ESS 203 - Glaciers and Global Change

Friday February 19, 2021.

Outline for today

- Today's highlights on Monday – *Angela Gaither*
- Highlights from Wednesday – *Brendan Beaudette*
- Reporters − please remember to upload your report in Canvas

- Dating ocean cores
- How far will a glacier retreat or advance after an abrupt climate shift?

Monday

- How long for a glacier to adjust after a climate change?
- Response to an ongoing climate change?

HW 19 – due Monday

Please read Chapter 8, "Our Planet's Icy Past", p. 141-163 in *Frozen Earth*.

In half a page to a page, please record you thoughts, impressions, or insights about ice on Earth over the past billion years of Earth history, and put the Pleistocene Epoch (the last 2.6 Ma) in that context.

Midterm #1

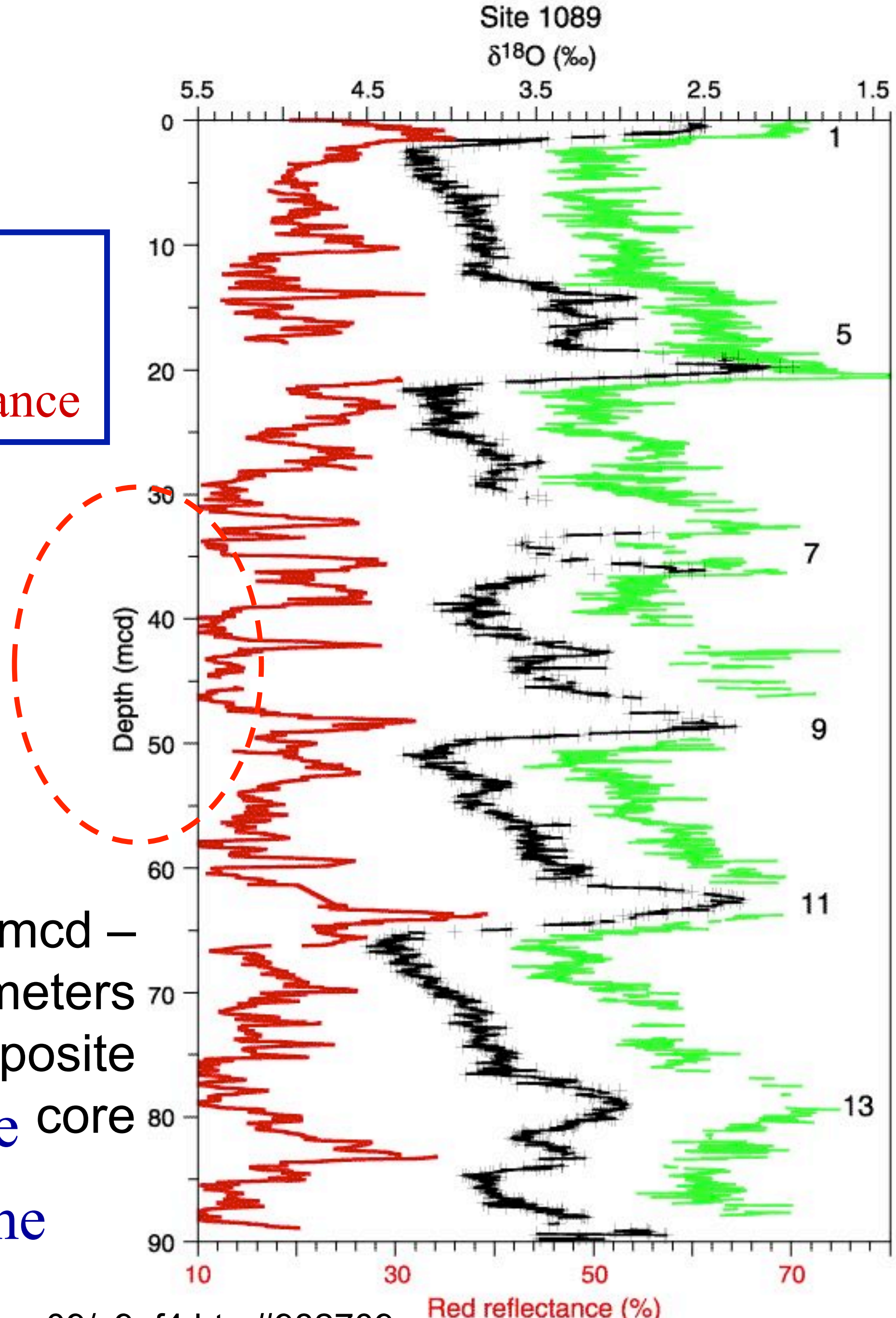
Have you been able to see my remarks about your answers?
Please get in touch with m if you have questions or concerns.

Mid-Quarter Class evaluation

Thanks for your ideas and assessments.
About 1/3 of you filled it in.
Seth, Jessica and I will review your thoughts.
Plesae remember that if you don't answer the questionnaires, we can't see your thoughts. ☺

A $\delta^{18}O$ record from the sea floor

Benthic
Planktonic
Red – core % reflectance



Benthic and planktonic records are very similar.

- So the the major signal is ice volume on land.
- Temperature signal (in planktonic) is a subtle addition.

mcd – meters composite core

- High $\delta^{18}O$ → large ice volume
- Low $\delta^{18}O$ → Small ice volume

http://www-odp.tamu.edu/publications/177_SR/chap_09/c9_f4.htm#982709

Oxygen isotope record in deep-sea sediment

$$\delta^{18}O = \frac{R_{sample} - R_{standard}}{R_{standard}} \times 1000, \qquad R \equiv \left(\frac{^{18}O}{^{16}O}\right)$$

or, $$\delta^{18}O = \left(\frac{R_{sample}}{R_{standard}} - 1\right) \times 1000$$

- $\delta^{18}O$ **more positive** => relatively **more ice** on land
- $\delta^{18}O$ **more negative** => relatively **less ice** on land

… δ shows changes relative to the standard used, which is based on modern-day sea water … so relative to present-day ice volume.

But, here are no annual layers to count. Sea worms continually churn the mud ("bioturbation", just like earthworms in your garden).

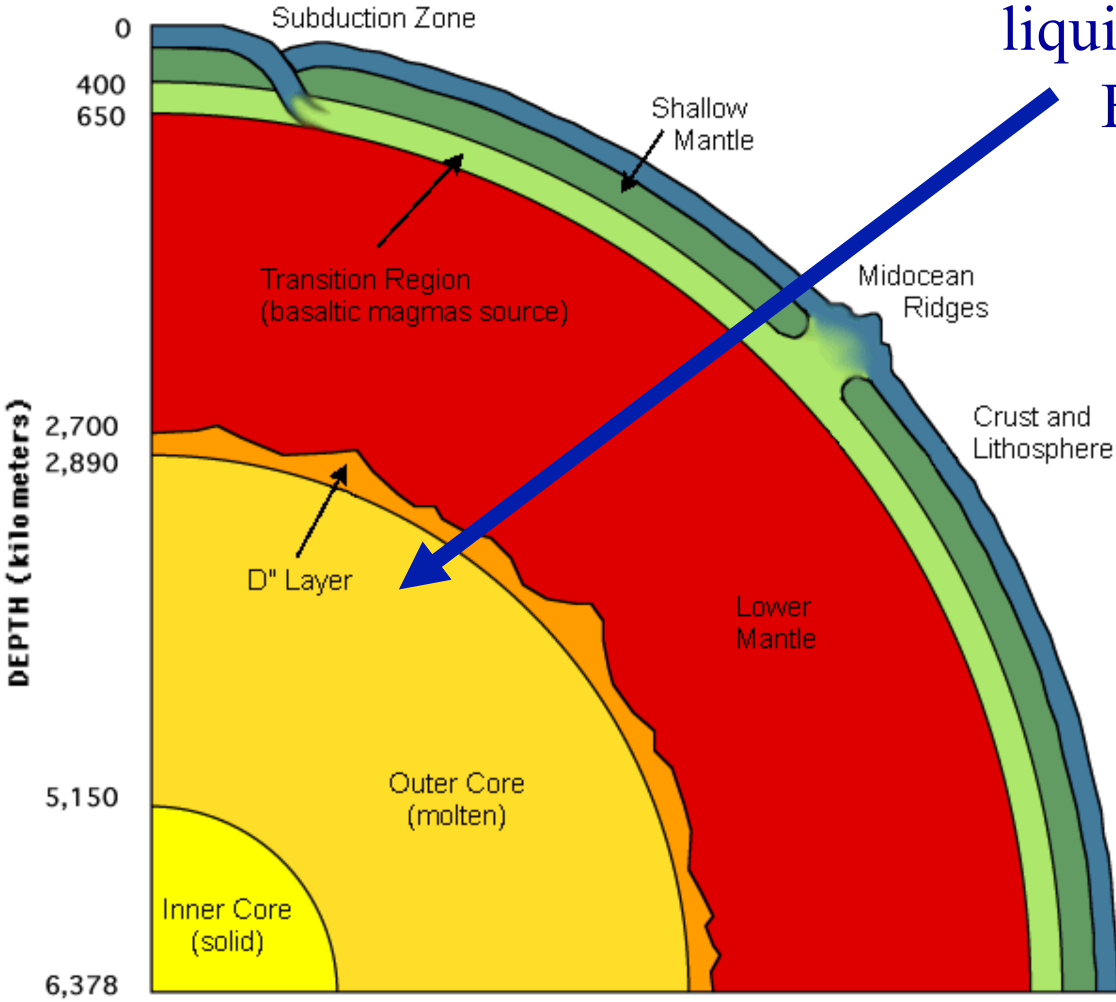
- So, how can we ***date*** the ocean sediments?

Bugs
High and Low

We're foraminifera
and we live in the sea
Some folks call us little bugs
How insulting can they be!?
We Planktonics live shallow
and frolic in sunlight
where SST varies ⋯
We Benthics live deep
where the temperatures keep.
We all are what we drink and eat;
Our ^{18}O goes up
when ice-sheets build up
Our ^{18}O goes down
when ice-sheets melt down.
Our Planktonic cousins also know SST.

(Anon.)

Earth's Dynamo



Electrical currents in conductive liquid-iron outer core generate Earth's magnetic field.

- Earth's magnetic field has reversed or "flipped" many times over Earth history.

http://www.windows.ucar.edu/

Eos

GEOLOGY & GEOPHYSICS News

How Geodynamo Models Churn the Outer Core

New simulations of Earth's outer core have reproduced magnetic fields that—for the first time—match paleomagnetic data collected from rocks.

