# What processes have controlled Earth's climate at time scales of millions to billions of years?

Earth is 4.5 billion years old

To this point:

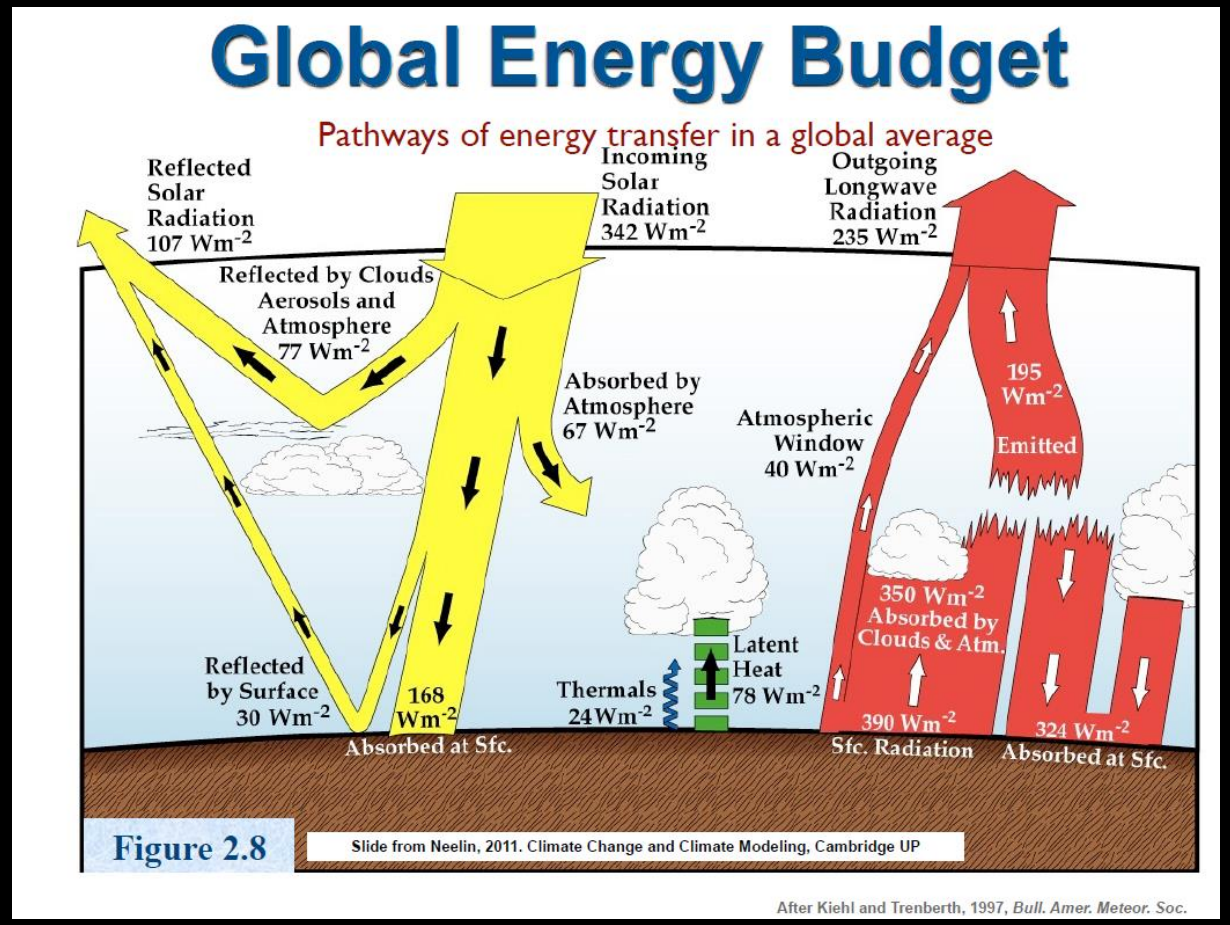
1) Earth's greenhouse effect is powerful.

How much does the greenhouse warm Earth?

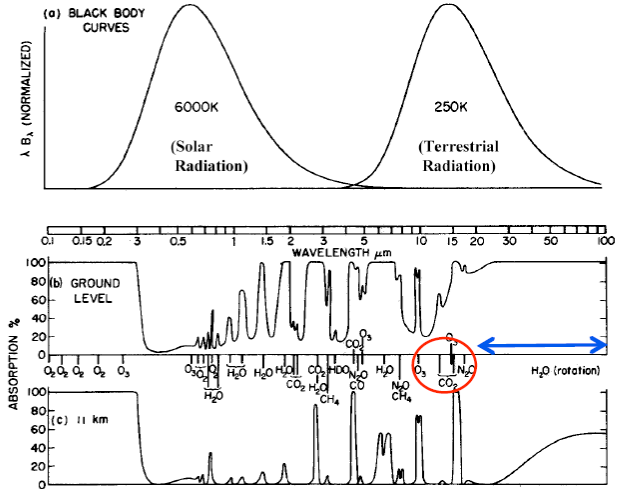
At present, roughly 30% of the incoming solar radiation is reflected back to space by the clouds, aerosols, and the surface of Earth.

Without naturally occurring greenhouse gases, Earth's average temperature would be near 0°F (or -18°C) instead of the much warmer 59°F (15°C).

# processes underlying Earth's radiation budget




## Wien's Law: Wavelength of maximum emission inversely proportional to Temperature




- Visible not absorbed
- Ozone absorbs most incoming solar radiation
- 4 micron break
- $CO_2$ vibration-rotation absorption key wavelength
- Water vapor absorption between 12-100 microns

*Atmospheric absorptions. (a) Blackbody curves for 6000 K and 250 K. (b) Atmospheric absorption spectrum for a solar beam reaching ground level. (c) The same for a beam reaching the temperate tropopause. The axes are chosen so that areas in (a) are proportional to radiant energy. Integrated over the earth's surface and over all solid angles, the solar and terrestrial fluxes are equal to each other; consequently, the two blackbody curves are drawn with equal areas. Conditions are typical of mid-latitudes and for a solar elevation of 40° or for a diffuse stream of terrestrial radiation.*

Figure 04

You can imagine that radiation is NOT easy to model!

*comparison with Venus*

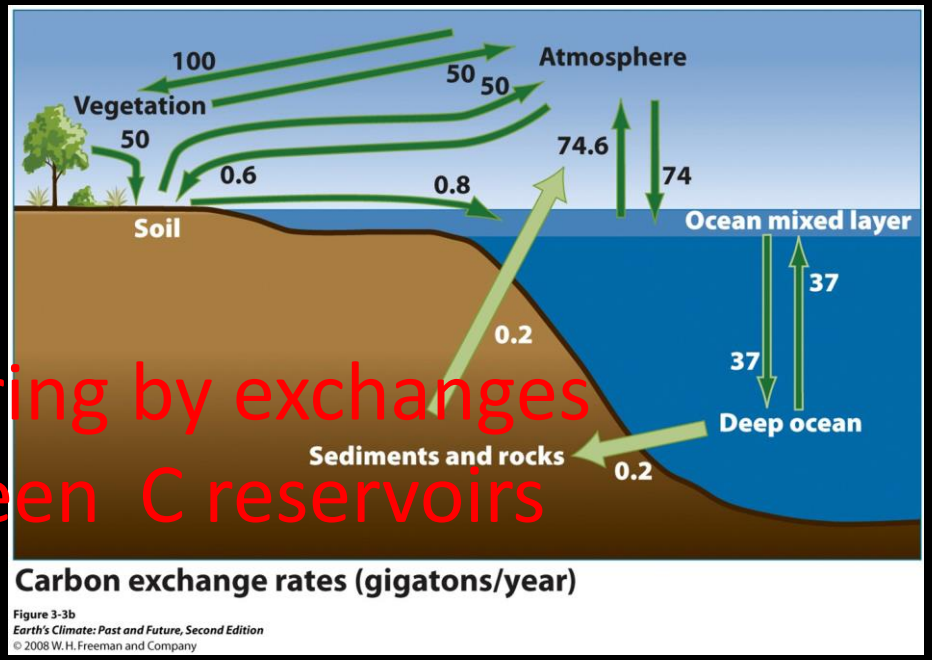
0.8 albedo

96% of atmosphere is $CO_2$

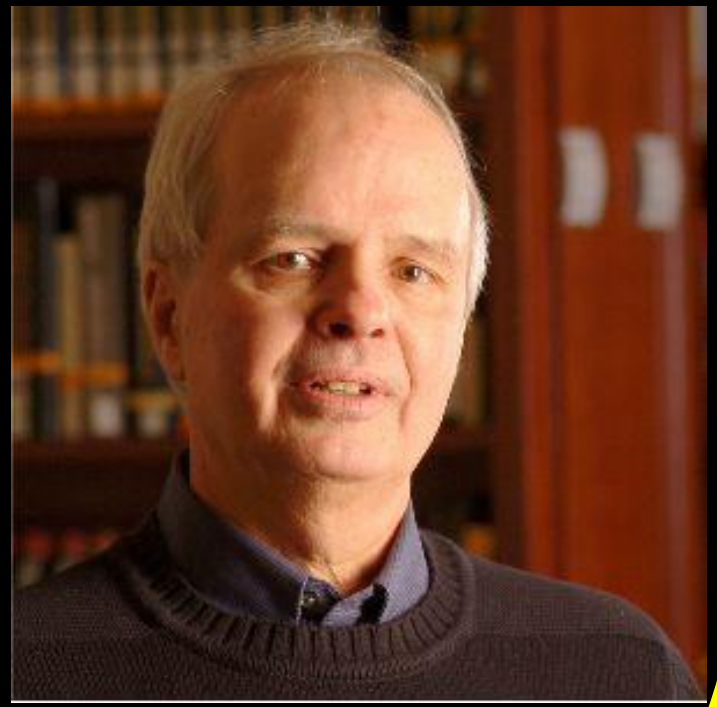
285° C greenhouse effect

# 2) Volcanism can strongly affect Earth's climate over shorter time scales (years to centuries) but not over longer time scales (millennial to millions of years)

buffering by exchanges between C reservoirs




# But why can't volcanism be the controller of Earth's long-term climate dynamics? No feedback mechanism



Ruddiman says...."no way"
because.

