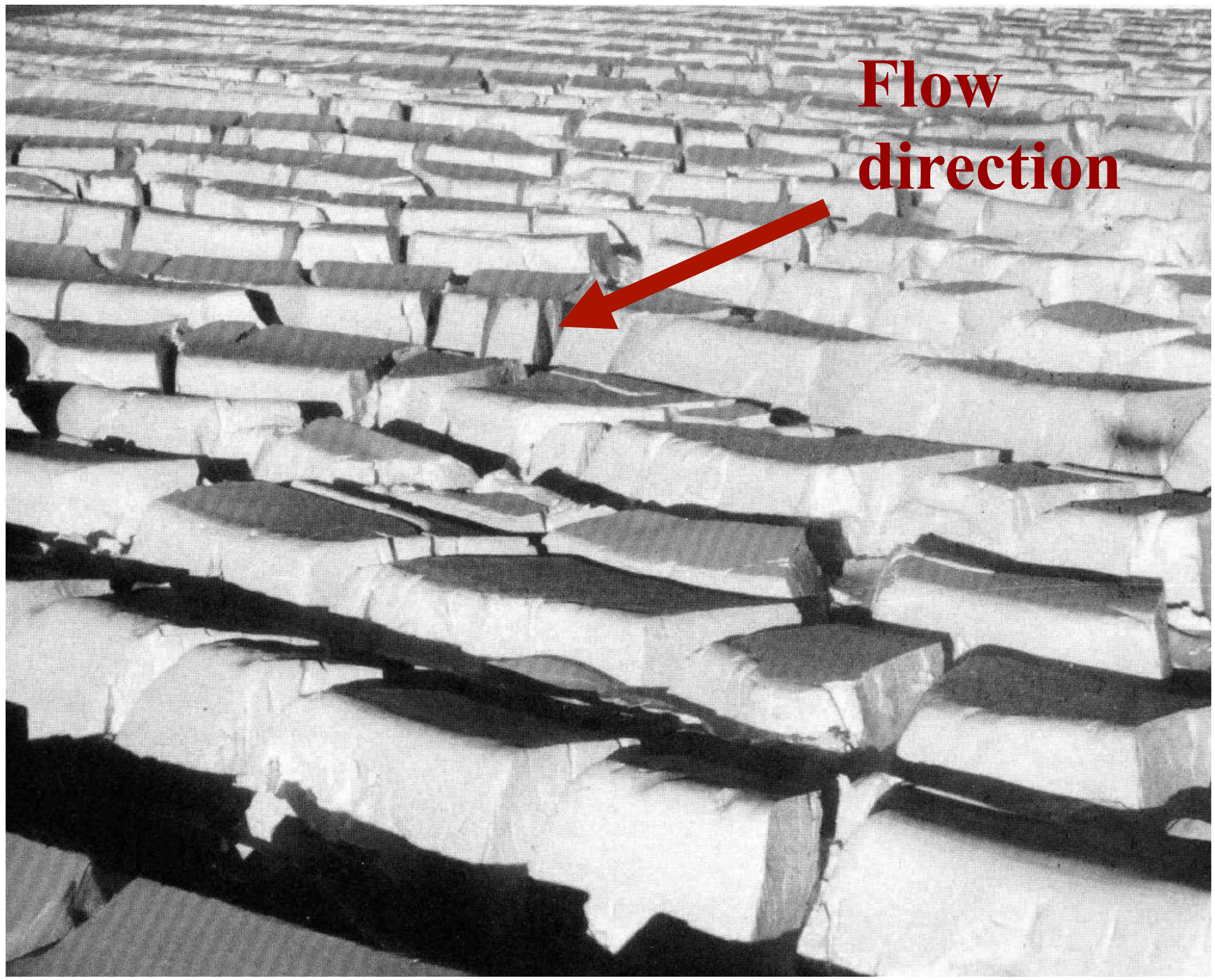
http://www.swisseduc.ch/glaciers/

Crevasses on an Antarctic Outlet Glacier

Ice accelerated into a valley through the Transantarctic Mountains, then slowed down and spread sideways.