By Alka Tripathy-Lang 16 February 2021

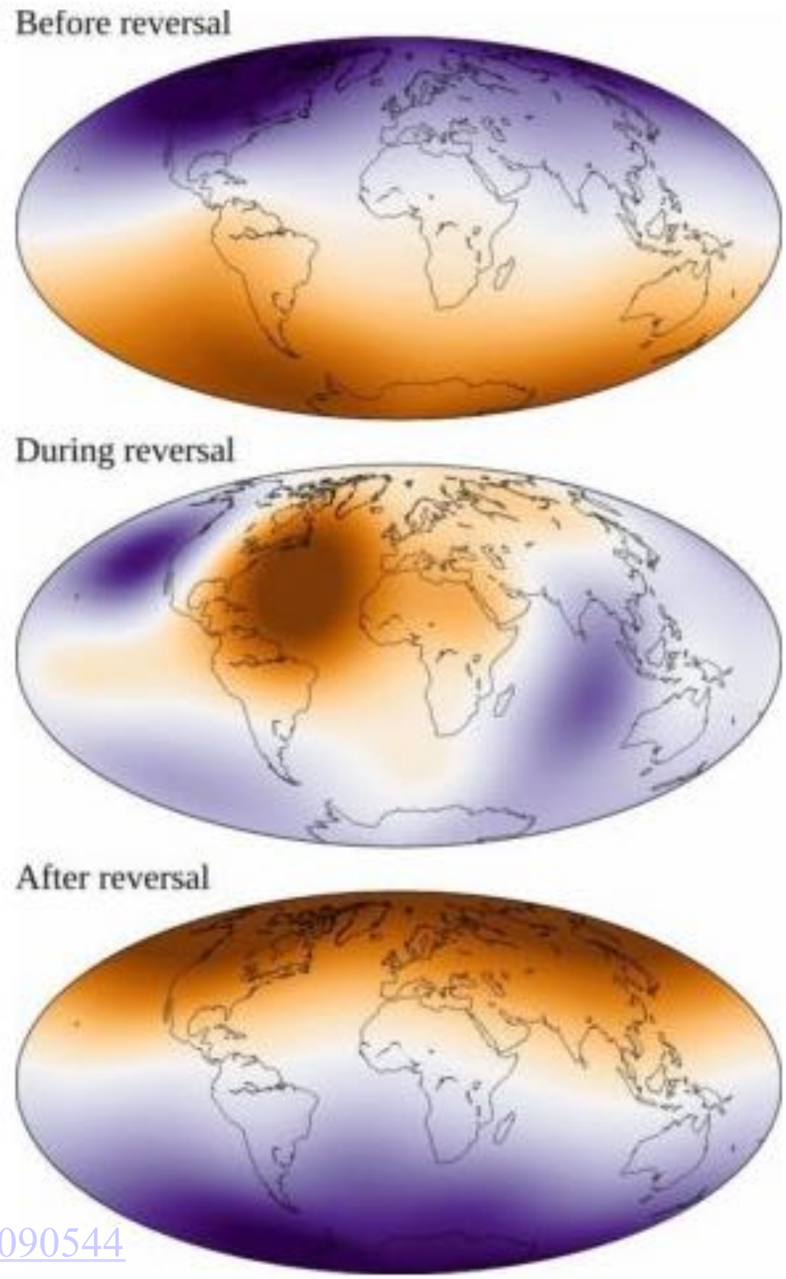


FIGURE: *Purple indicates a magnetic field pointing inward, toward the core, and orange indicates a magnetic field pointing outward and away from the Earth's surface.*

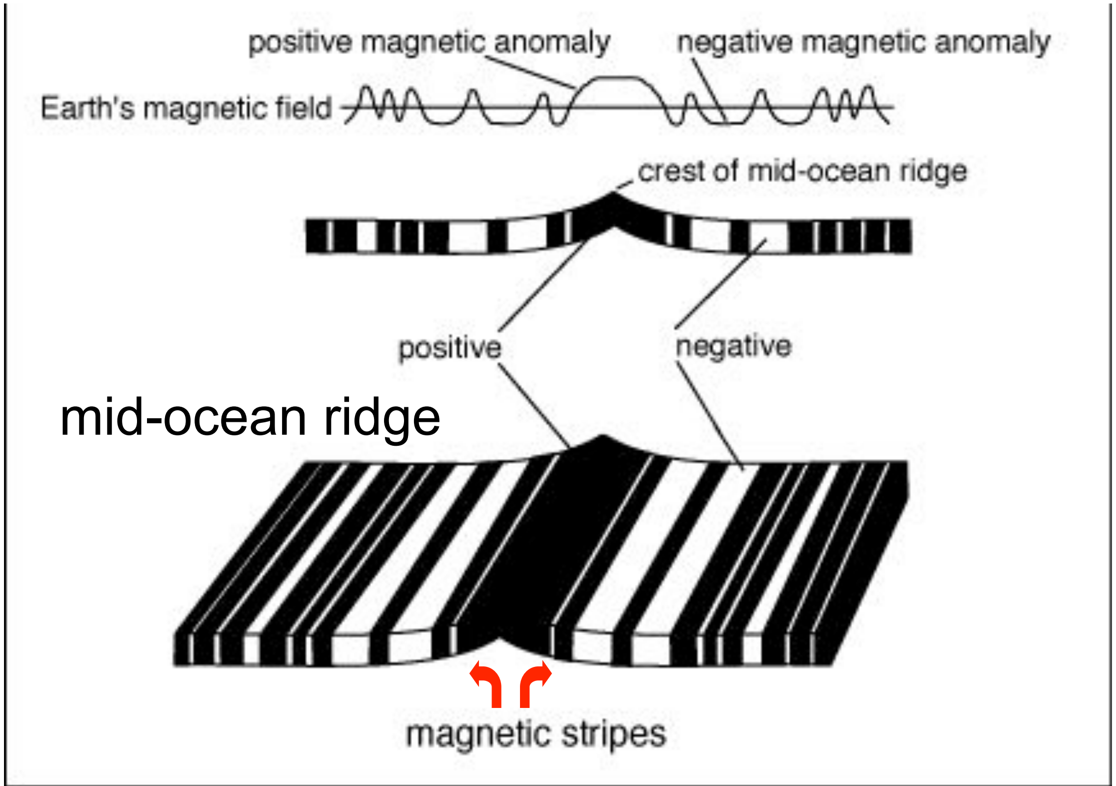
Magnetic field is *not* a dipole during reversals.

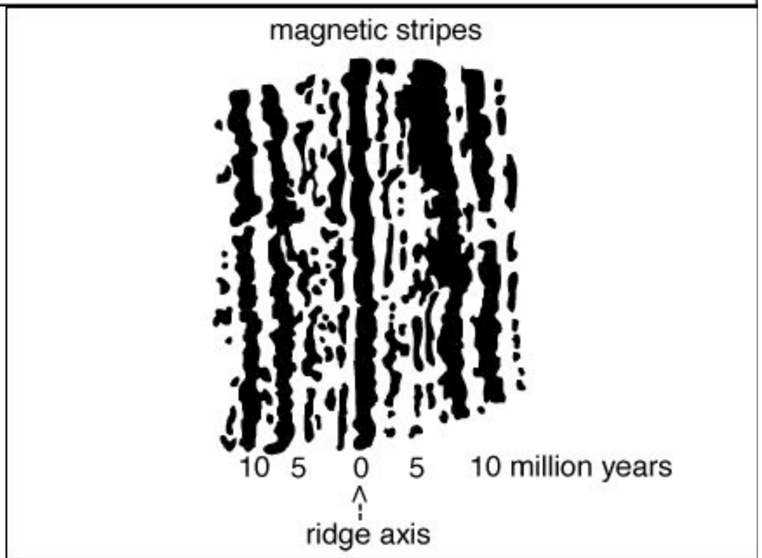
The peer-reviewed research paper was published in *Geophysical Research Letters* in January 2021.
https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2020GL090544

Citation: Tripathy-Lang, A. (2021), How geodynamo models churn the outer core, *Eos, 102,* https://doi.org/10.1029/2021EO154727. Published on 16 February 2021.

So what? Plate tectonics ⋯

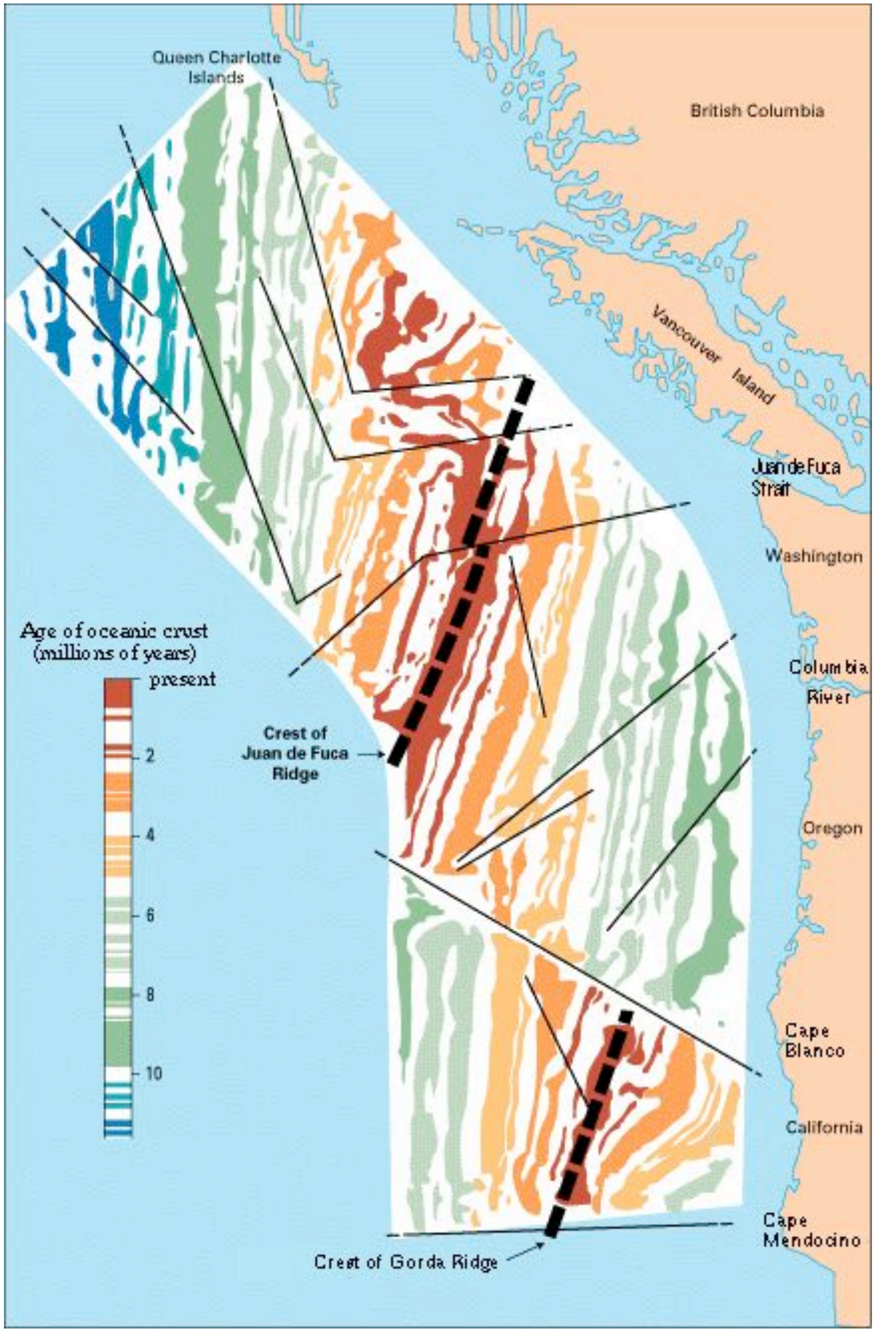
- Mid-Ocean Ridge Basalts are magnetized with the current magnetic field as they cool and move away from a mid-ocean ridge.
- Magnetic stripes are created on the sea floor.
- Knowing the spreading rate *v* at the ridge, and width *L* of a stripe, we can estimate the time *t* between every 2 field reversals: $t = L/v$





Pattern created by magnetic stripes along the Mid-Atlantic Ridge south of Iceland.