1) The other C reservoirs blunt the effects of changes in volcanism

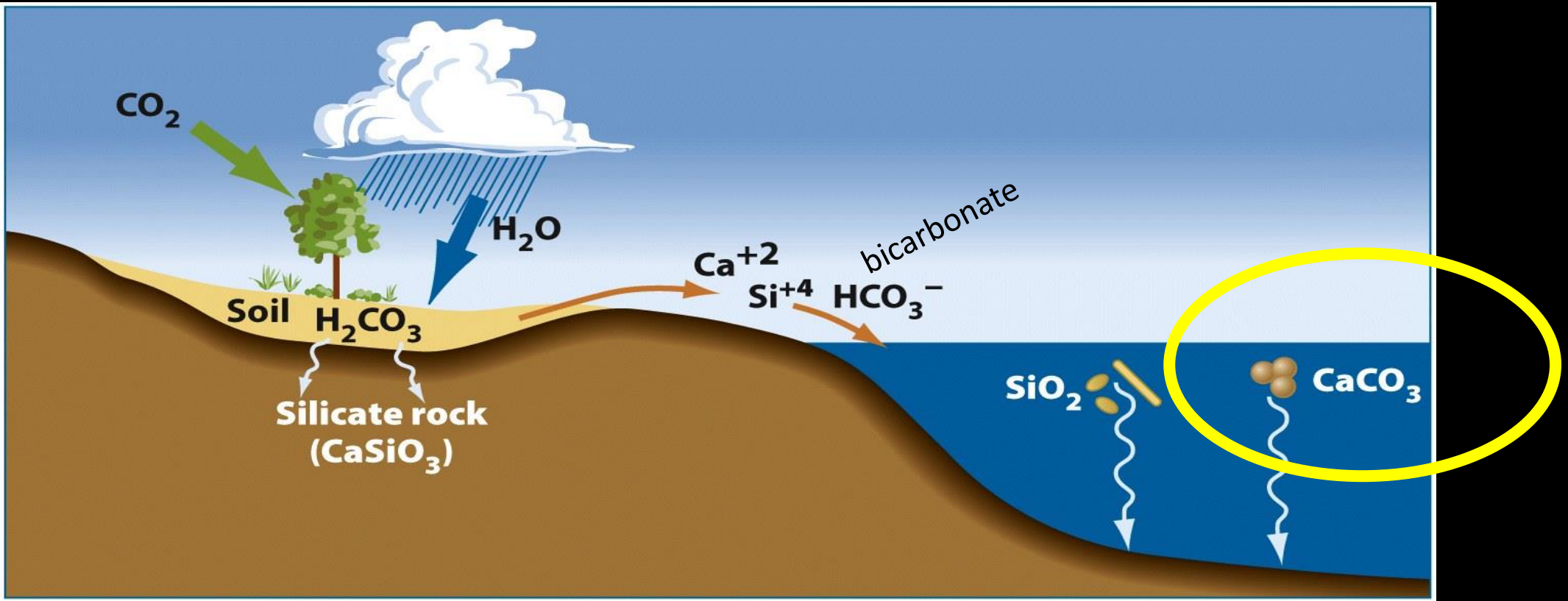
2) Climate happens above ground, and volcanism is driven by processes deep in Earth's interior.

...which means there is no basis for a thermostat involving volcanism.

# Chemical Weathering Hypothesis:

## Does silica-mineral weathering control the global thermostat?

# Chemical Weathering Hypothesis based on the Urey Reactions




$CaSiO_3$ + $H_2CO_3$

Silicate bedrock + Carbonic acid in soils

Weathering on land

$Ca^{+2}$ $Si^{+4}$ $HCO_3^-$

Ions dissolved in river water

Transport in rivers

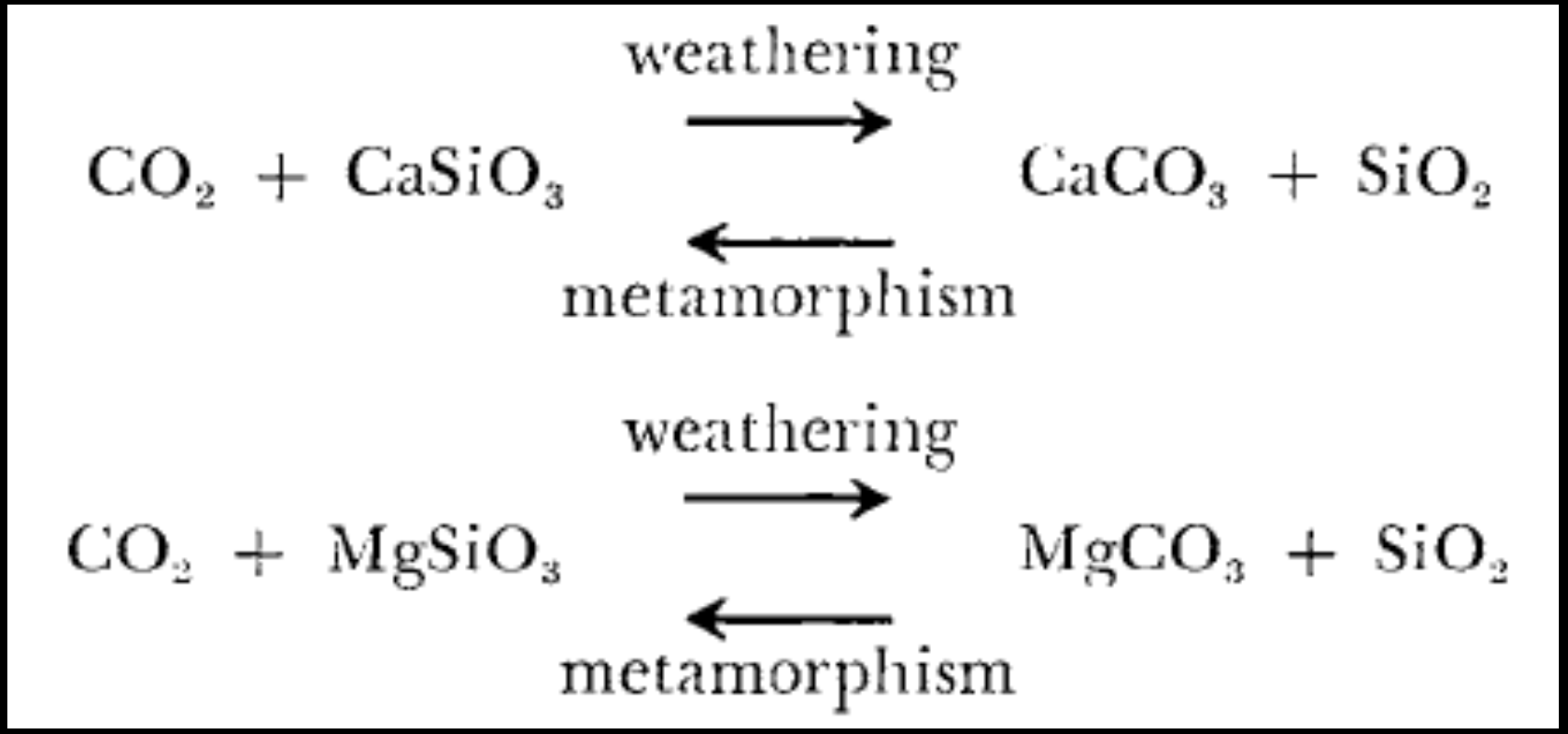
$SiO_2 + CaCO_3$

Shells of ocean plankton

Deposition in ocean

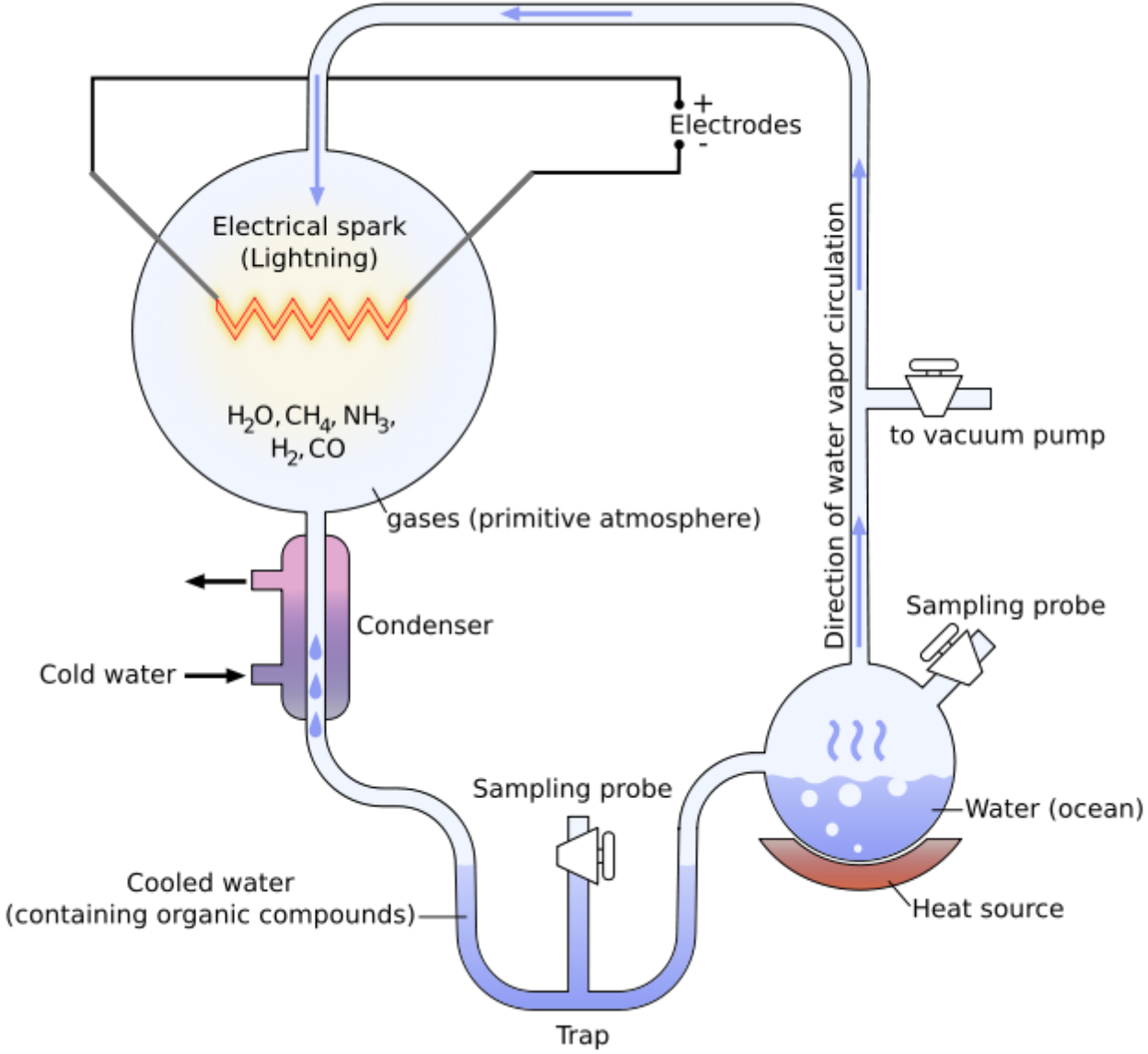
Figure 3-5
*Earth's Climate: Past and Future, Second Edition*

# The Urey Reactions (the chemical weathering hypothesis)




Urey, H. C., 1952, The Planets, Their Origin and Development: New Haven, Yale Univ. Press, 245 p.