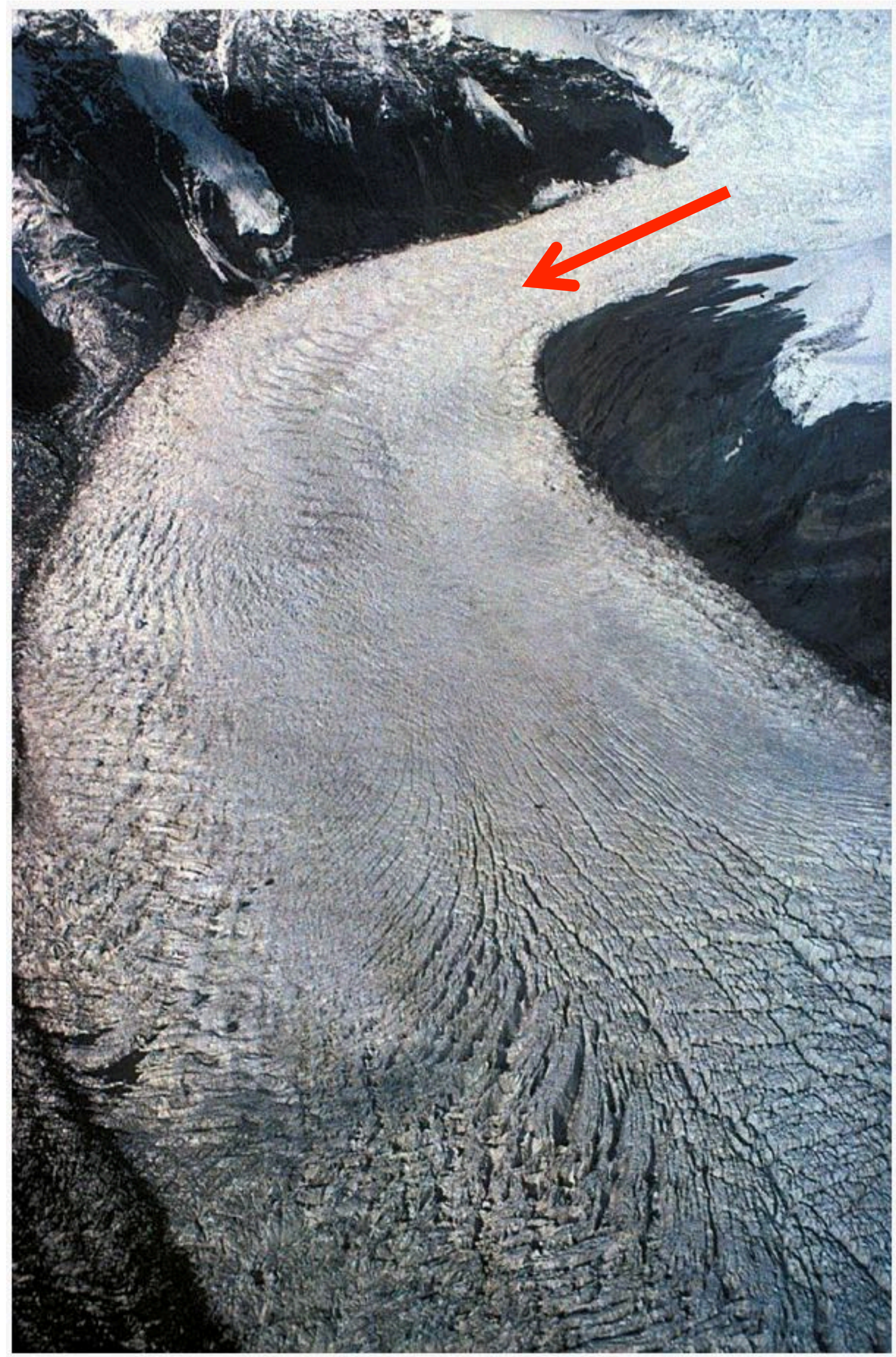
- When did each set of crevasses form?