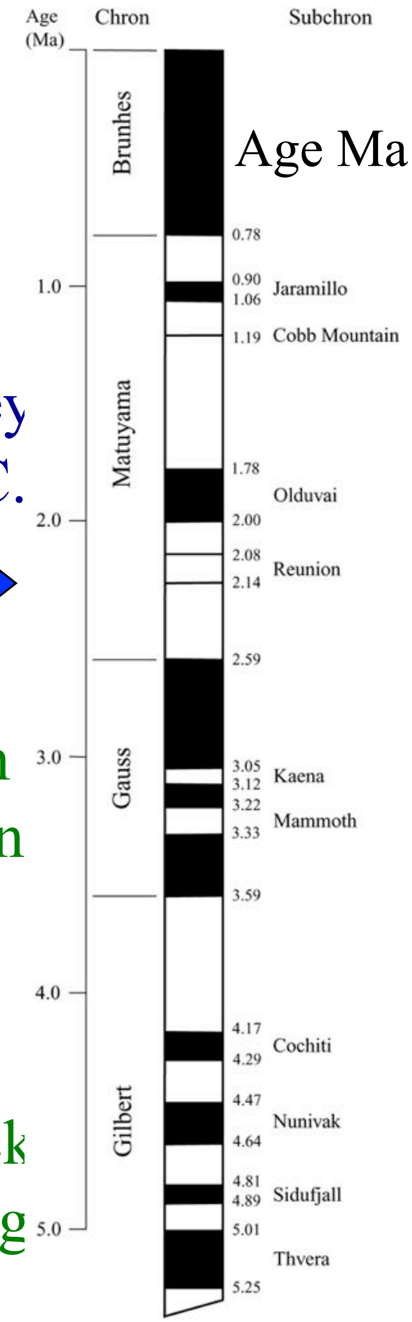
http://www.newgeology.us/presentation25.html



Dating field reversals

Basalt lavas on mid-ocean ridge are magnetized when they cool through ~ 400^{o}C.

Geologists can measure the direction of their magnetization They can also date when the rocks cooled, using their radioactivity (to check on the ridge spreading rate through time).



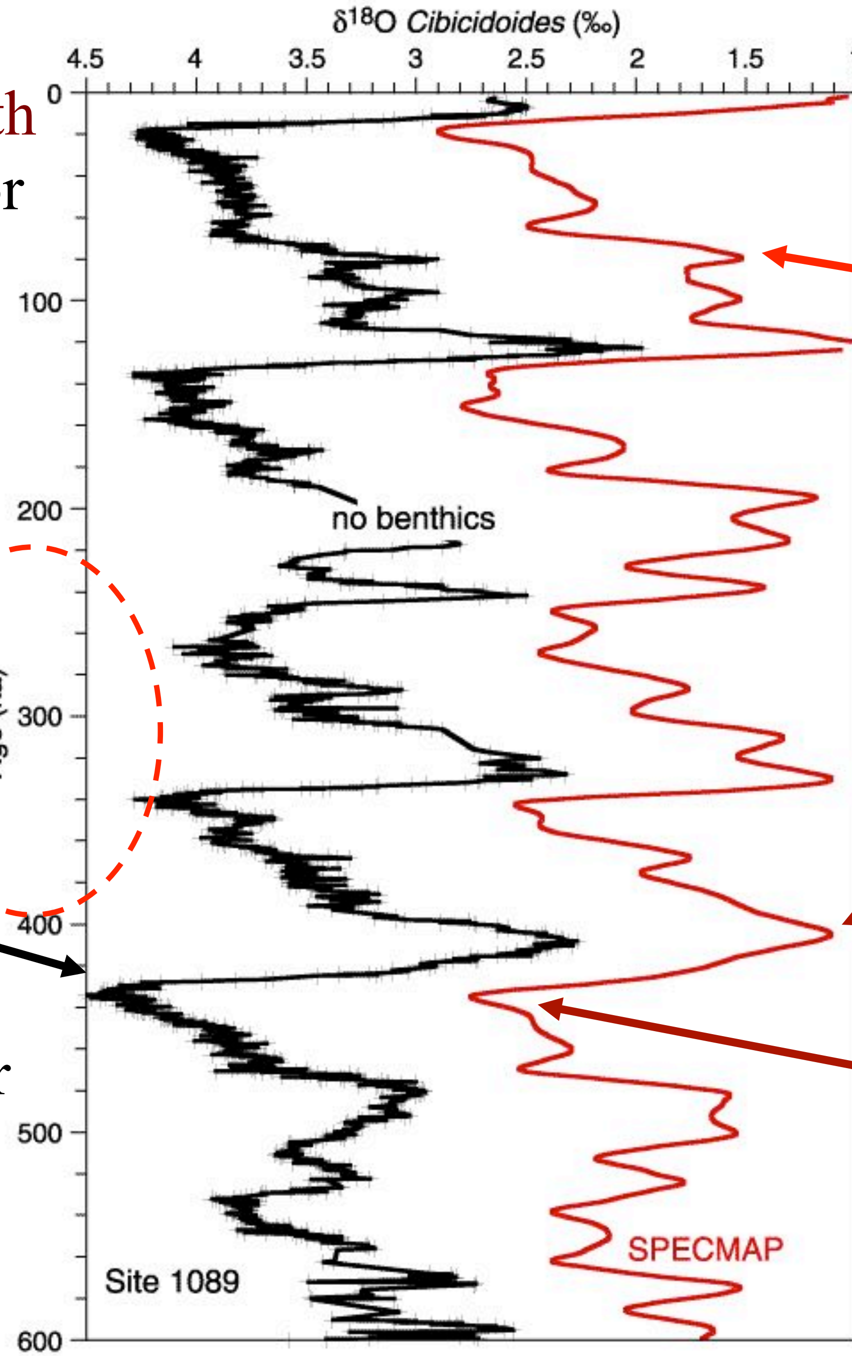
http://www.newgeology.us/presentation25.html

http://upload.wikimedia.org/wikipedia

So what?! How does this help us to date the sediment cores?

- Tiny mineral grains are washed into the oceans by rivers.
- They slowly settle out and become part of the ooze on the ocean floor, along with the forams.
- Some grains contain magnetite.
- They act like tiny magnets.
- As they settle slowly through deep, quiet ocean water, they can align themselves with Earth’s magnetic field at the time.
- Direction of magnetization can be measured in an oriented sediment core,
- and reversals can be correlated with dates of reversals known from the magnetic lava stripes on the sea floor.

And now depth in the sea floor can be converted to Age.