Harold Urey




The Miller-Urey Experiment

# Is this (the Chemical Weathering Hypothesis) the crucial, global thermostat?

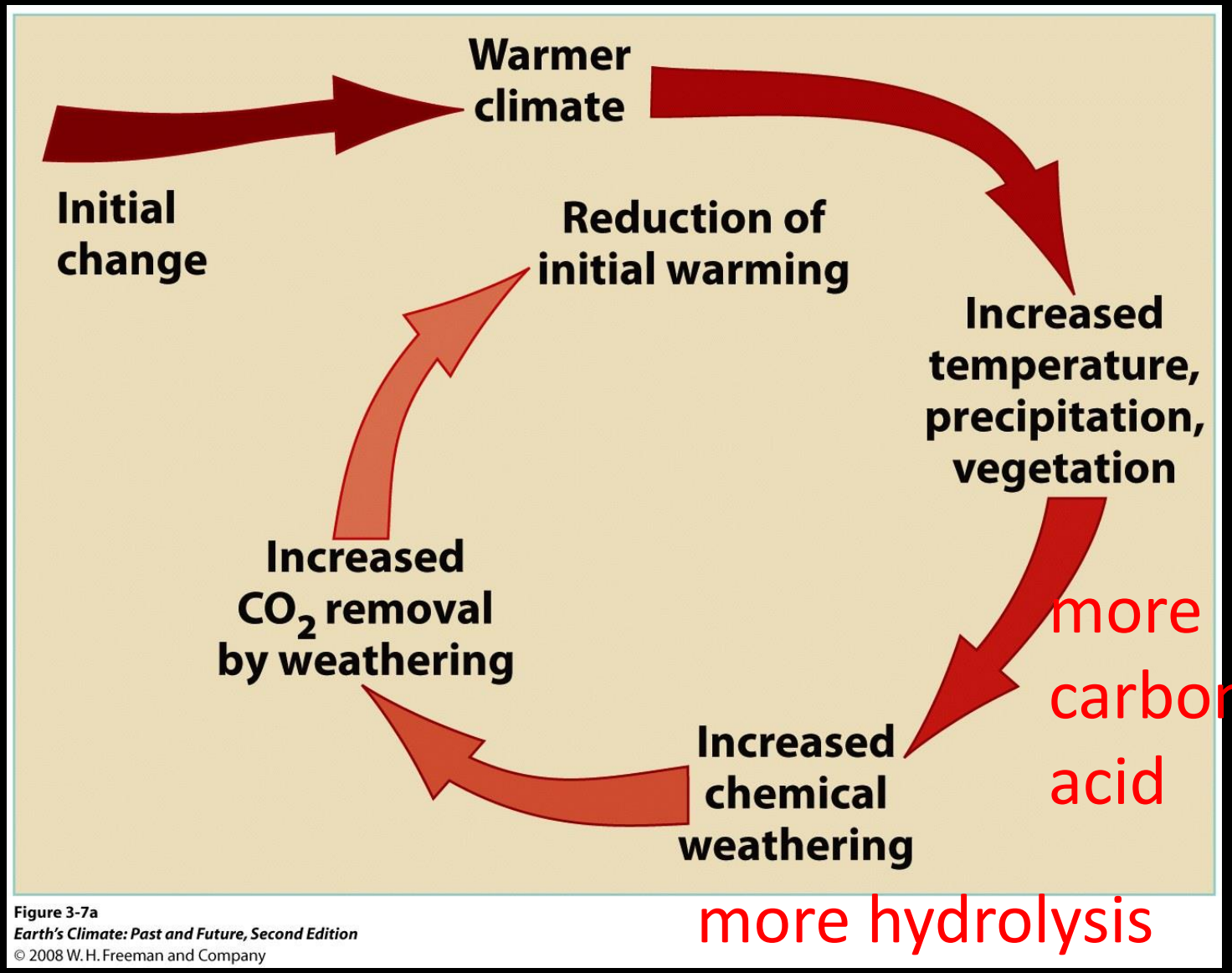



Figure 3-7a
*Earth's Climate: Past and Future, Second Edition*

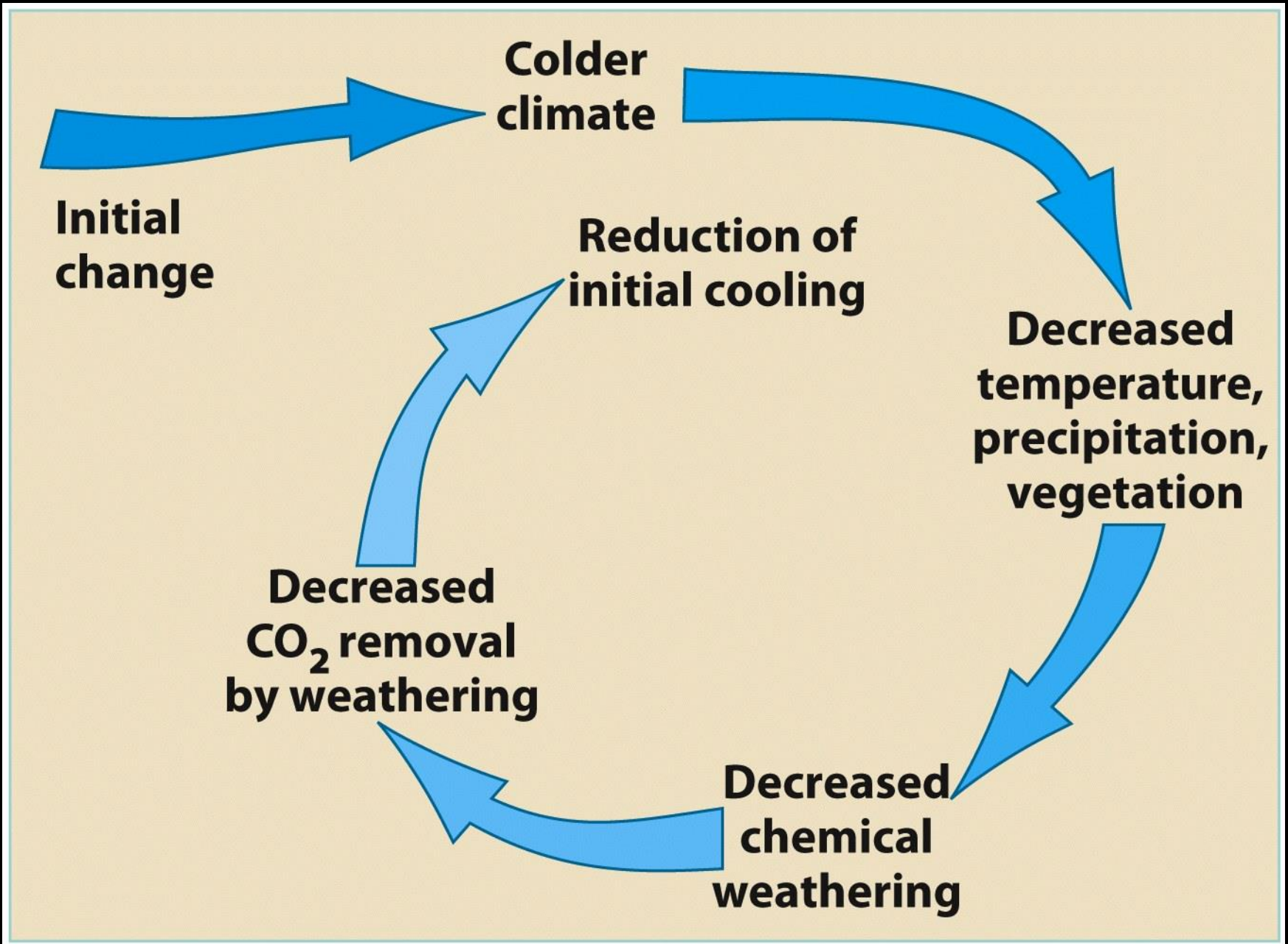
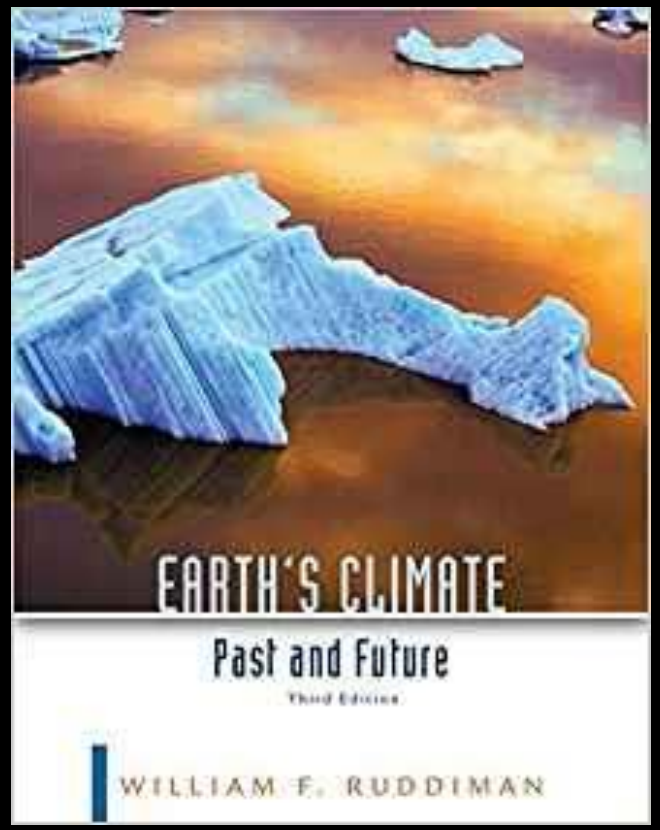



**Figure 3-7b**
***Earth's Climate: Past and Future, Second Edition***

# But there must be more to it than simply rock weathering….the Earth is tectonically dynamic.

# Chapter 5. Plate Tectonics and Long-Term Climate




We Are Here

We are looking for Earth's thermostat.

## $CO_2$ + *What Else?*

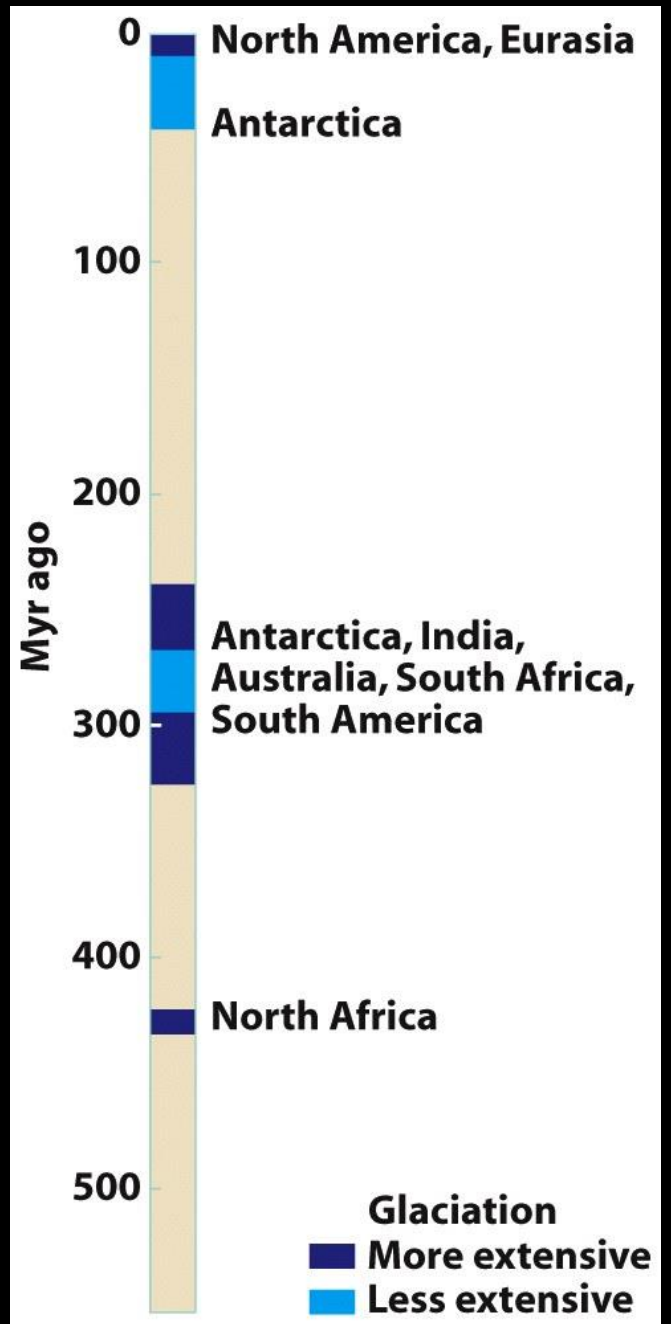



Figure 4-1
*Earth's Climate: Past and Future, Second Edition*


A natural experiment in climate change:

global glaciations during the past 550 my

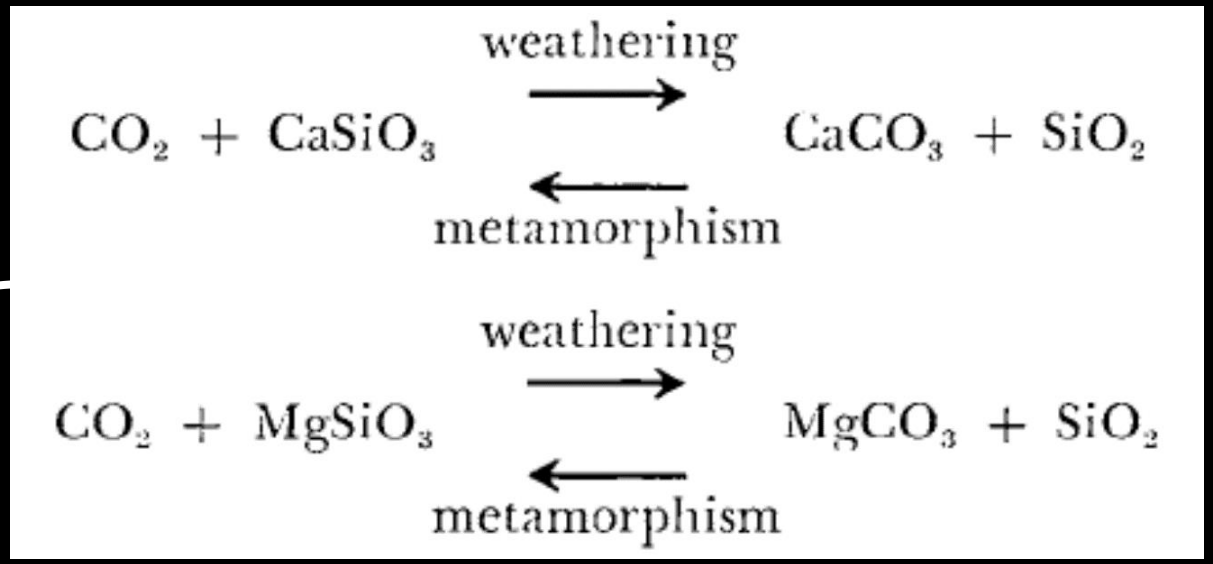
What caused them?

# How do plate tectonics interact with silicate weathering to affect climate?


Is $CO_2$ the global thermostat,
and tectonics the finger that pushes it?

global tectonics

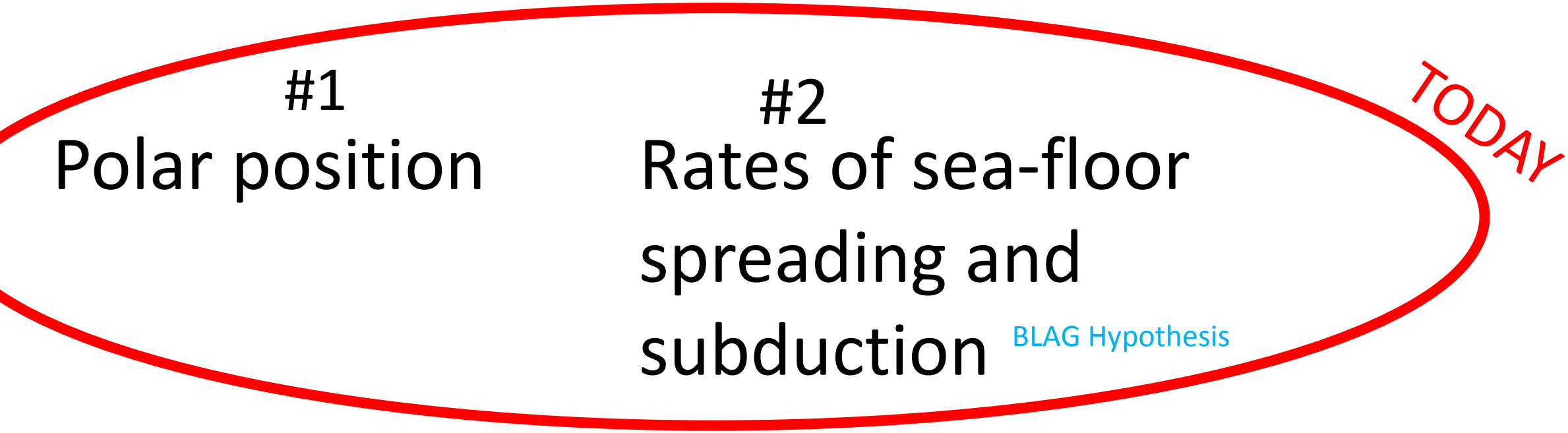
Urey reactions




$CO_2$ in atmosphere

climate

# Tectonics as a contributing factor to Earth's long-term climate




#3
Mountain building

Wednesday

Could the geographic positions of tectonic plates determine the timing of ice ages?