R.P. Sharp. 1988. *Living Ice*



1. Alaskan Glaciers

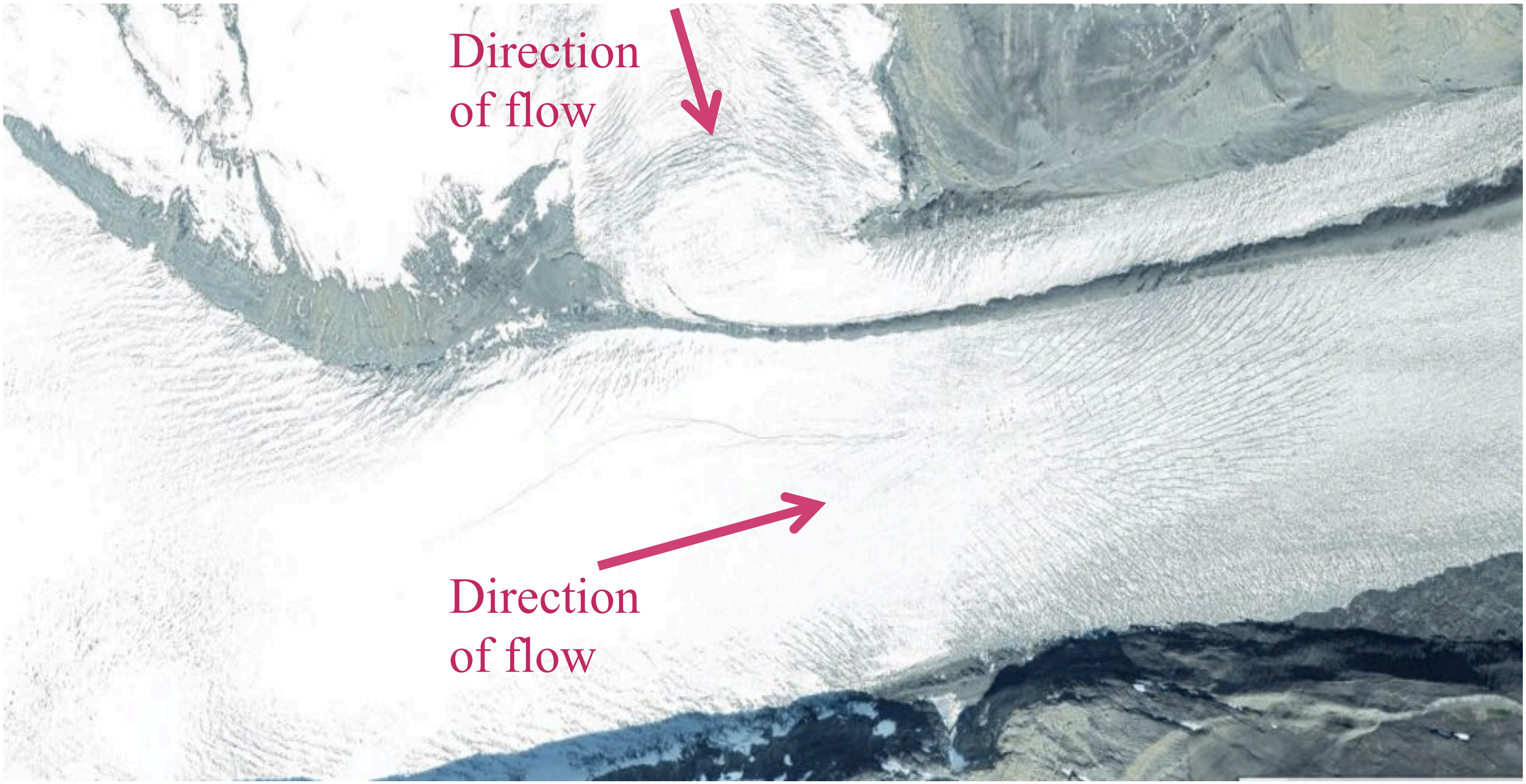
- Locate examples of all 3 types of crevasses (transverse, marginal, and splay) and explain why they formed.



http://www.antarcticglaciers.org/modern-glaciers/structural-glaciology/splaying-crevasse/

2. Crevasses on Saskatchewan Glacier

- Locate examples of all 3 types of crevasses (transverse, marginal, and splay) and explain why they formed.