SPECMAP

"stack" of many cores from ocean basins around the world

Not much land ice

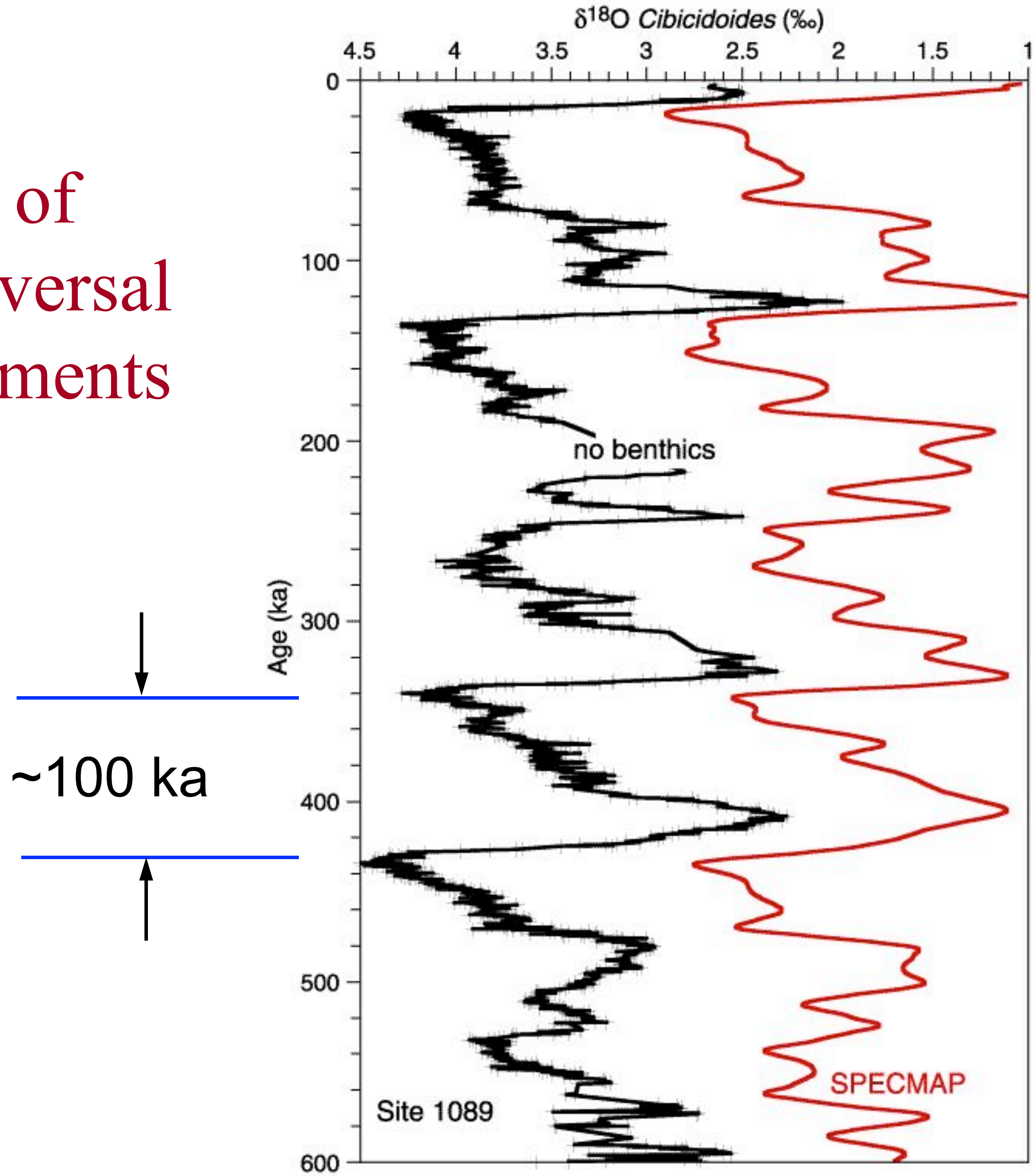
Lots of land ice

single core

~100,000 year periodicity emerges

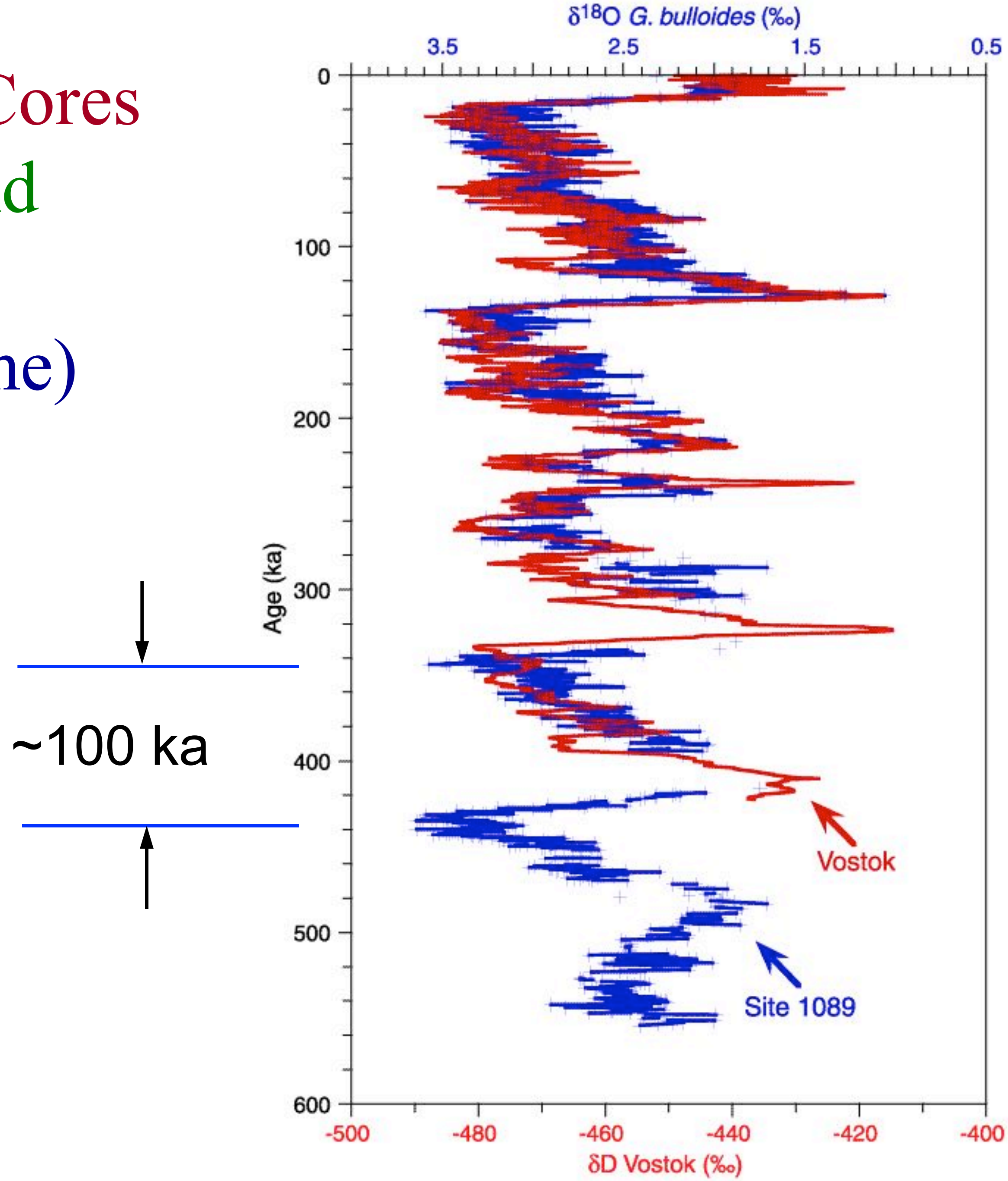
http://www-odp.tamu.edu/publications/177_SR/chap_09/c9_f5.htm#982733

Transfer of magnetic reversal ages to sediments



http://www-odp.tamu.edu/publications/177_SR/chap_09/c9_f5.htm#982733

Changes in Ice Cores (temperature) and Ocean Sediment Cores (ice volume) agree on Timing



http://www-odp.tamu.edu/publications/177_SR/chap_09/c9_f6.htm#982743

Summary of deep sea records

- Records show history of changes in $\delta^{18}O$ in seawater over time.
- This is directly related to history of changes in ice volume on land.
- Records show ***many*** glacial and interglacial periods over the last ~1 Ma.
- Ice cores show a record with similar ups and downs, but for temperatures in polar regions.
- For the last ~800 ka, ice-age periodicity is ~100 ka … Why?

- Stay tuned for Lab next week …

The other way that glaciers tell us about changing climate

Without studying the detailed geochemistry inside the ice sheets, we can still learn about past climate change.

- How's that?
- By seeing how much glaciers grew or shrank …

Perspectives on Flow and Change

Kinematic perspective

- Describes ***how*** a body moves or changes (a movie)

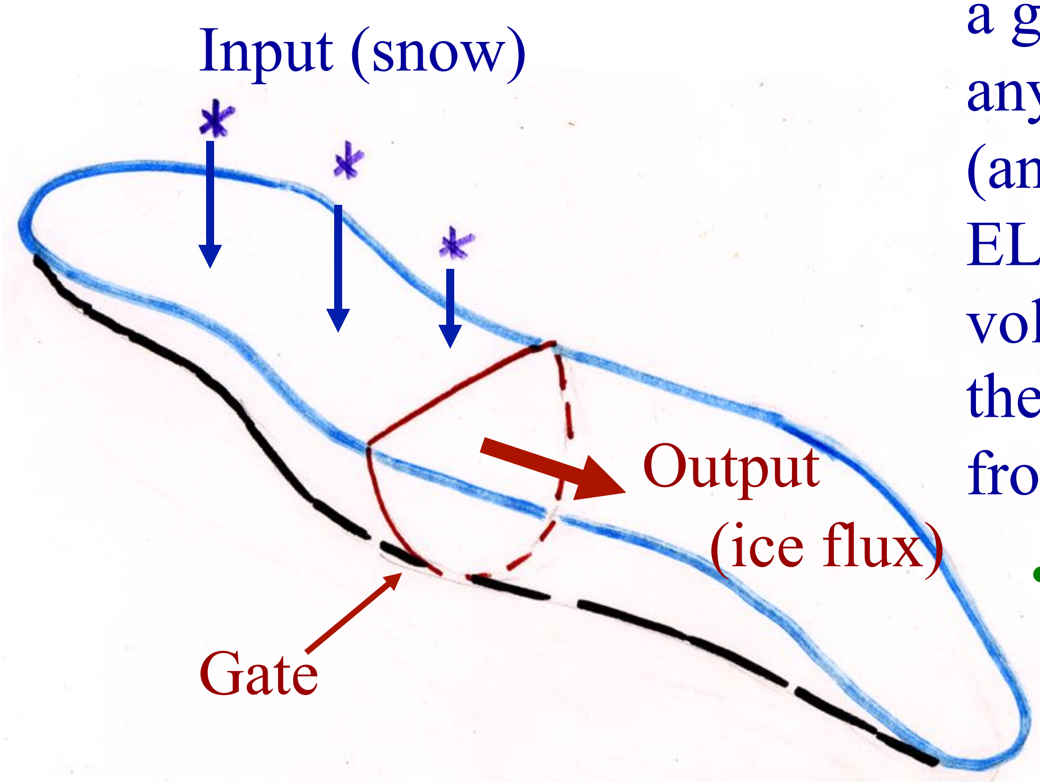
Dynamic perspective

- Describes ***why*** the body moves or changes (forces)

- Both of these concepts 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

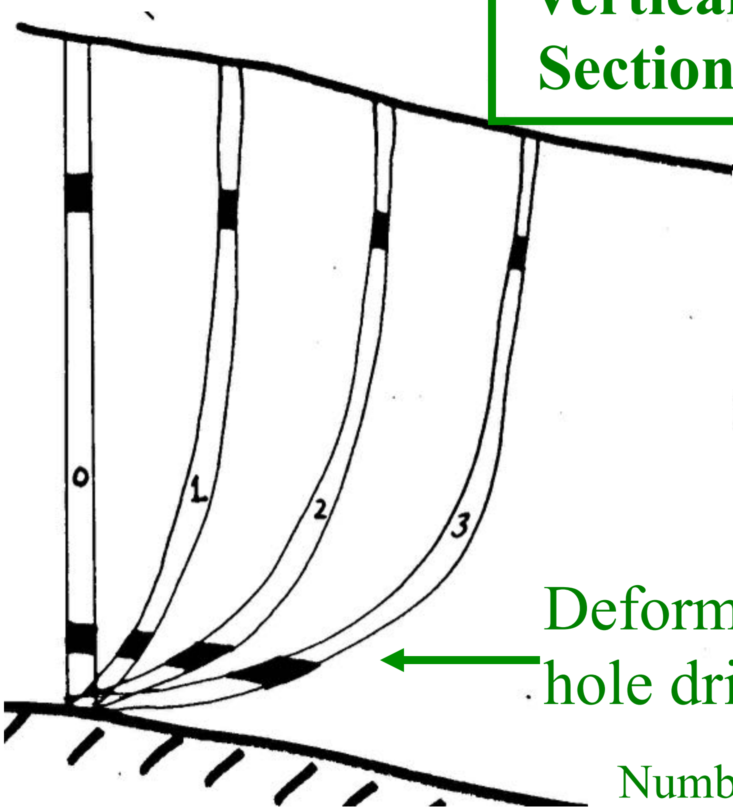
Money managers can view investments from a dynamic perspective too.

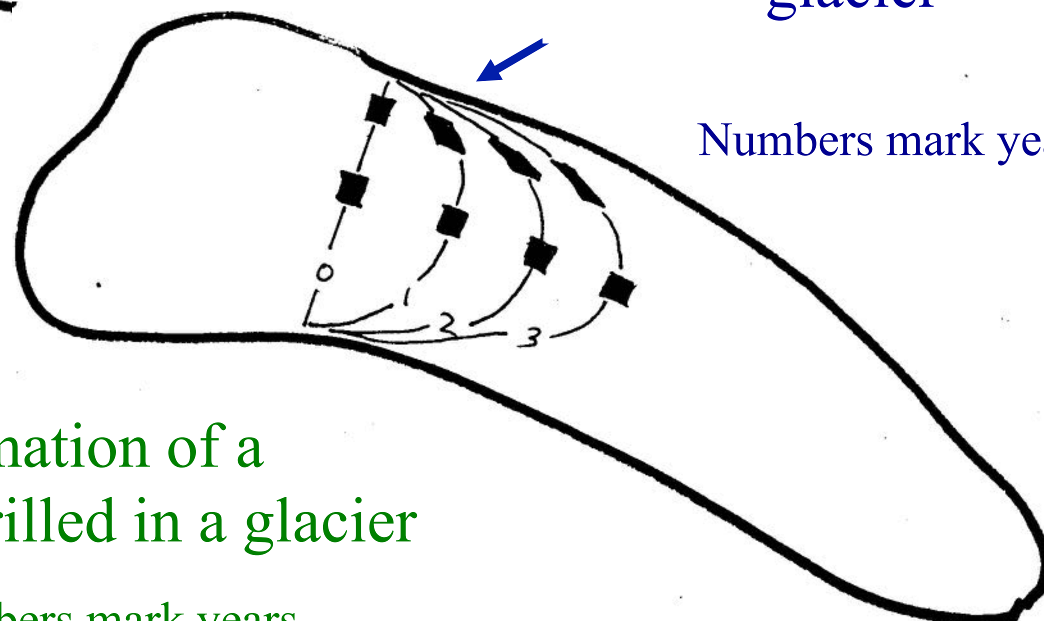
- They talk about "market ***forces***" and "***pressure*** on the dollar".
- Market forces control the rate at which money flows into an investment account. (e.g. through interest rates).
- Or the rate at which it disappears from my invetment portfolio. ☹

Dynamic View: How does speed vary on a glacier?