1. Where were the plates when glaciation occurred?

2. Do global climate models support the idea that plate positions make a difference to global climate?

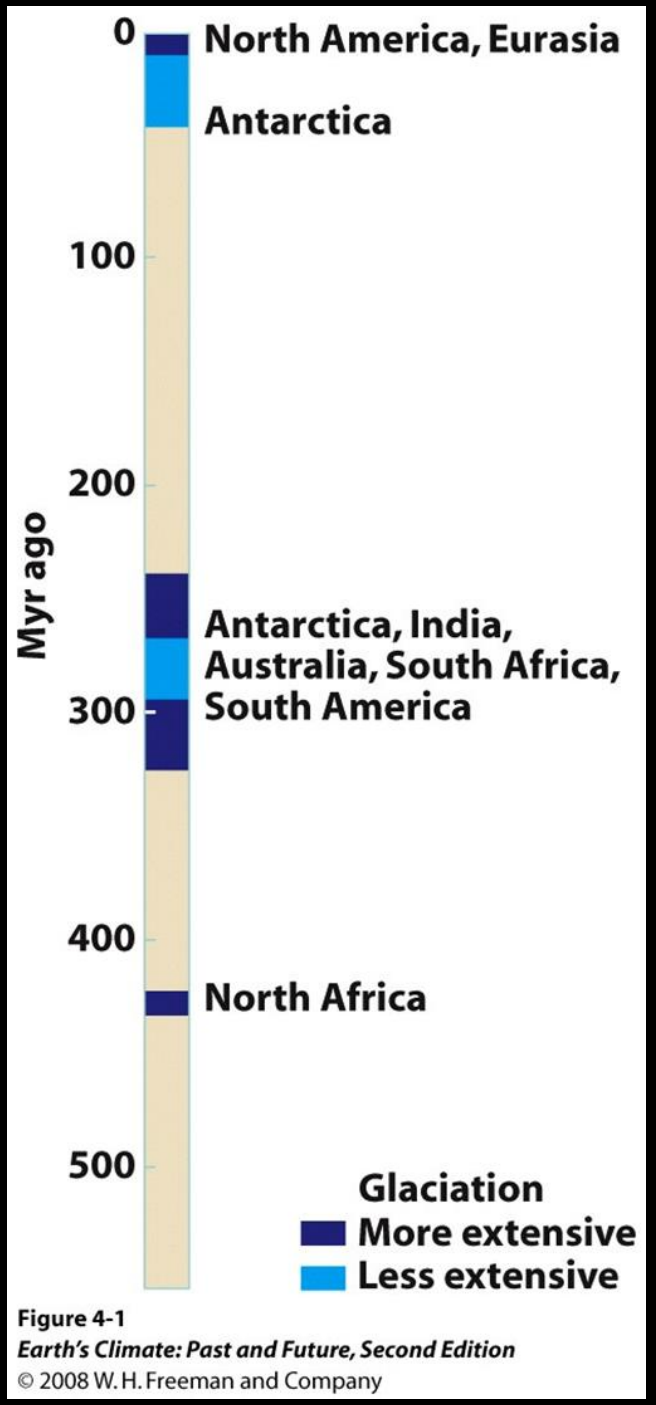



Figure 4-1
*Earth's Climate: Past and Future, Second Edition*

Deep Review

# Earth's structure

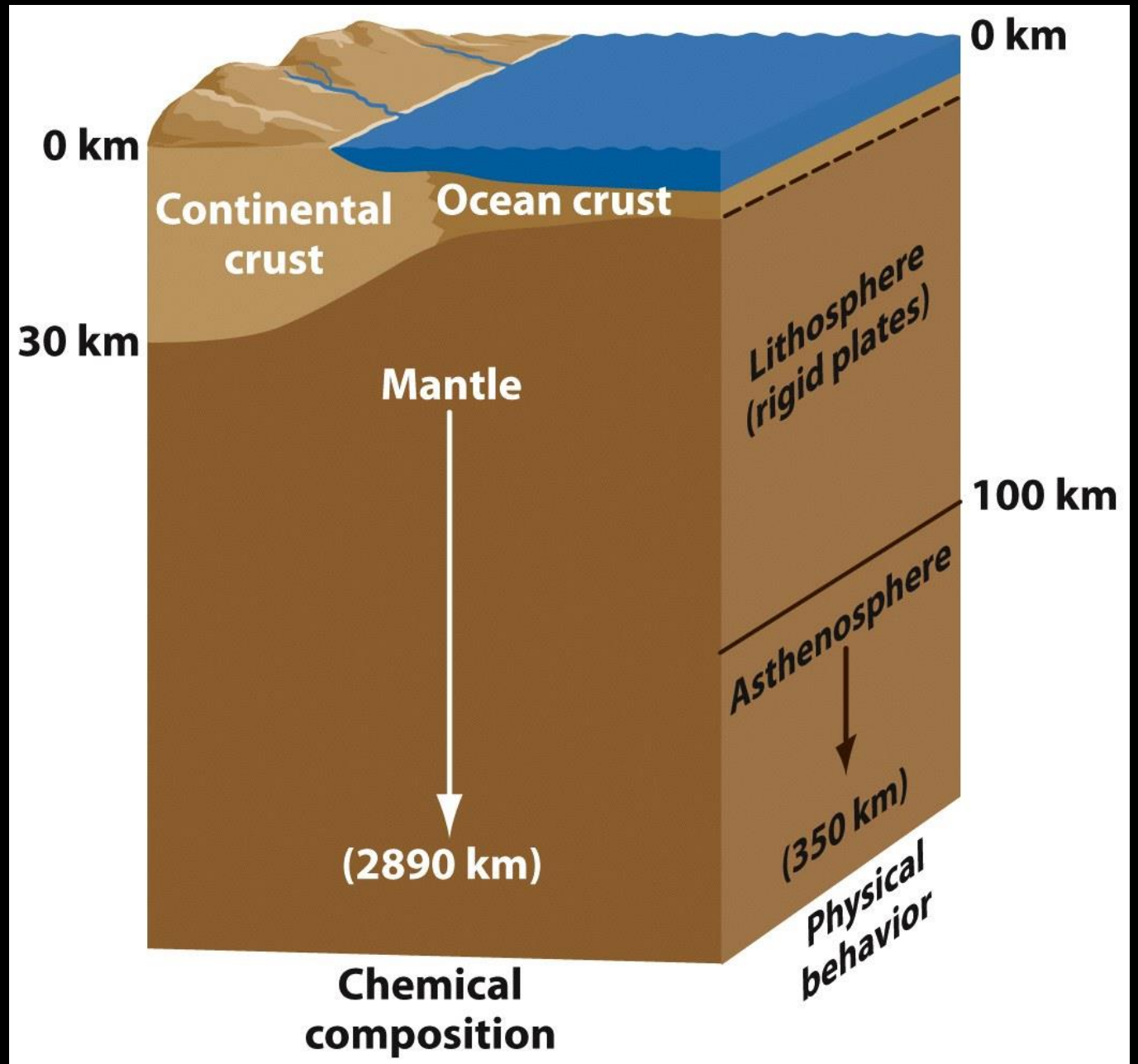



Figure 4-2
*Earth's Climate: Past and Future, Second Edition*

Si-rich,
andesite/granitic
+
sedimentary
*2.7 g/cm3*

*3.3 g/cm3*

rigid

ultramafic:
abundant iron,
low silica

flowing

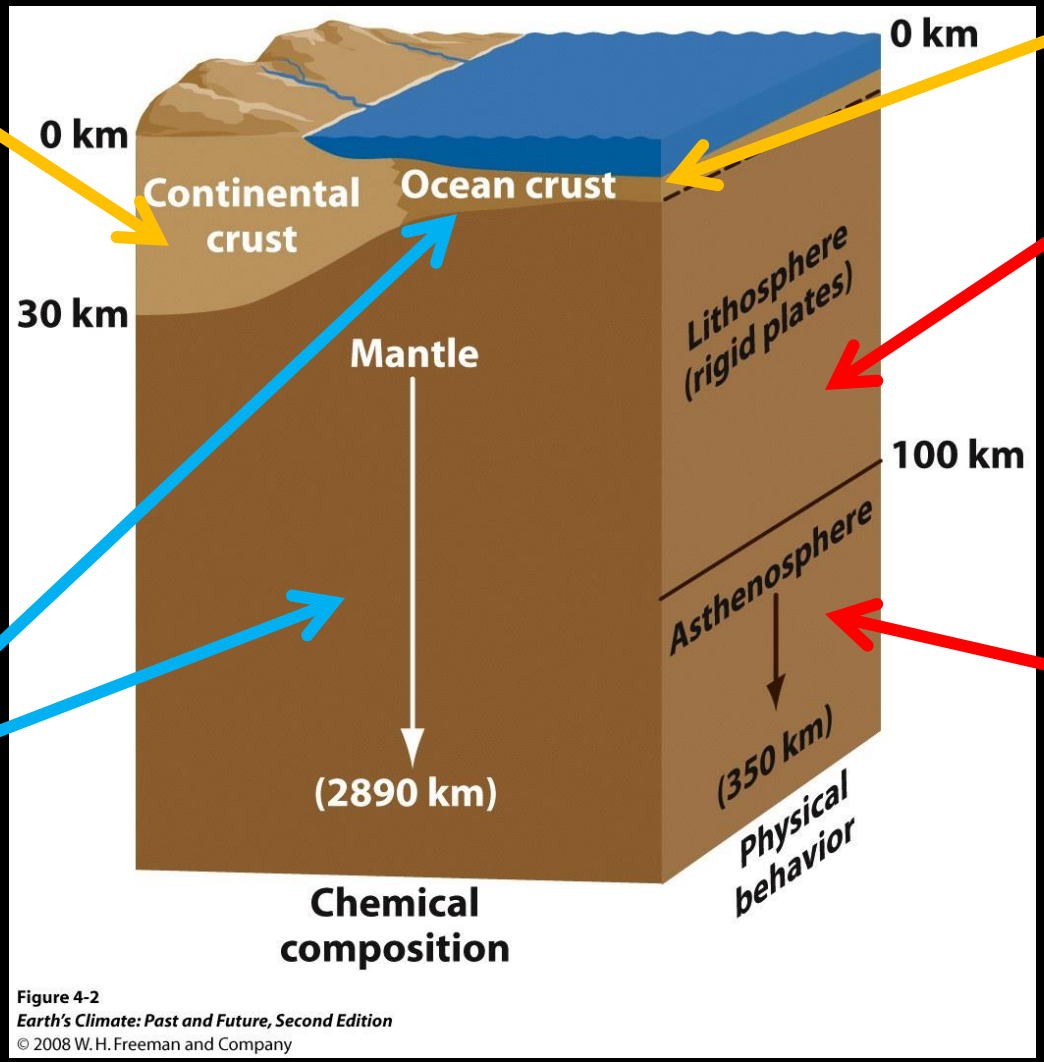
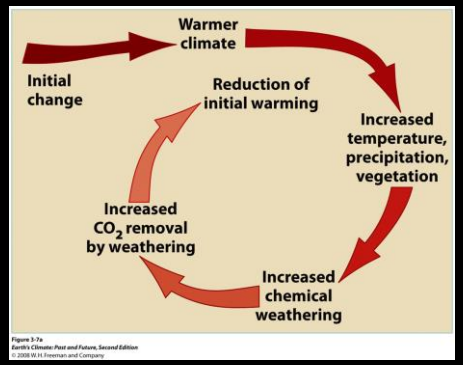
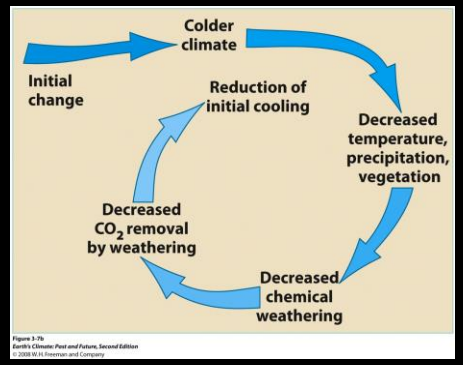
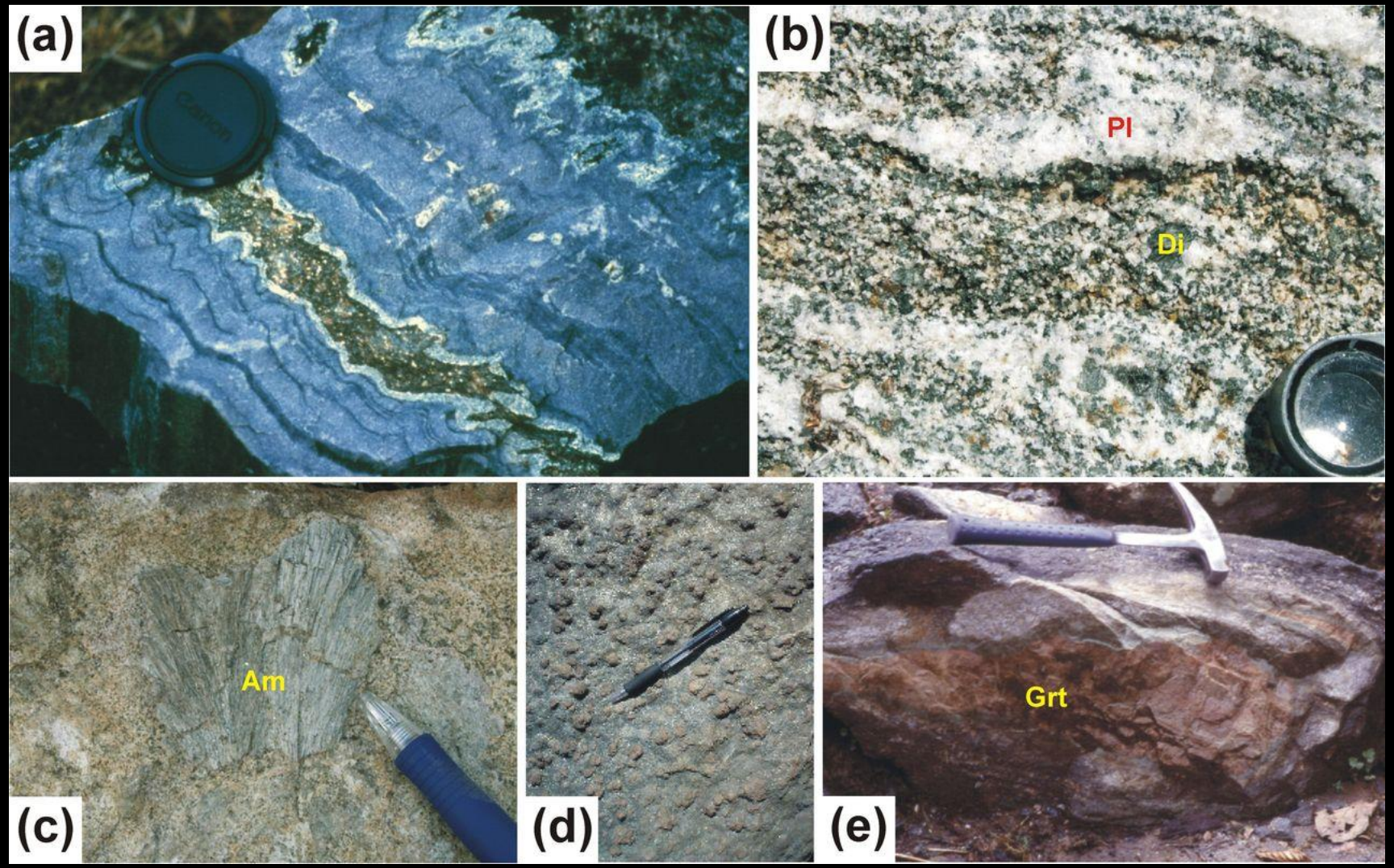



Figure 4-2
*Earth's Climate: Past and Future, Second Edition*

# Where will you find bedrock rich in Ca-Si minerals?




calc-silicate rocks

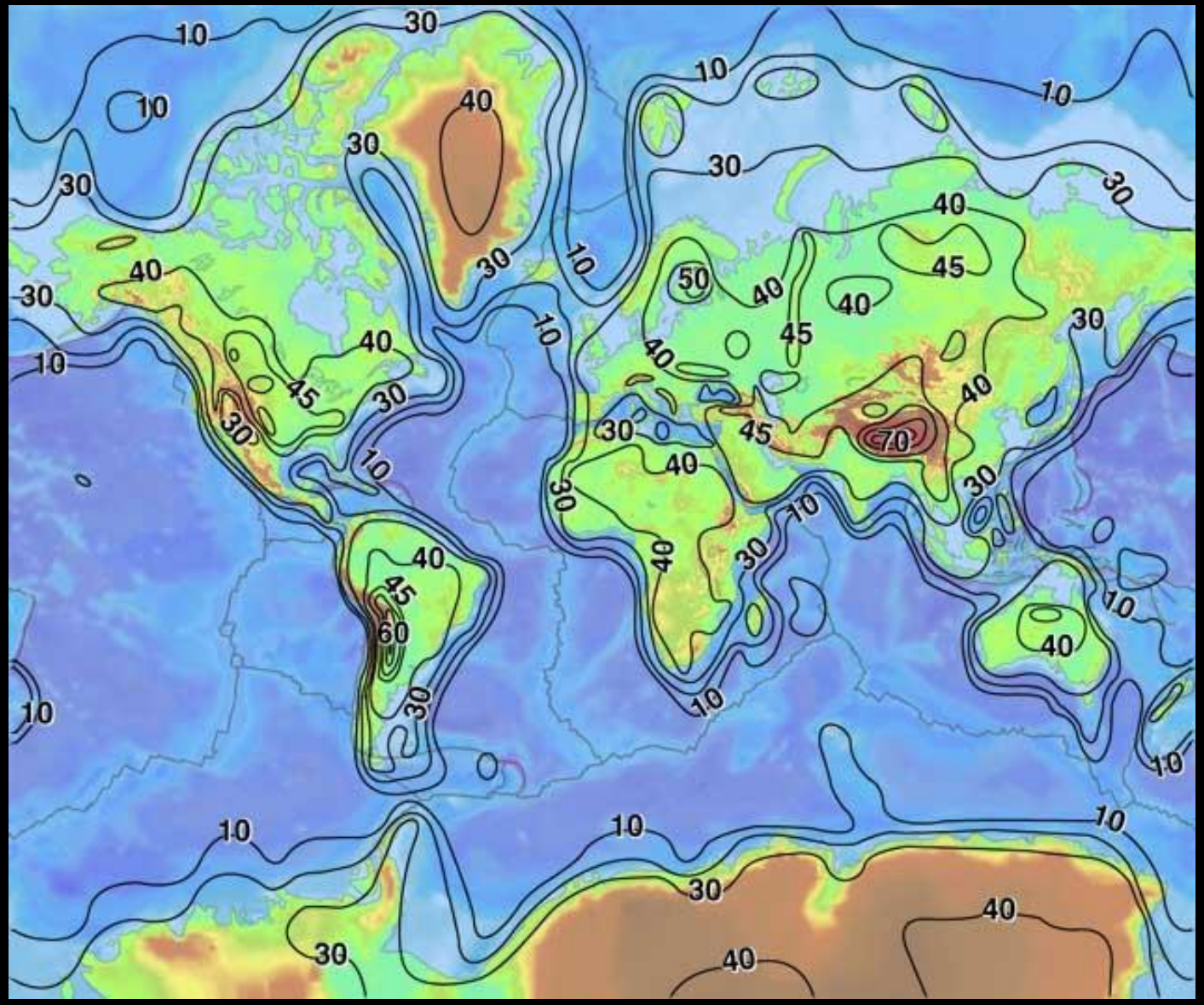
Metamorphic CO2 production in calc-silicate rocks from the eastern Himalaya
Franco Rolfo, Chiara Groppo, Pietro Mosca. 2017. Italian J Geeology