Google Earth

Glacier-Flow Video

This 11-minute video shows historic time-lapse footage shot at

- Blue Glacier, Mt Olympus
- Nisqually Glacier, Mt Rainier

Do these glaciers really move, or change shape, or flow?

- Watch for ***evidence*** of viscous flow, brittle failure, and basal sliding.

Break-out rooms – Curious Scientists find evidence of glacier behavior

Based on the Blue Glacier video, work with your group to identify and describe as many lines of evidence as you can to support or refute

1. Viscous flow
2. Brittle fracturing
3. Basal sliding

Take about 10 minutes.

https://docs.google.com/document/d/1uauDraPME-6JKgdLVSs7dbby8jL0s4RIdmYjlBFKMPw/edit#

Ice flows in glaciers

- What evidence did you see for viscous flow in the video?

Closing the tunnel

- How long did it take?
- Does the videographer need to run for it?
- Tunnel closed in about 20 seconds on film.
- Film was speeded up 5,670 times
- Actual closure took ≈ 5,670 × 20 s = 113,400 s
- How many days is this?

$$113400\,\cancel{s} \times \left(\frac{\cancel{1\,\text{hour}}}{3600\,\cancel{s}}\right) \times \left(\frac{1\,\text{day}}{\cancel{24\,\text{hours}}}\right) = \left(\frac{113400}{3600 \times 24}\right)\text{days} \approx 1.3\,\text{days}$$

Glacier's Revenge …

With wanton abandon the human scourge assails me.
Burrowing relentlessly, deep into my bowels,
with air, water, electricity,
Leviathan that I am,
I am powerless to resist their mighty tools.

But always their tenacity will fail.
Slowly, slowly, I envelope
all their constructs
And victory is mine.

(Anon.)

Ice fractures in glaciers

We could try hitting an ice cube with a hammer.

- What would happen?

What evidence did you see for brittle fracture in the video?

Crevasses

- Where were they?

Jack hammer and chain saw

- Did the ice break?

Ice sliding off basal ledges

- Did it ever break?

What about sliding over the substrate?