Drag or friction from the rock walls and bottom

- Speed increases as the distance from the bottom or from the valley wall increases





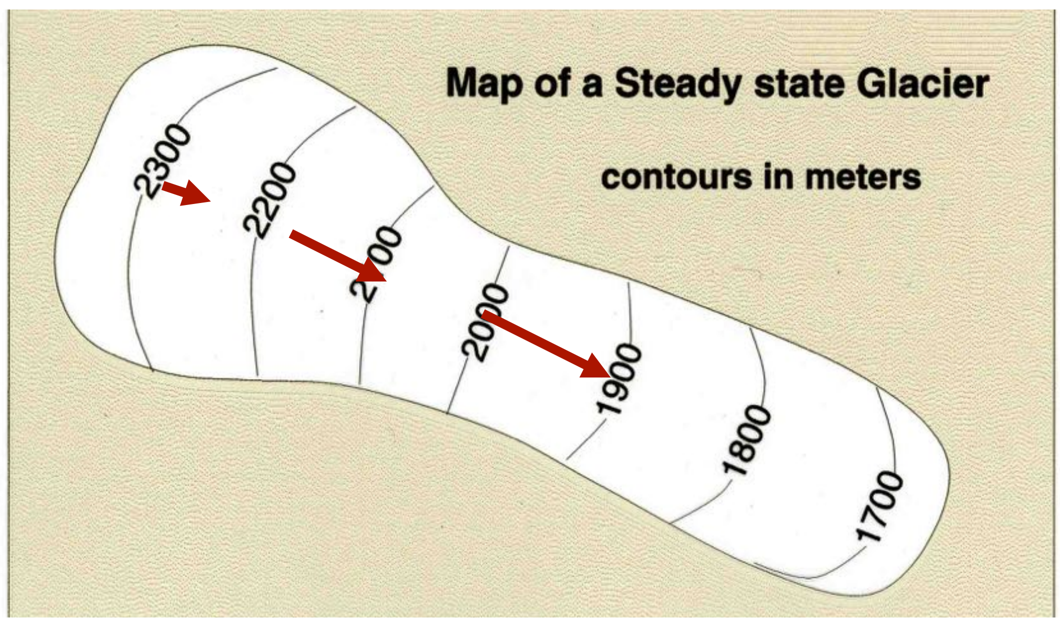
Longitudinal flow pattern in Accumulation area

Kinematic view

- Flow tends to be faster closer to the Equilibrium Line, because the amount of that 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.



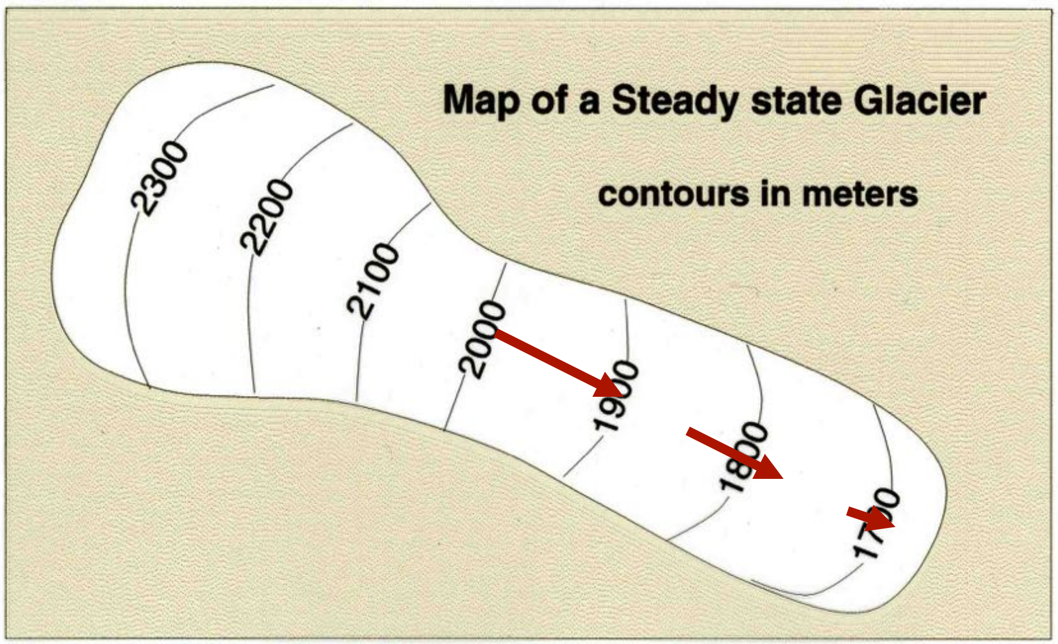
Longitudinal flow pattern in ablation area

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.



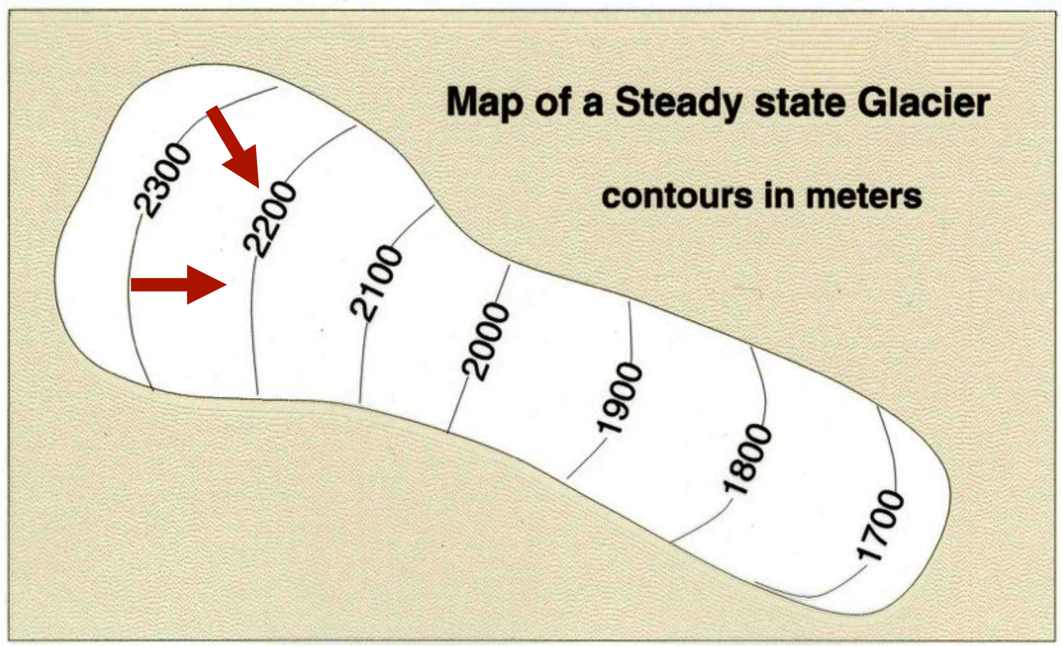
Transverse flow pattern in Accumulation area

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.



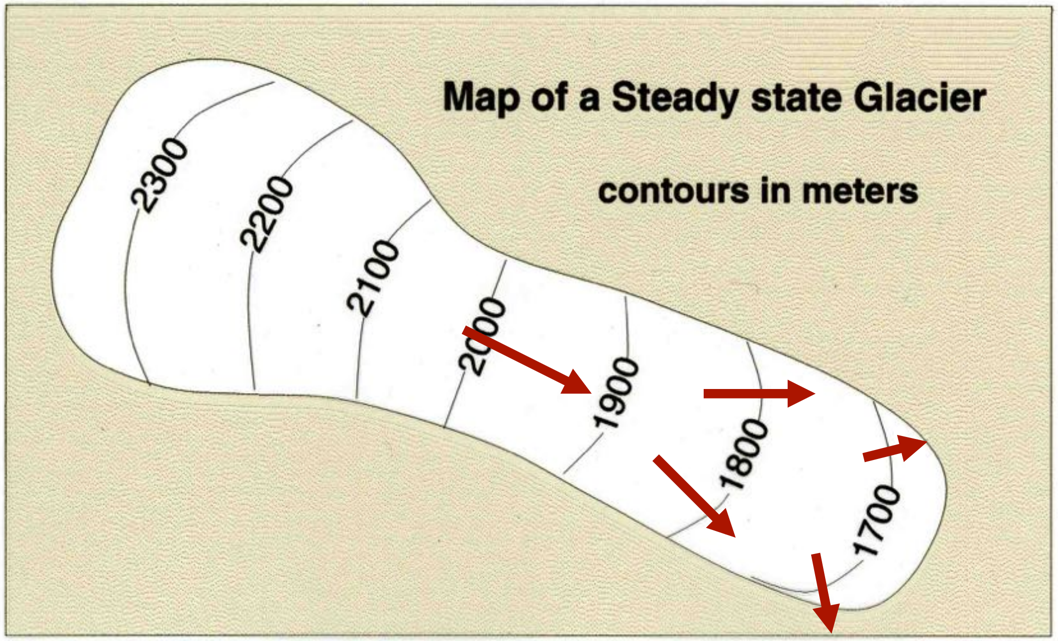
Transverse flow pattern in ablation area

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.



Glaciers and Climate Change

- How much does a glacier change when climate changes?

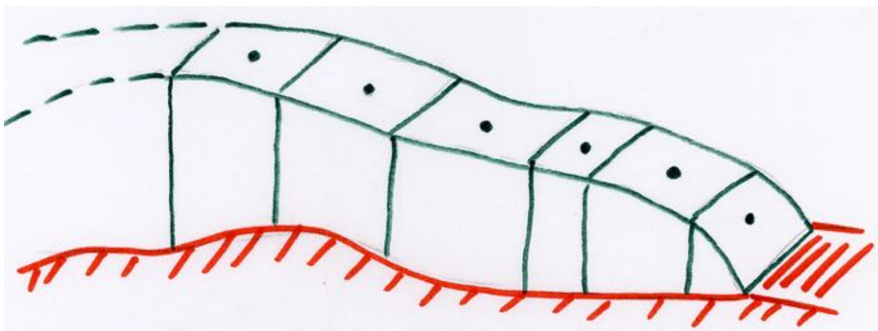
- Can we ask the question the other way around?
  - If we know how much a glacier changed, can we figure out how much the climate changed?

- Let's start with a simpler question.
  - Let's look at an ***abrupt*** climate change.
  - Climate jumps from one steady state to a different steady state.
  - Then climate stops changing.

Find the new steady-state Glacier

There will be a ***new steady-state thickness, length, and volume*** for the glacier.

- How will we find it?