Himalaya:

lots of calc-silicate rocks

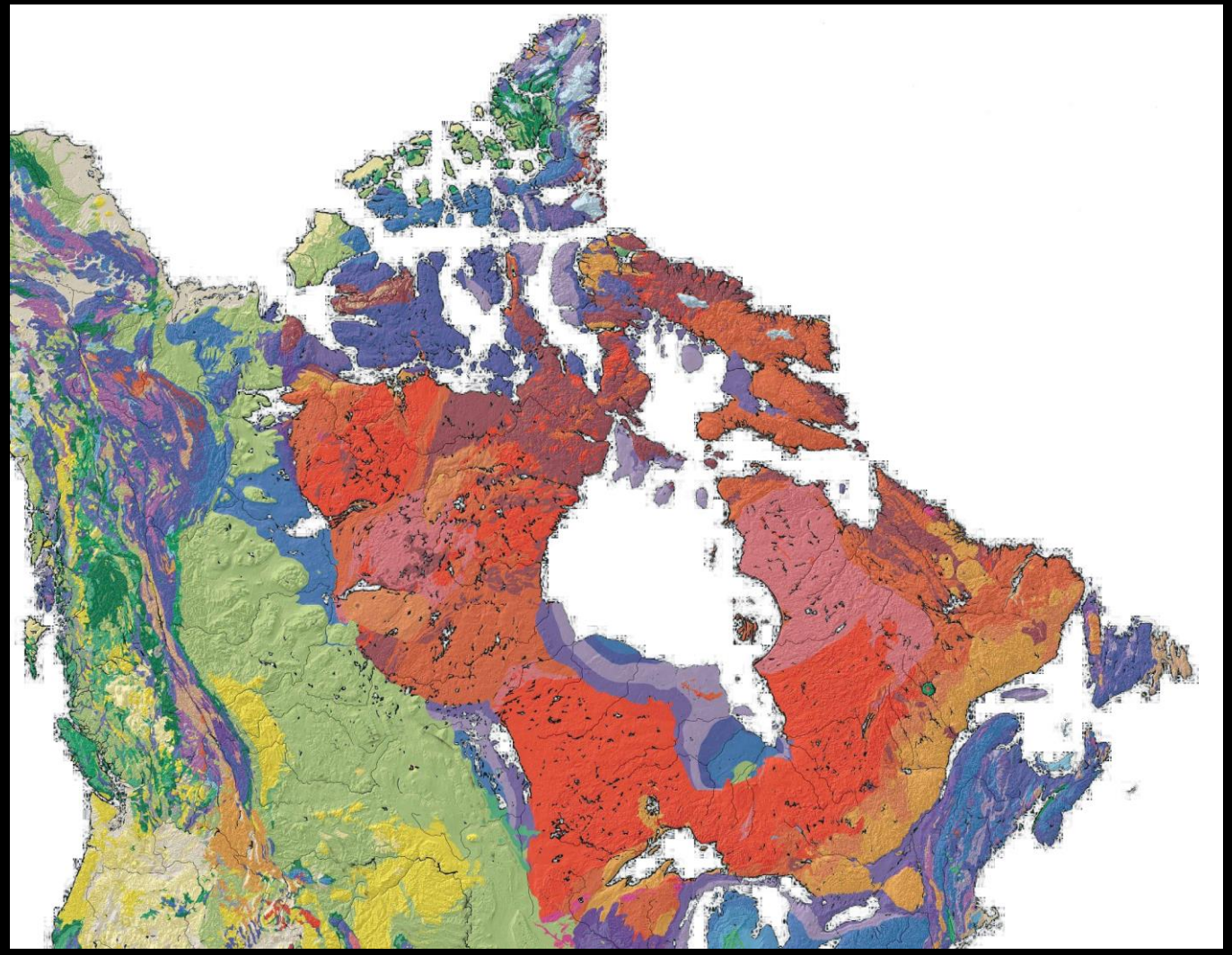
Tectonics create topography,

which creates opportunities for silicate mineral weathering.




thickness of the Earth's crust (km)

# Cratons, shields: ancient crystalline rocks forming stable interiors of continental plates:



Tectonic stability, scarce calc-silicate bedrock
= low rates of $CO_2$ sequestration