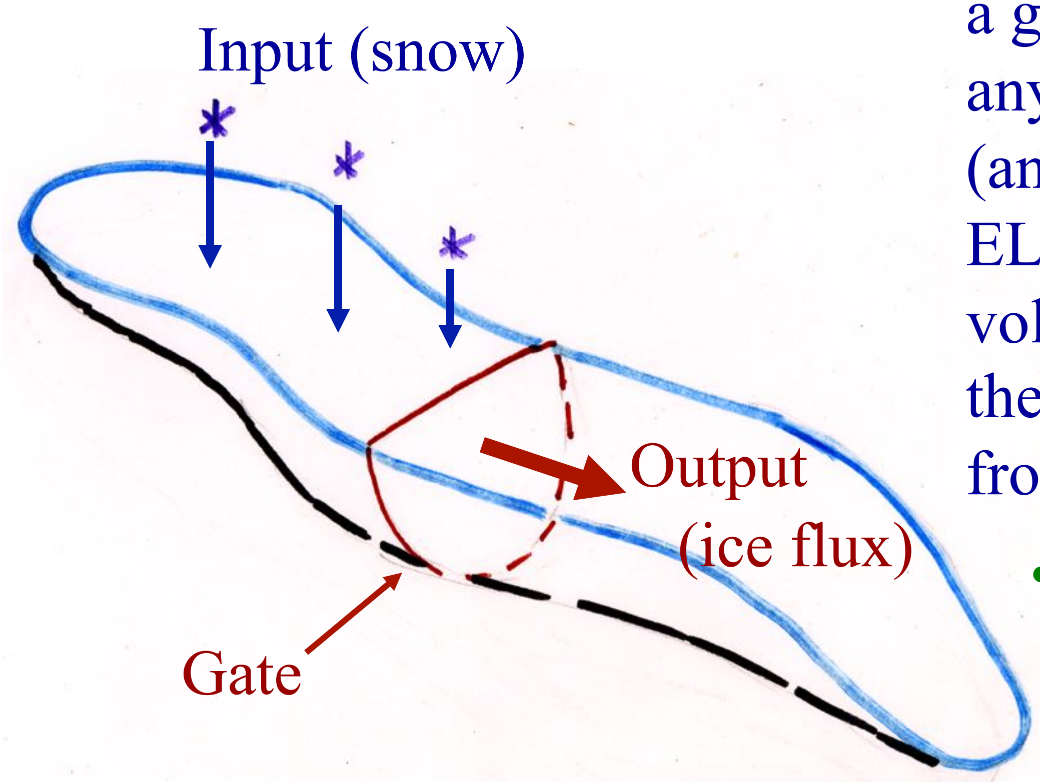
Perspectives on Flow and Change

- Kinematic perspective
- Dynamic perspective

- Both of these ideas are useful for understanding steady flow or changes, and for predicting flow and changes in many other systems where inventory matters (besides glaciers ☺).

Kinematic Perspective

Until now, we have looked at glacier flow from a ***kinematic perspective.***



- How much volume of ice must a glacier carry by flow past any "gate" in a year, (ice flux) (any gate, not just gate at ELA) in order to evacuate a volume of ice equivalent to all the accumulated snow or ice from upstream in a year?
  - Or if the flux carried doesn't equal the total upstream accumulation, how fast does the glacier thicken or thin?

Kinematic Perspective

We assumed steady state –

- Left to its own devices for long enough, the glacier had already achieved the appropriate combinations of thickness and speed to carry the necessary ice flux.

- (If it had not, it would still be growing or shrinking, and from kinematics we could figure out by how much.)

Kinematic Perspective

What did we ***not*** need to know?

- We did ***not*** need to know anything about gravity, or forces, or ice thickness, or slope of the surface.
- We did not need to know anything about how ice deforms at the microscopic level (crystal properties).
- We did not even need to know anything about the bulk mechanical properties of ice, such as its viscosity, e.g. how soft or pliable is glacier ice, in comparison to motor oil, or honey, or stainless steel …

That we could get this far, is a bit surprising …!

Kinematic View of a Glacier

Ice flux = ice volume carried through a cross-section or "gate" each year. (Units are $m^3\ a^{-1}$)

Accumulation area

- Additional ice is added all along glacier.

Equilibrium Line

- Last place where ice is still being added.
- Flux is as big as it is ever going to get.

Ablation area

- Some ice is lost to melting at every point.

Terminus

- It is where the ice is all gone.

Kinematic View of your Bank Account

You start a new job and a new
bank account on Sept 16 (Bergschrund)
Fall Quarter Work Study job)

- You add some $ weekly (Accumulation area)
- Account Balance = $ carried forward (ice flux)

End of Fall Quarter and end of job

- Last time when you are still adding $.
- Your balance is as big as it is going to get.
(Equilibrium Line)

Winter Quarter (no job)

- You withdraw some $ every week. (Ablation area)

End of Winter Quarter

- Money is all gone. (Terminus)

Kinematic View of your Bank Account

We don't need to know how you earn your $, or how your banker invests your $.

- the amount just appears in your account or disappears from your account each week.
- You calculate how much gets carried forward to the next week.

Dynamic Perspective

Glaciers flow by Quasi-viscous deformation in response to applied forces.

- How fast does a glacier flow when it has a particular shape (thickness and slope), a certain softness (temperature), and is driven by the force of gravity (e.g. “Greenland” demo).
- If you pile up a bunch of ice, it is going to move if gravity can pull it down a slope.
- The flow speed is not necessarily determined by the upstream accumulation or ablation pattern.

Later, we can combine the two perspectives to see whether a glacier is growing or shrinking.

What Drives Ice Flow?

The force driving flow of glaciers is ***gravity***.

- Ice flows from places where the surface is high, to places where the surface is low (like water in a stream.)

- Speed of a glacier increases as the surface slope gets ***steeper***.
- Speed of a glacier increases as the ice gets ***thicker*.**
- Speed of a glacier increases as the ice gets ***warmer***.

Dynamic Perspective and your Bank Account

Money managers can view investments from a dynamic perspective too.