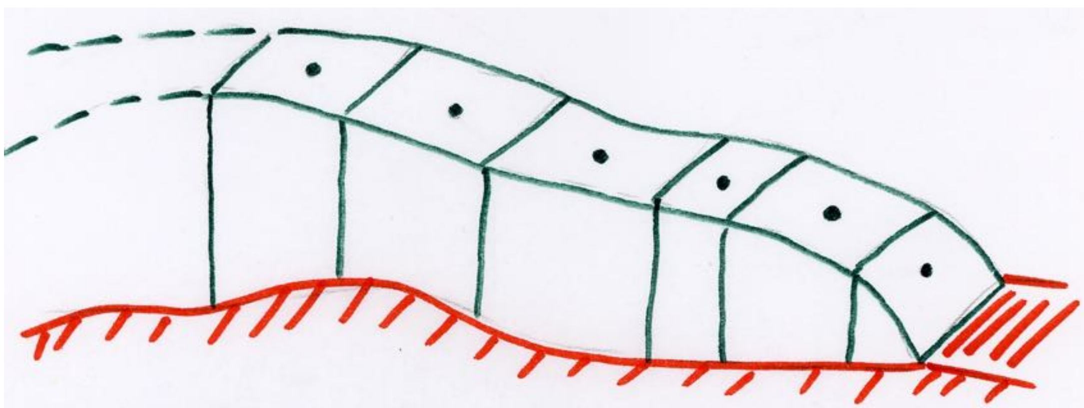
One approach

- Find the new accumulation and ablation-rate pattern under the new climate.

- Calculate ice flow from ice thickness, slope, and basal water pressure (dynamics).
- Calculate input and output for all the boxes (kinematics).
- Watch how the boxes thicken or thin, and see where the glacier will ultimately end under the new climate.

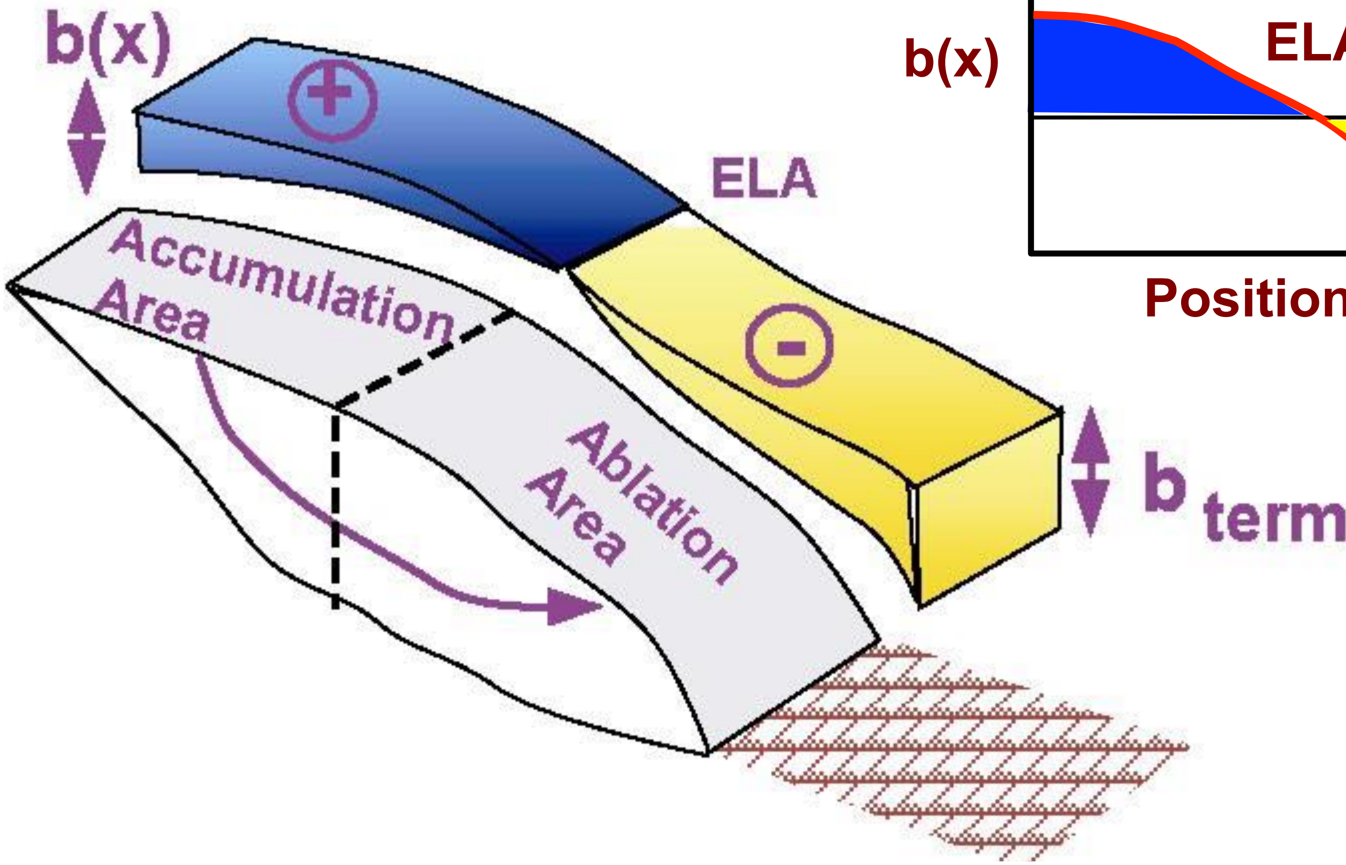
I don't want to do it …

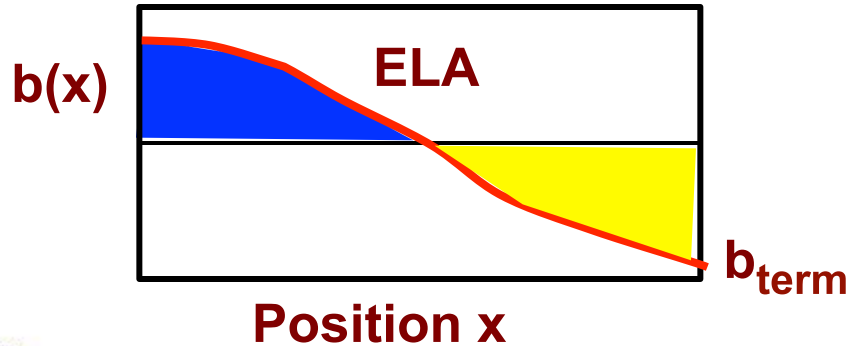
Building a big glacier flow model sounds hard.



- As curious scientists, let's do a simpler estimation problem instead …

Cartoon of Original Steady-State Glacier



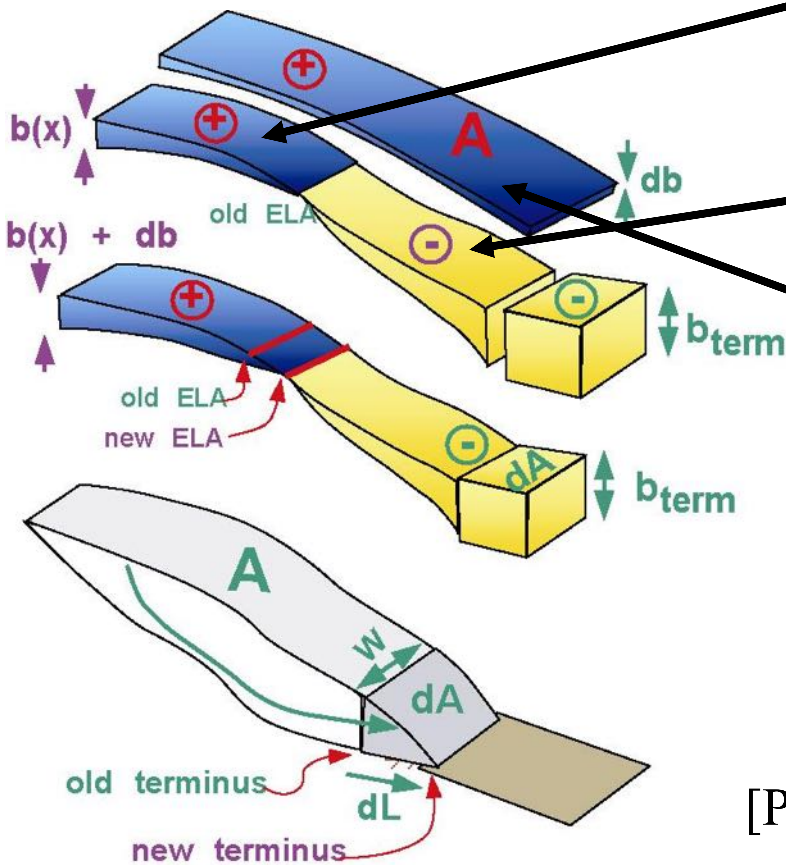


Volume added annually in accumulation area (+, blue slab)

is equal to volume removed from ablation area annually (-, yellow slab)

Now Climate Shifts to New State

We know the original mass balance (accumulation or ablation) *b*(*x*) at all places *x* along a glacier.



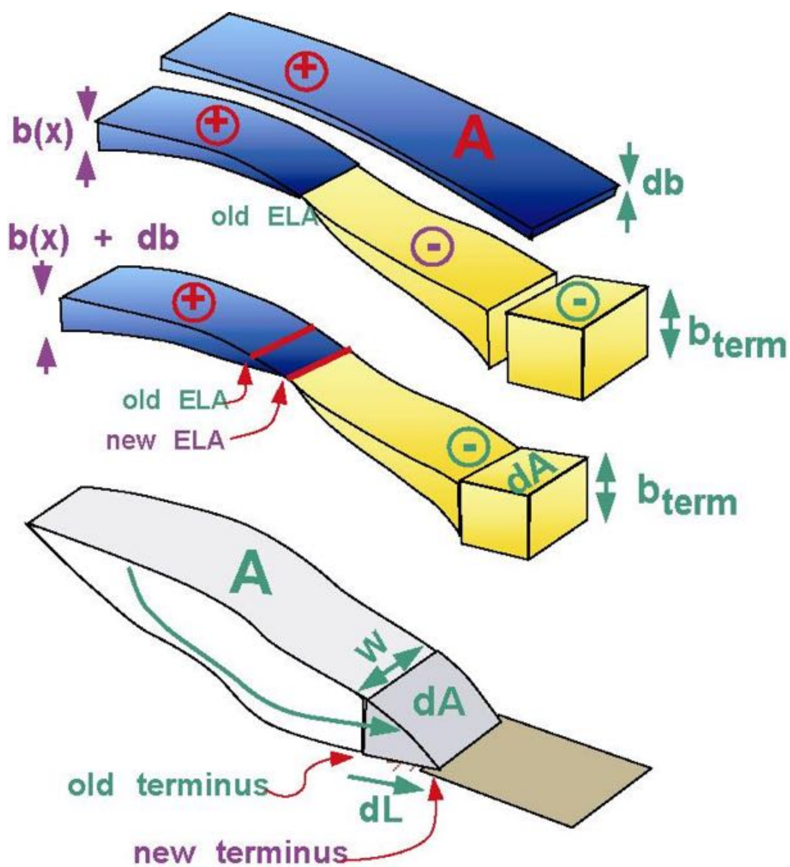
- b(*x*) > 0, we are in the accumulation area.
- b(*x*) < 0 we are in the ablation area.