Canadian shield (red)
formed 2 billion years old
during the Archaean

# Today……12 tectonic plates

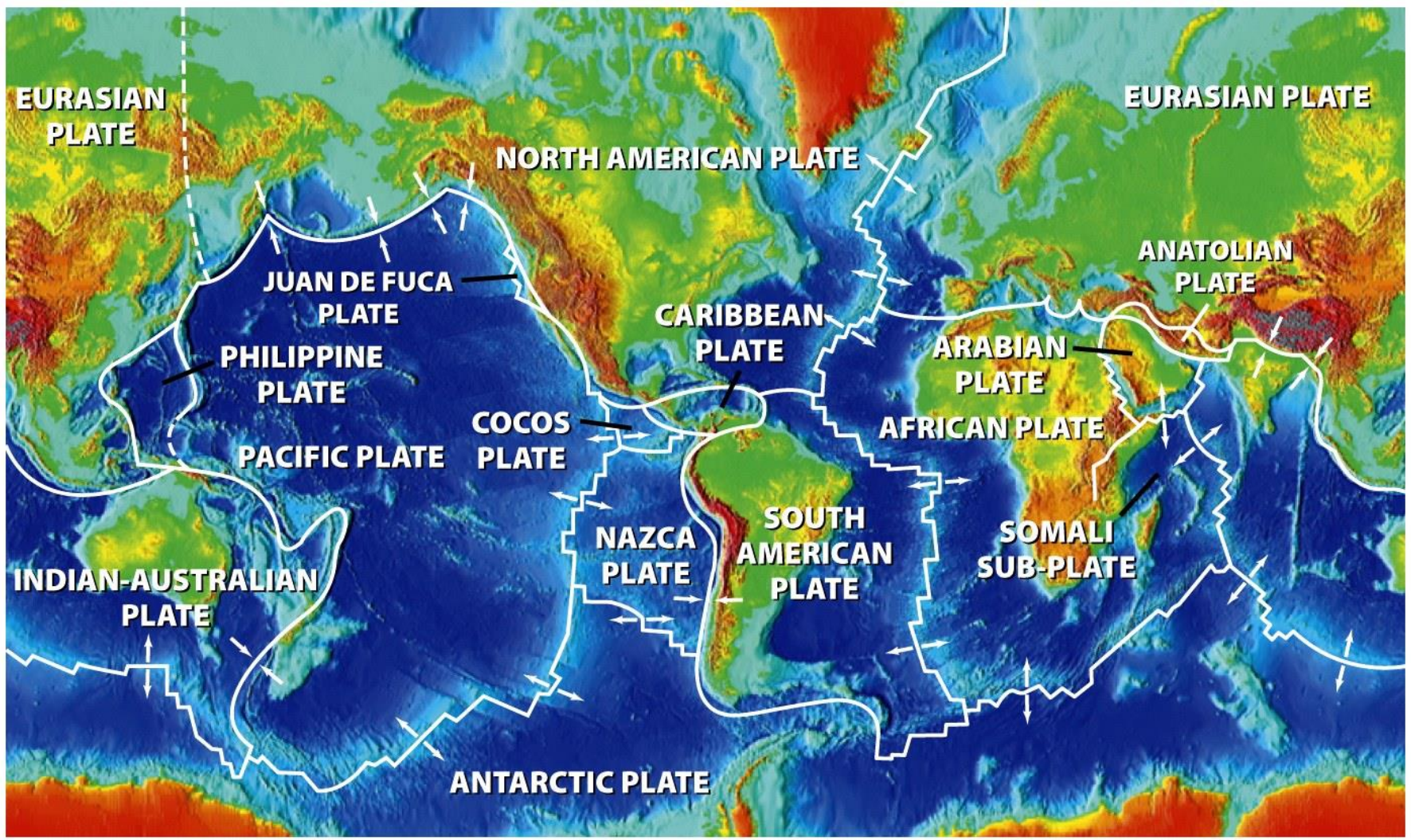



**Figure 4-3**
***Earth's Climate: Past and Future, Second Edition***


most plates are combinations of continental and oceanic crust

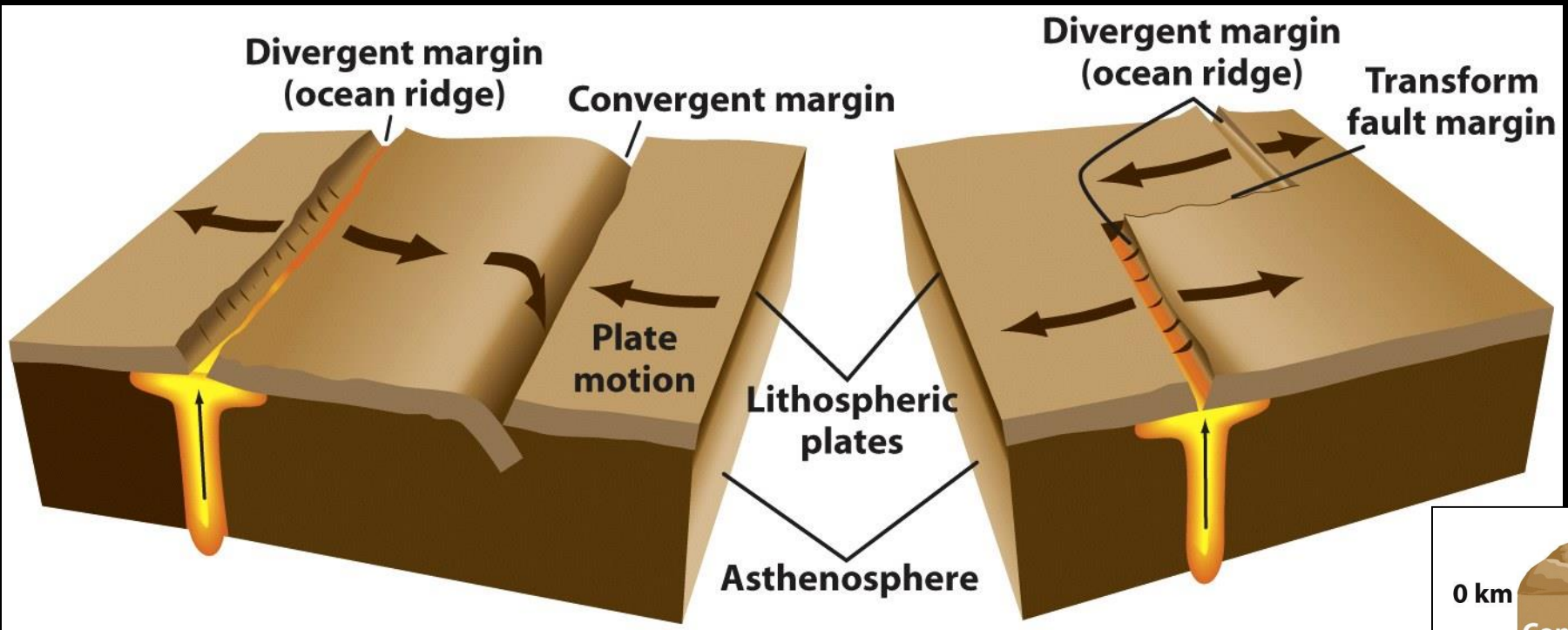



**Figure 4-4**
***Earth's Climate: Past and Future, Second Edition***

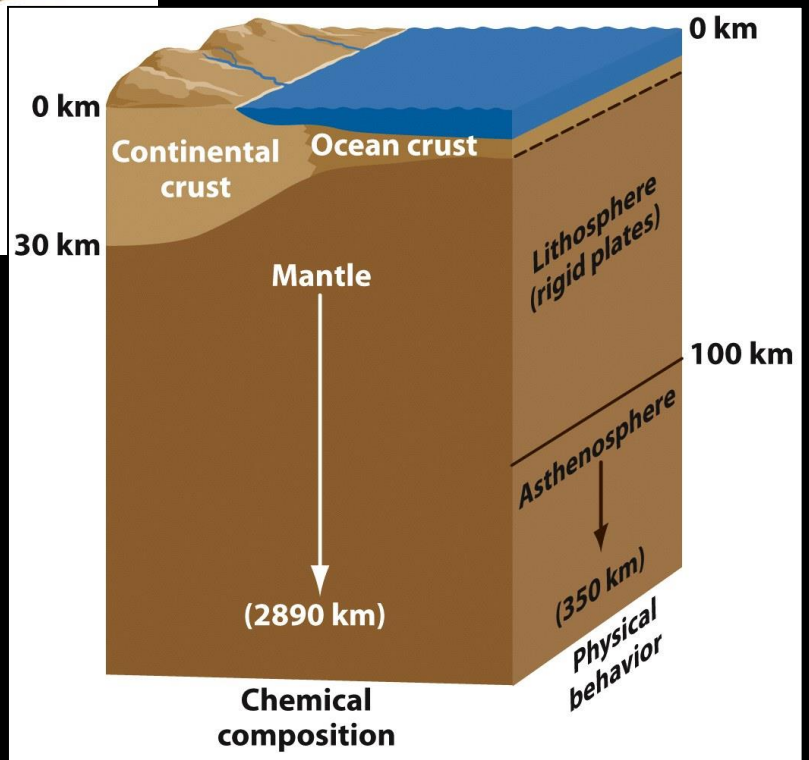
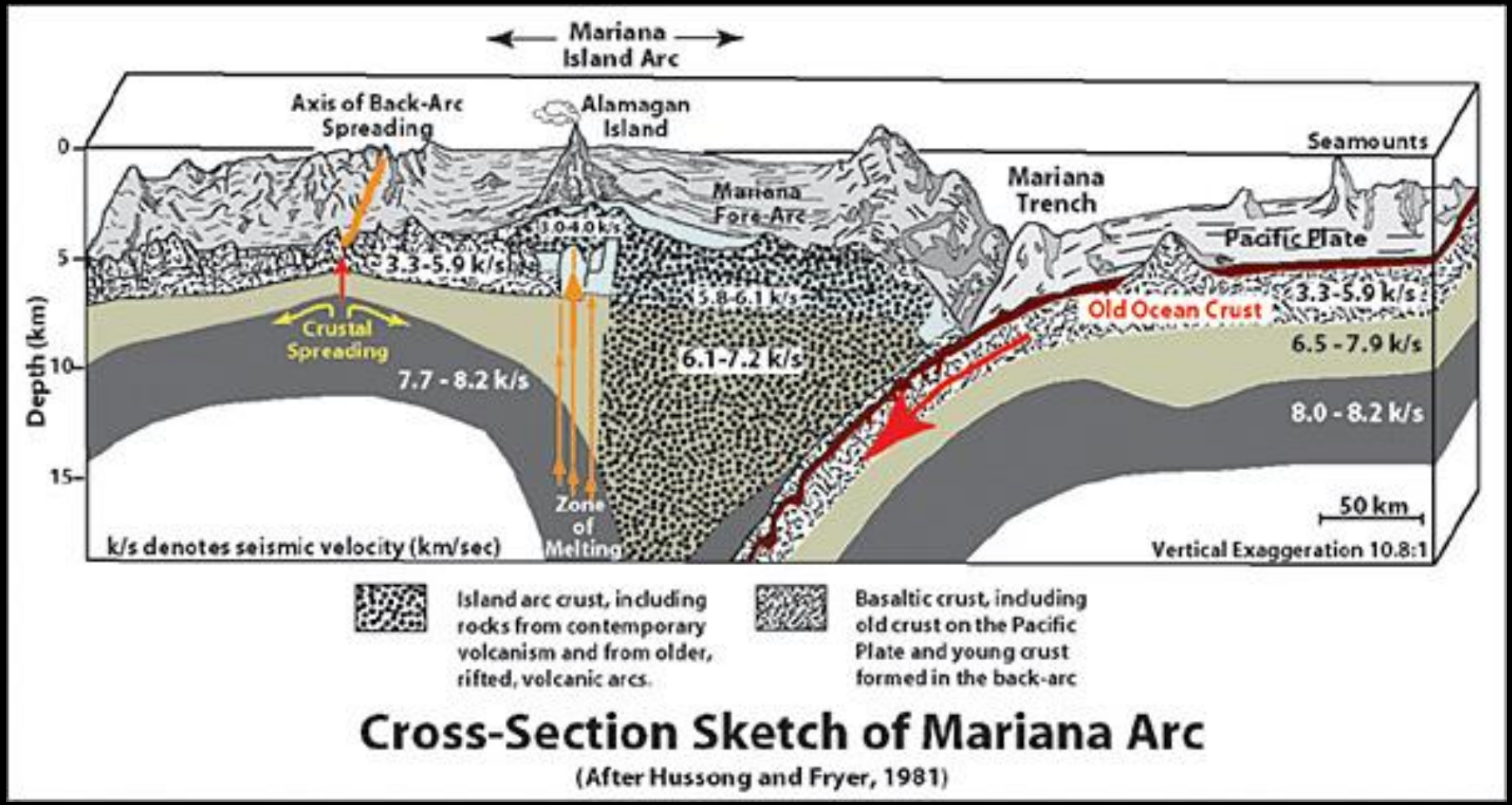




**Figure 4-2**
***Earth's Climate: Past and Future, Second Edition***

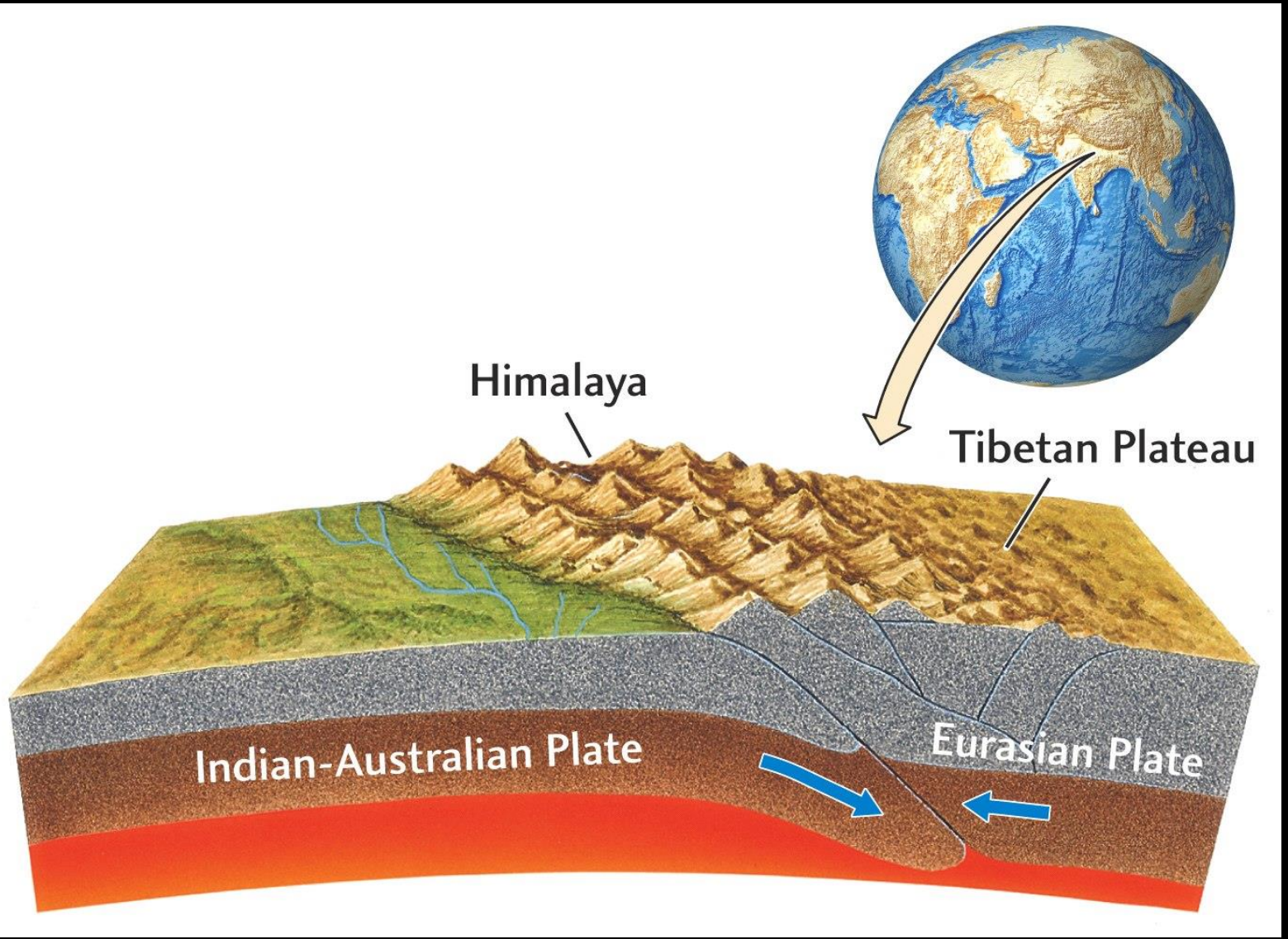
# Convergent margins: continental/oceanic plates or oceanic/oceanic