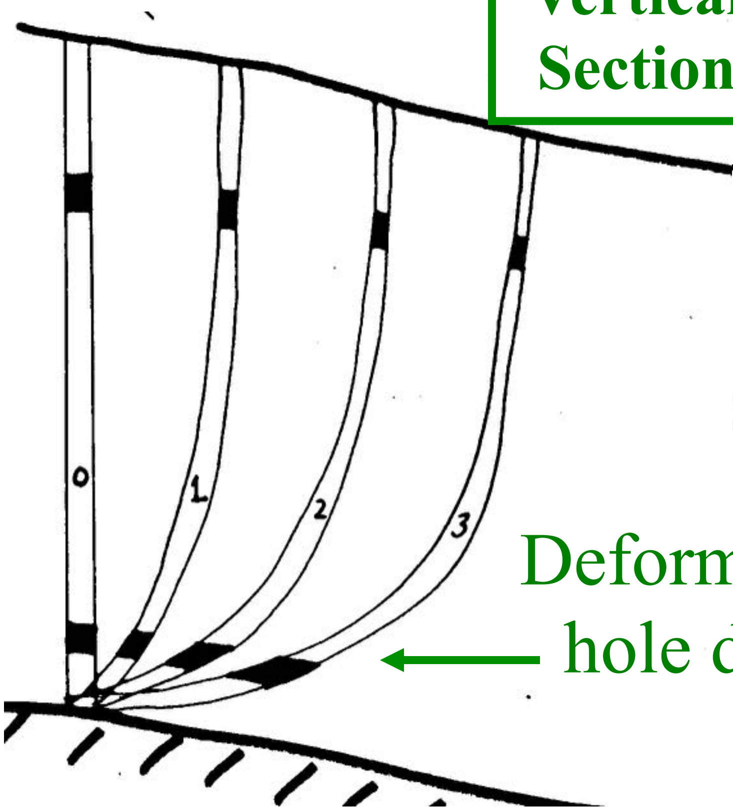
- They talk about "market forces" and "pressure on the dollar".
- Market forces control the rate at which money flows into an investment account.
  (e.g. through interest rates).
- Or the rate at which it disappears from a stock portfolio. ☺

Dynamic View: How Does Ice Flow Vary?

Speed of a glacier increases as the distance from the bottom or from the valley wall increases

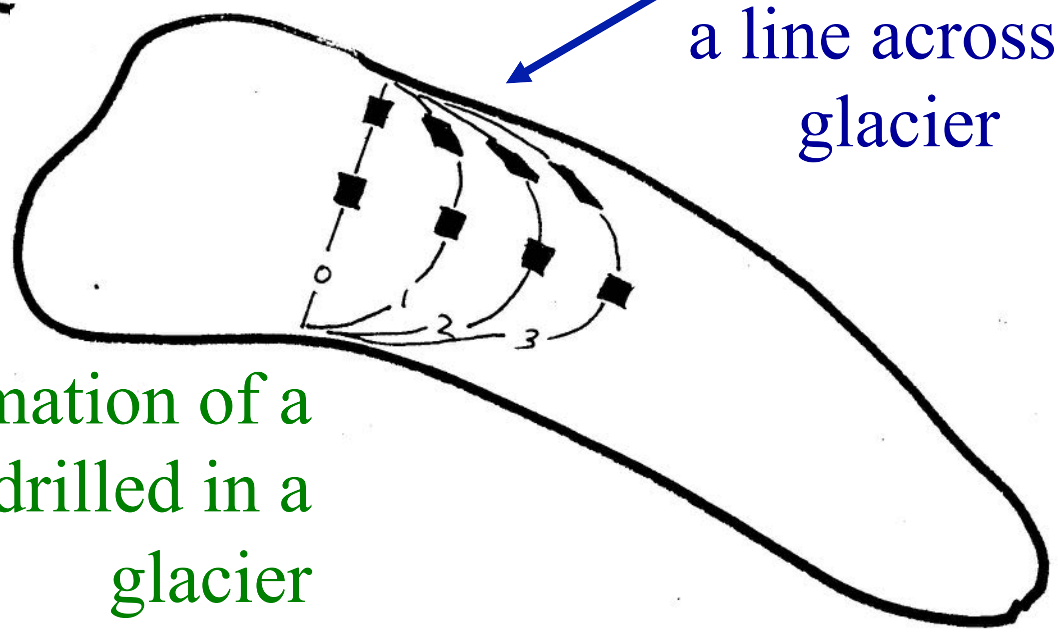
- Drag or friction from the rock walls and bottom