Now *b*(*x*) increases by a small amount d*b* everywhere due to climate shift (I am using d*b* to indicate a *change* in b, or a ***d****ifference* in b).

$$b(x) \rightarrow b(x) + db$$

[Please forgive me if this sounds like calculus – just focus on thinking about the ideas ☺]

What happens to glacier length?



If db > 0:

- More snow in accumulation area.
- Less melting in ablation area.
- Glacier gets thicker.
- Glacier terminus will advance, and cover additional area dA

If db < 0:

- Less snow in accumulation area.
- More melting in ablation area.
- Glacier gets thinner.
- Glacier terminus will retreat, and expose a new area dA of bedrock.

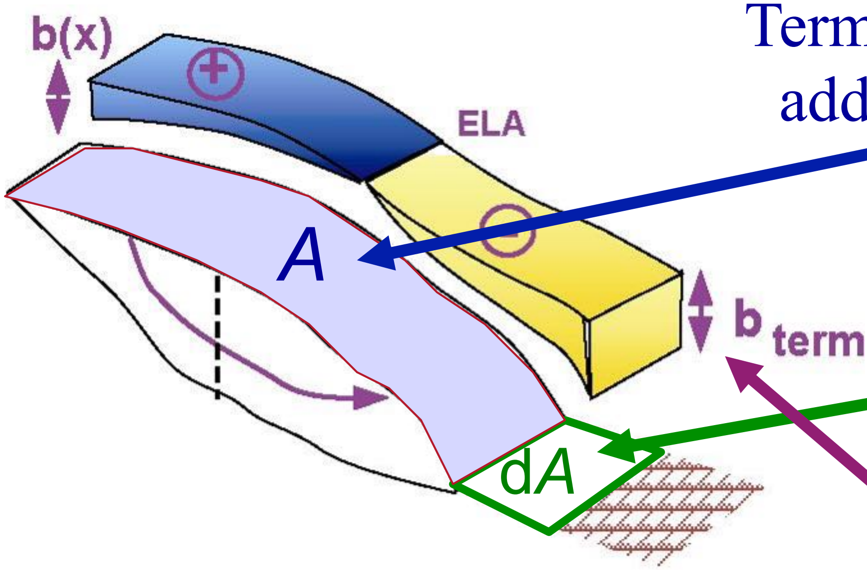
(Ice stills flows forward, but "glacier conveyor belt" is shorter.)

If d*b*>0, Glacier Advances …

Original steady-state glacier covered some area "*A*".

Terminus now extends to cover some additional area.

- We call this (as yet unknown) additional area "d*A*".



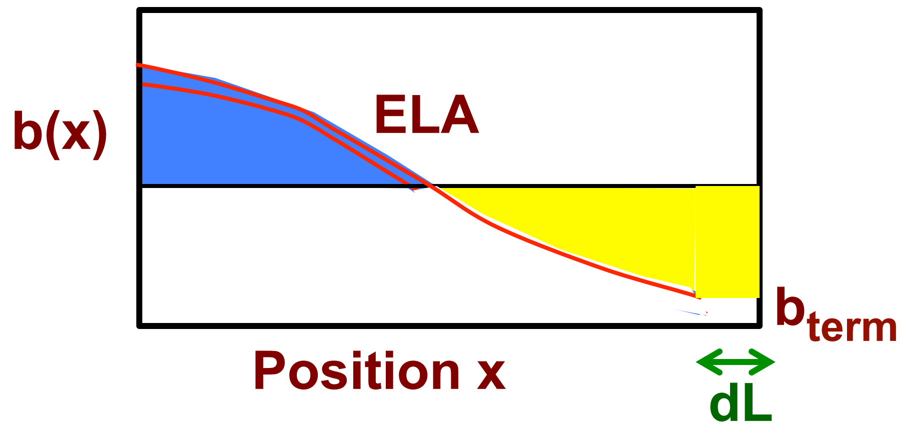
Every year, some ice melts off in this new area.

How much ice melts off each year in this newly created part of the expanded glacier?

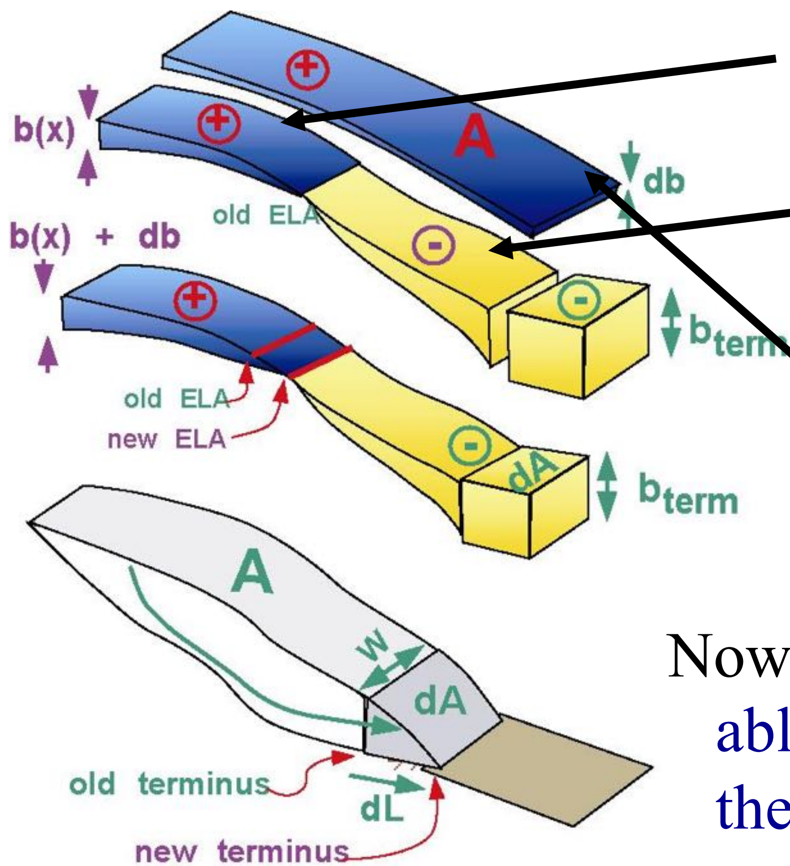
- It is the ablation rate at the terminus, called "b_{term}".
- (We measured it by measuring the height of an emerging pole each year.)

How much ice is melted off *in total* on this new area every year? We will see …

OK. Let's do that again …



We know the original mass balance (accumulation or ablation) b(x) at all places x along a glacier.



- b(x) > 0 we are in the accumulation area.
- b(x) < 0 we are in the ablation area.

Now $b(x)$ increases by a small amount d**b** everywhere

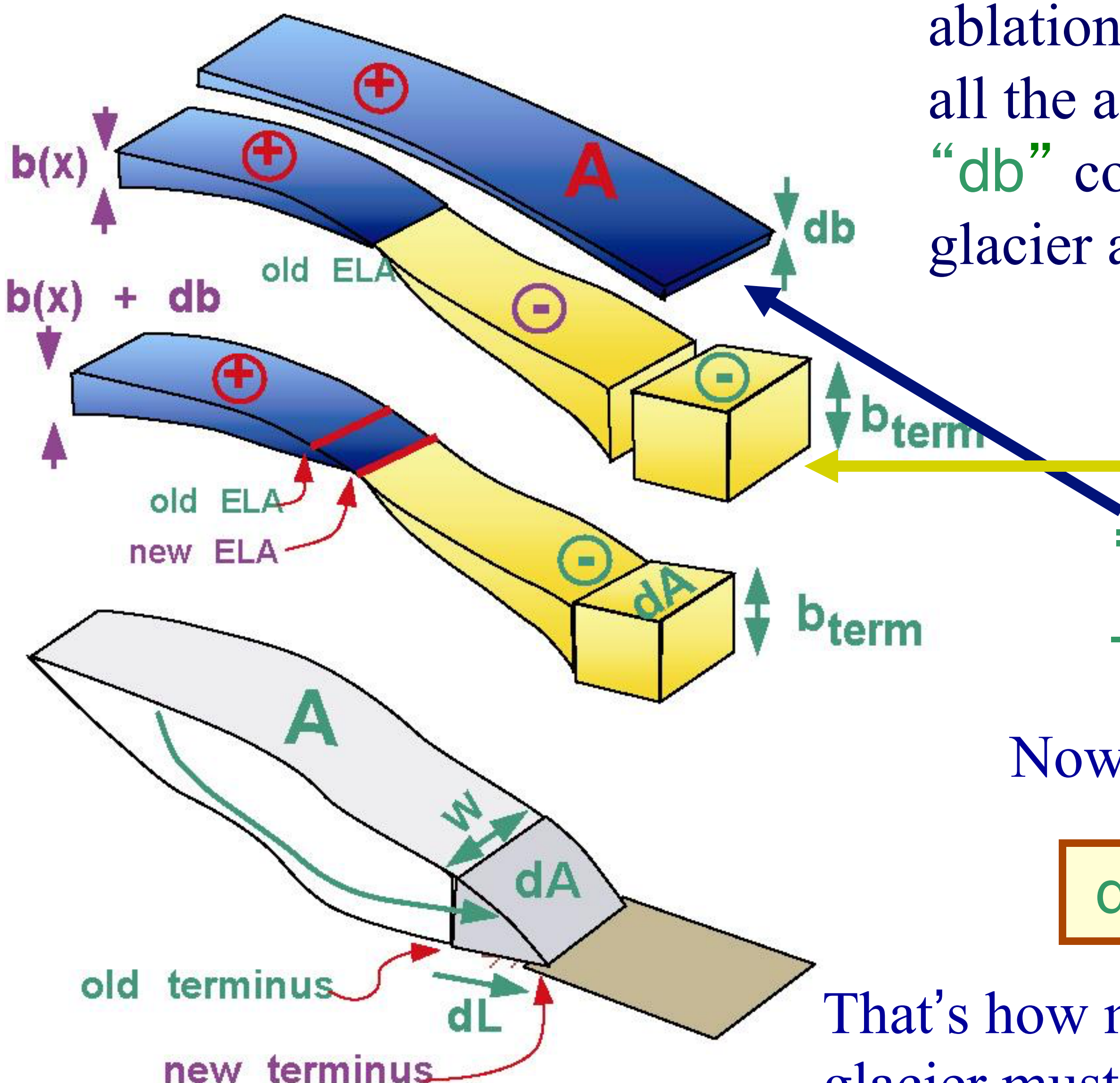
$$b(x) \rightarrow b(x) + d\mathbf{b}$$

Now there is more accumulation (blue) than ablation (yellow), so glacier advances until they are equal again.

I thought this was not a math course!!! Why are you doing this to me?

- The goal is to show you how ***you*** can figure out answers to some very fundamental questions about climate change.
- Whether you want to be a scientist, or whether you prefer to be a social anthropologist, studying an exotic tribe of *Homo Sapiens* called "the Curious Scientists", seeing how they think is key to understanding what they do, and assessing their results.
- To answer a very complex and difficult question, members of the Curious Scientists Tribe will first try to formulate a simpler question whose answer they can get more easily.
- In this case, they are replacing partial differential equations and big computer models with a couple of multiplications and divisions.

Area Change



Additional area "dA" must be large enough so that the ablation there "b_{term}" can melt all the additional accumulation "db" collected upstream on the glacier area "A", every year.

Extra volume melted
= extra volume added

$$- b_{term}\, dA = A\, db$$

Now divide by $-b_{term}$ …

$$dA = - A\, db / b_{term}$$

That's how much more ground the glacier must cover for new state.

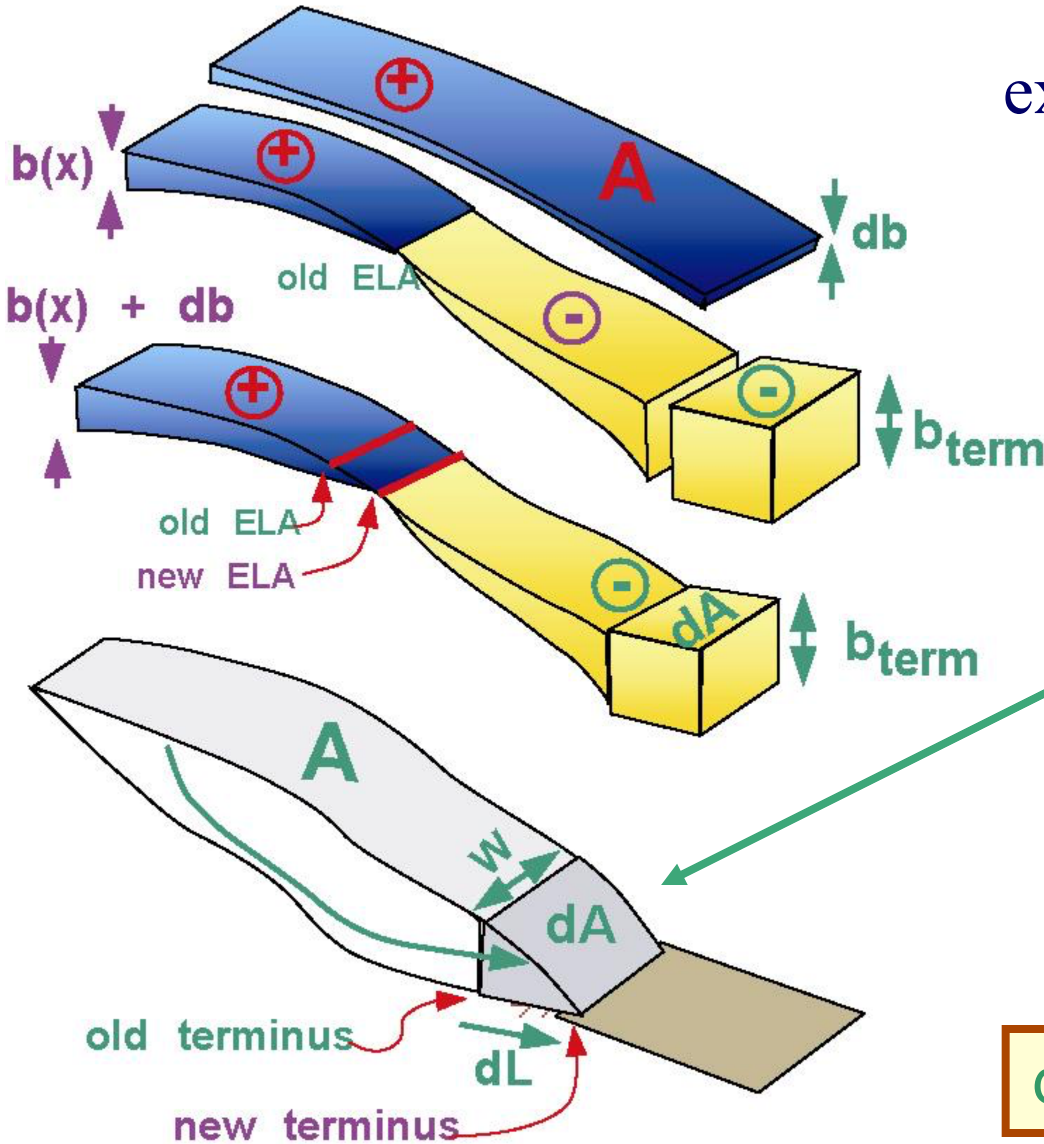
Length Change

$$dA = -A\, db / b_{term} \quad (1)$$

We can also describe the expanded glacier in terms of how far its terminus advances.

We can describe the new area dA in terms of its length dL and width W_{term}

$$dA = W_{term} \times dL \quad (2)$$



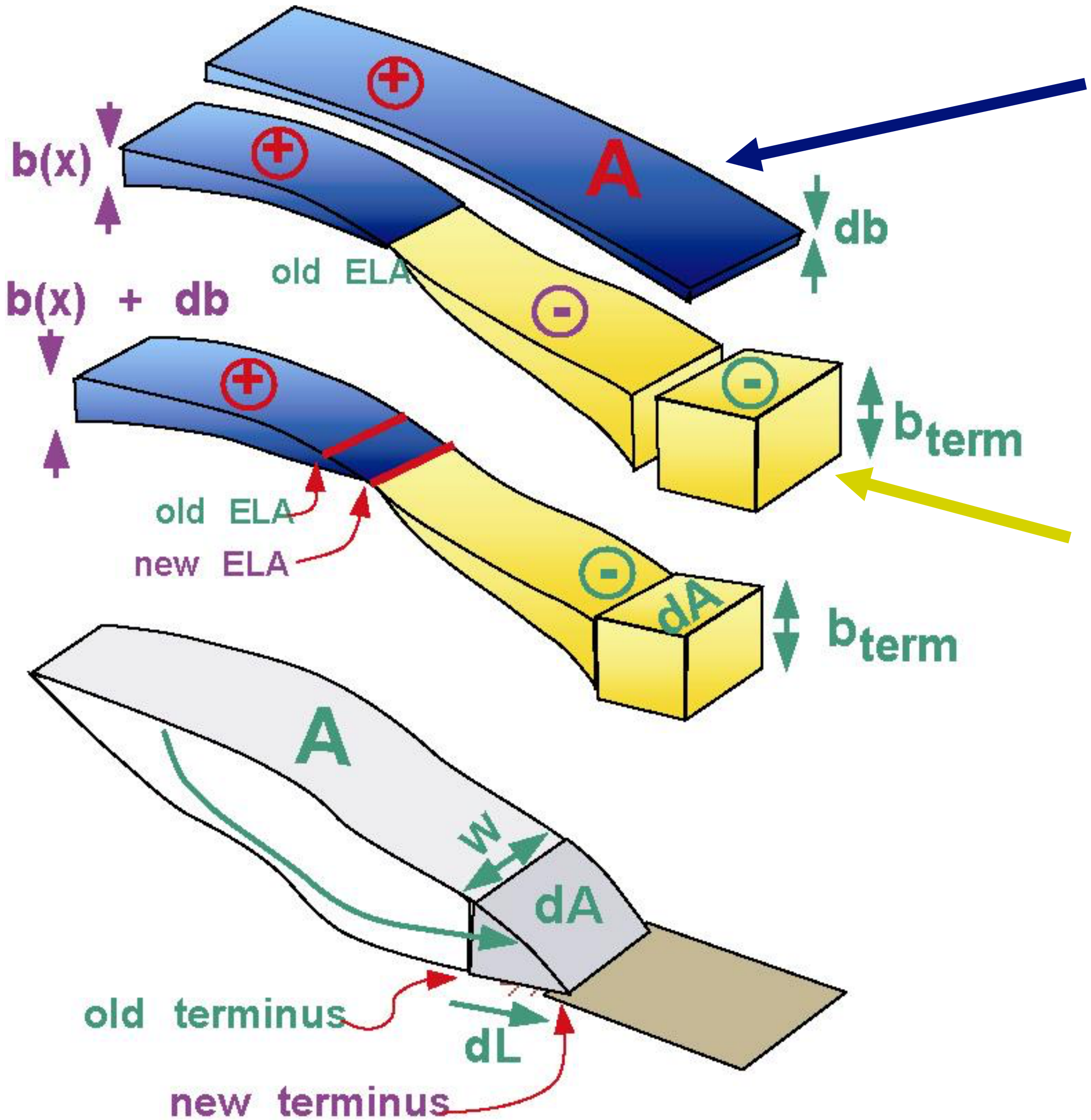
Equate (1) and (2)

$$W_{term} \times dL = -A\, db / b_{term}$$

then divide by W_{term}

$$dL = -A\, db / (W_{term} \times b_{term})$$

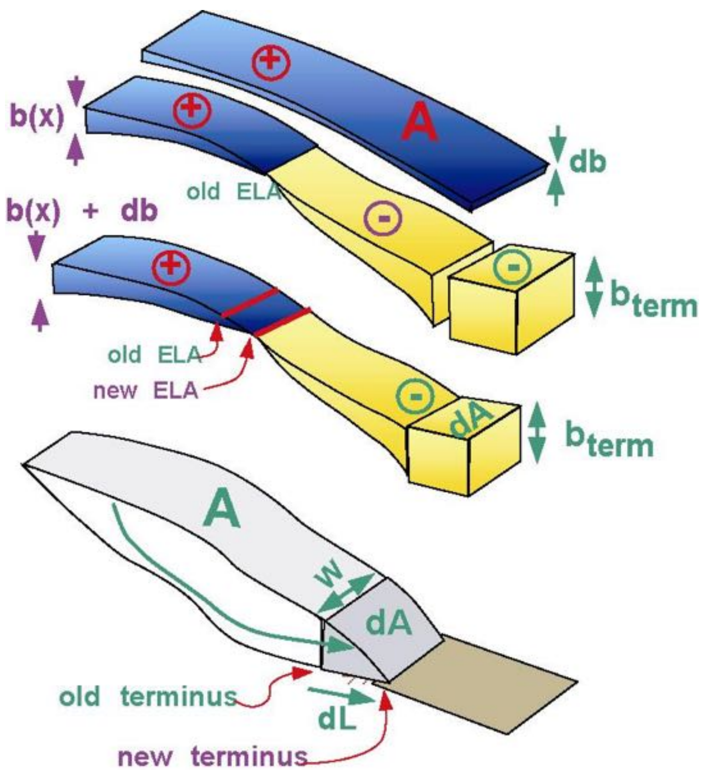
What did we do?



All we have really done is say that this slab (extra ice added or retained annually by the climate change)

has the same volume as this box (the additional melting loss each year at the extended terminus).

Curious Scientists –always askng questions …
How do glaciers respond to climate change?



$$dL = -\left(\frac{A \times db}{W_{term} \times b_{term}}\right)$$

Your group's task: Think about each factor in the numerator or denominator, and see whether its presence there makes sense to you.

For example, db, the size of the climate shift is in the numerator. That means that a larger climate change db causes a larger glacier advance dL. For example, if db doubles, then dL also doubles. Or hit the glacier with a bigger climate change (db), and the glacier advances farther (dL). Does that make sense?

Now think about the other 3 factors, i.e. A, W_{term}, and b_{term}.

Questions for Break-out rooms:
https://docs.google.com/document/d/15IhlMO8YU9jH2NIz2bSNy59fcC8cgXgsjX11WBiXpGQ/edit#heading=h.5spg5w2dqiai