Vertical Section



Deformation of a hole drilled in a glacier

Map



Deformation of squares on a line across a glacier

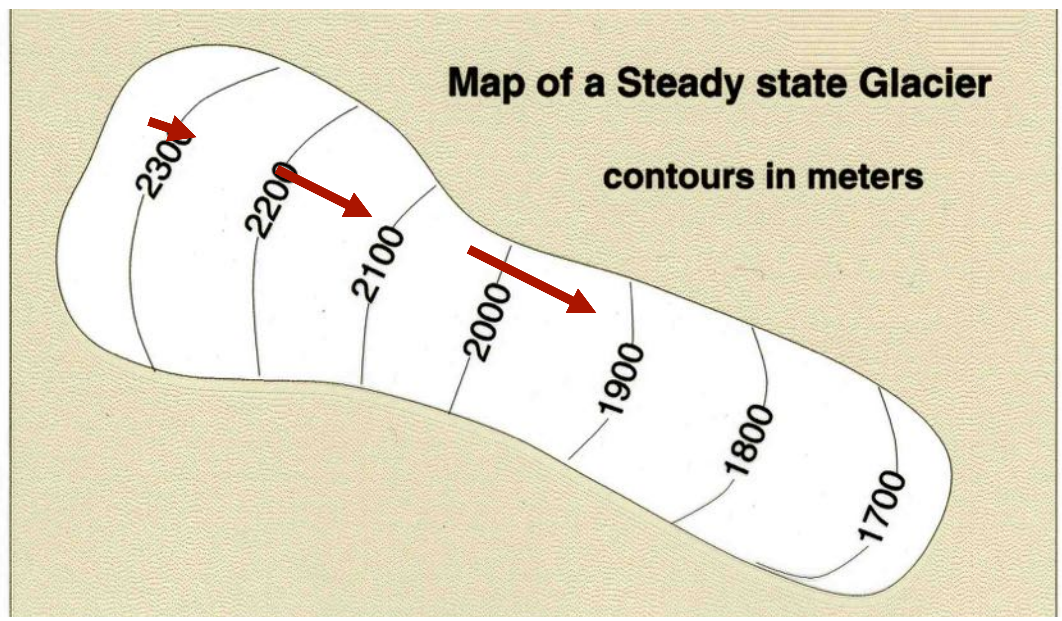
Longitudinal flow pattern in Accumulation area

Kinematic view

- Flow tends to be faster closer to the Equilibrium Line, because the amount of ice must be transported (to be equivalent to upstream snowfall) is greatest there.

Dynamic view

- The glacier is thicker at Equilibrium Line.
- Thicker ice flows faster.



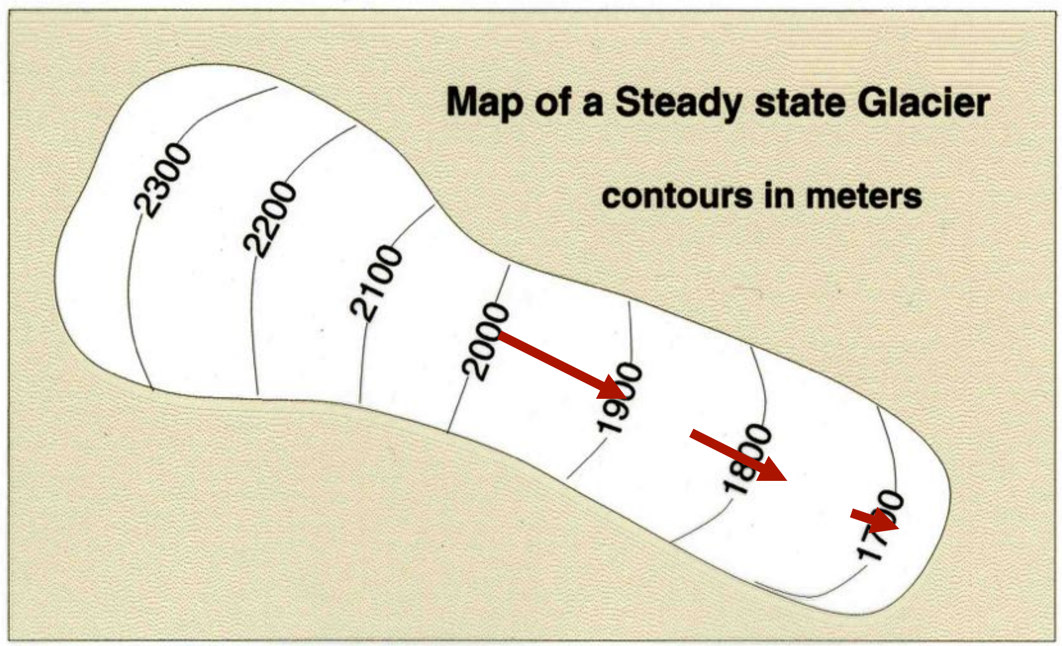
Longitudinal flow pattern in ablation area

Kinematic view

- Below the Equilibrium Line, the flow tends to slow down because the ablation upstream has reduced the amount of ice that is left to flow past each point each year.
- The glacier terminates and nearly stops flowing when there is no more ice left to melt.

Dynamic view

- Glacier gets thinner toward terminus
- Thinner ice flows more slowly.



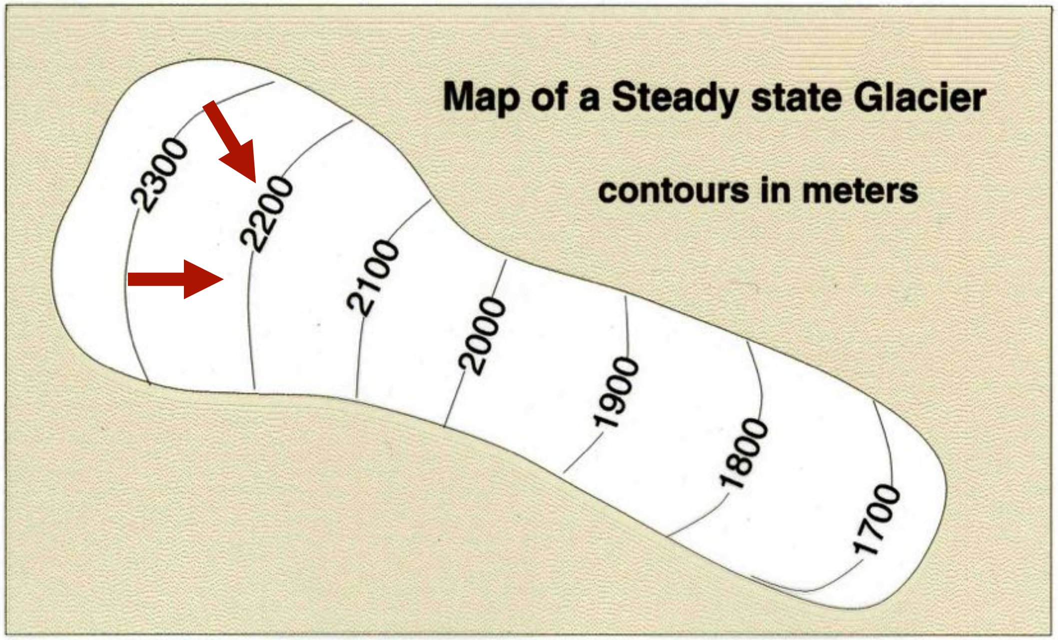
Transverse flow pattern in Accumulation area

Kinematic view

- Avalanches off valley walls pile up snow around edges.
- Ice flows toward the center of the channel to carry away high accumulation around the edges.

Dynamic view

- Surface is highest near edges.
- Ice flows down hill, toward valley center, where surface is lower.



Transverse flow pattern in ablation area

Kinematic view

- Below the Equilibrium Line, melting can be enhanced near dark valley walls.
- Ice must flow toward the edges to replenish the melting ice.

Dynamic view

- Melting near margins creates slope toward margins.
- Ice flows downhill, toward margins.