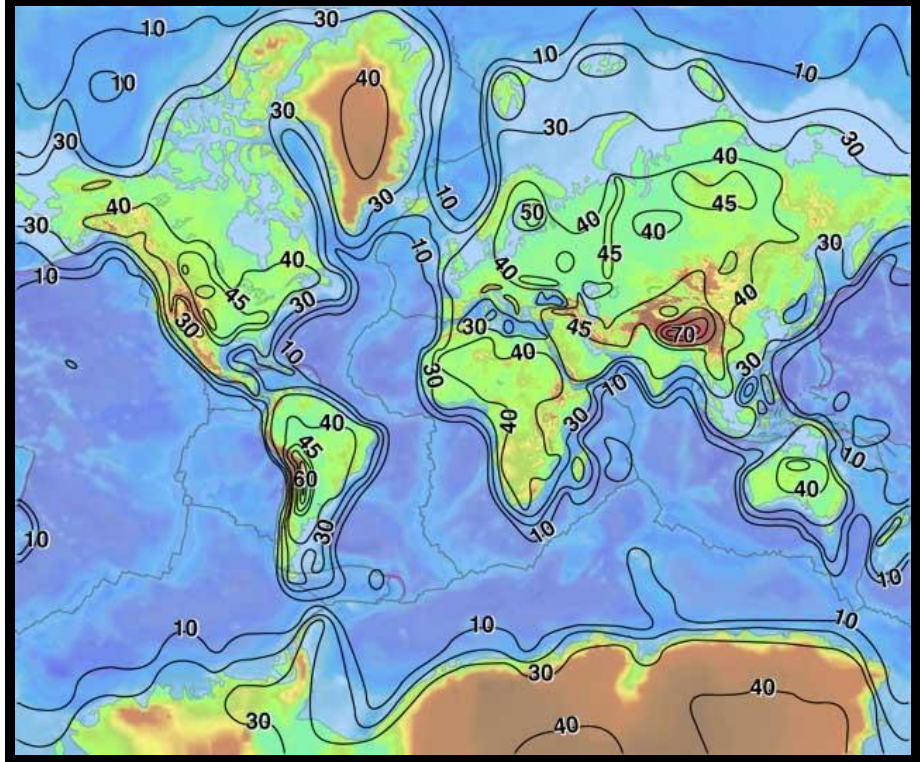



**Cross-Section Sketch of Mariana Arc**

(After Hussong and Fryer, 1981)

# continent – continent collisions: rare in Earth's history

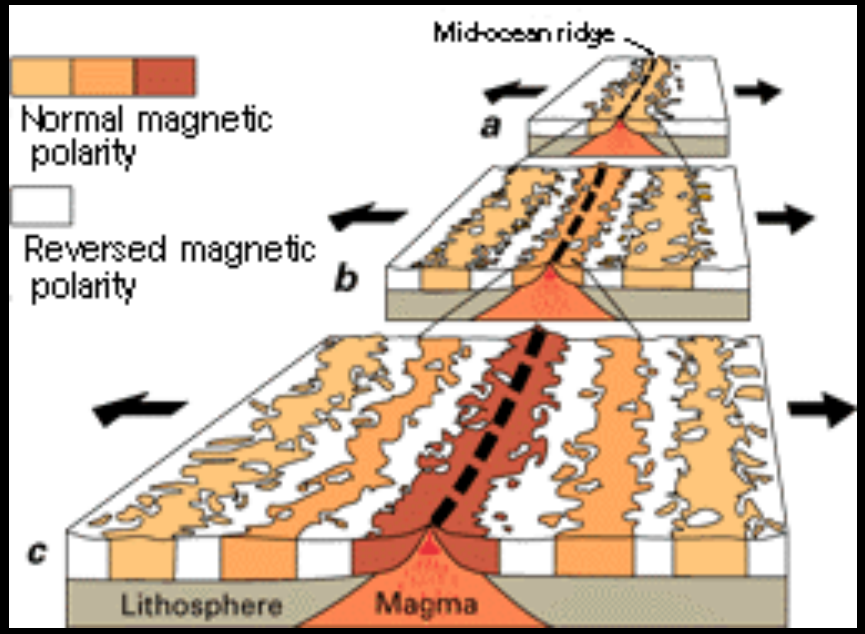


thickness of the Earth's crust (km)

Magnetostratigraphy:

chronostratigraphic technique used to date sedimentary and volcanic rocks




characteristic remnant magnetization: the polarity of Earth's magnetic field at the time of deposition.

Why the age of the sea floor is of interest here:

a) Dated magnetic lineations on seafloor can be used to reconstruct former plate positions

b) and we can use them to estimate past rates of sea floor spreading

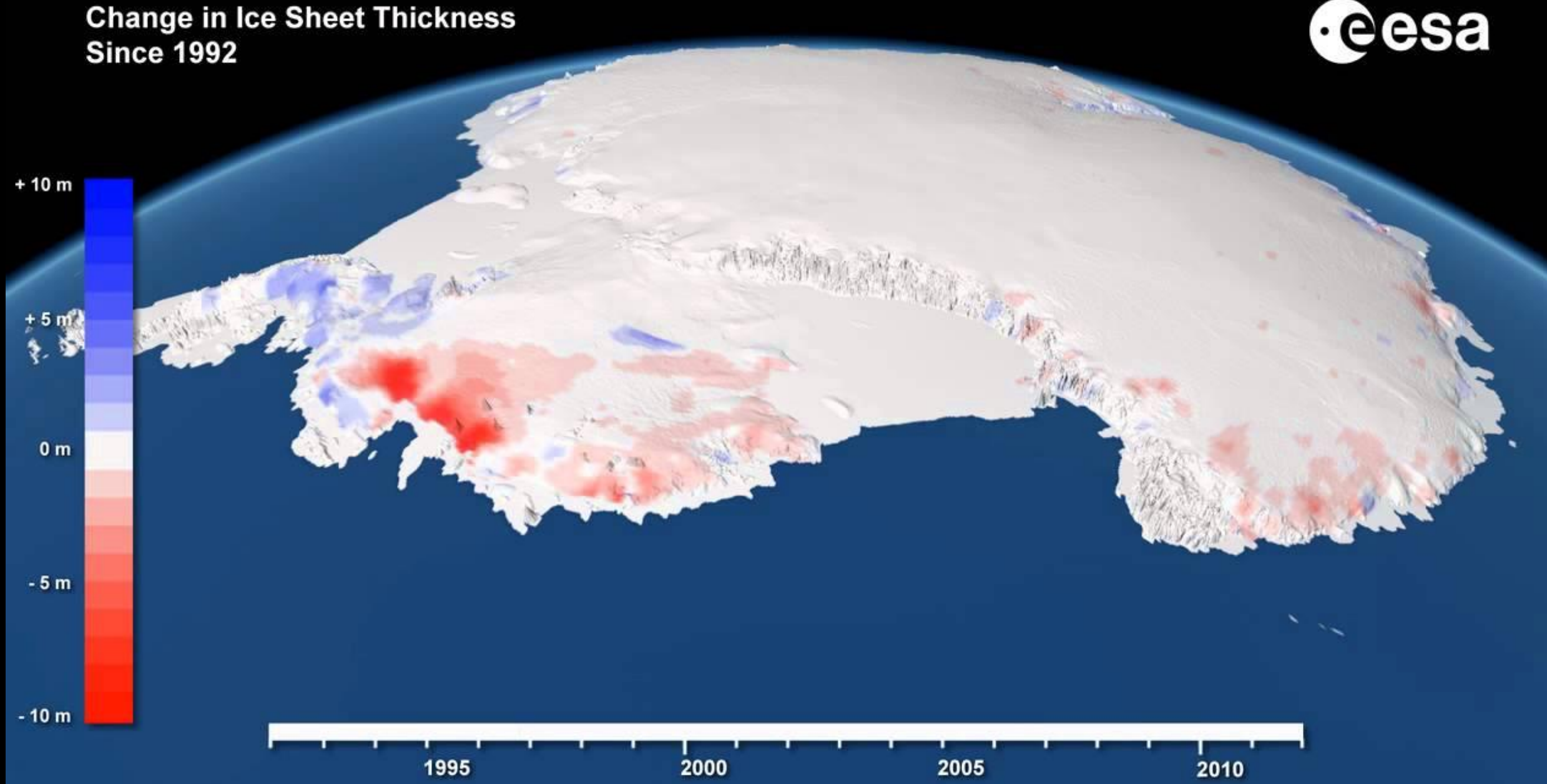
Why the age of the sea floor is of interest here:

a) Dated magnetic lineations on seafloor can be used to reconstruct former plate positions

Polar position H and BLAG H

b) and we can use them to estimate past rates of sea floor spreading

BLAG H


Change in Ice Sheet Thickness
Since 1992
esa
+ 10 m
+ 5 m
0 m
- 5 m
- 10 m
1995
2000
2005
2010

# The Polar Position Hypothesis

When the continents bunch together at the poles, they provide a place for ice sheets to develop.

When they move off the poles, the ice age ends.

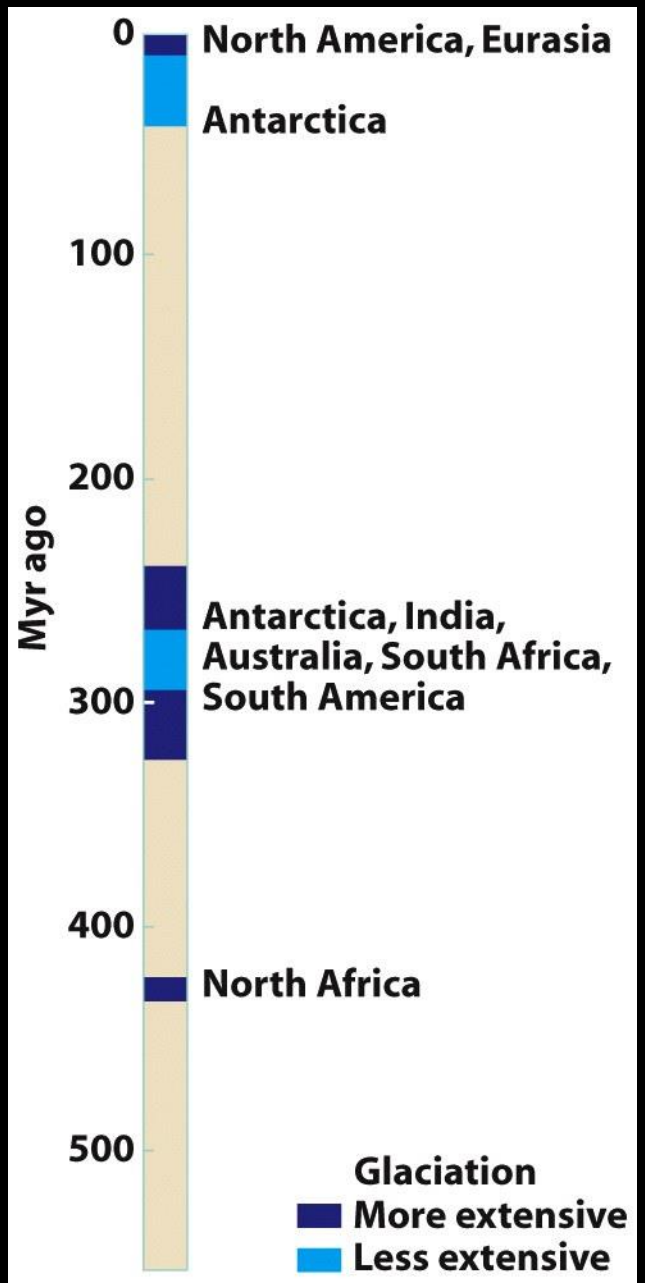
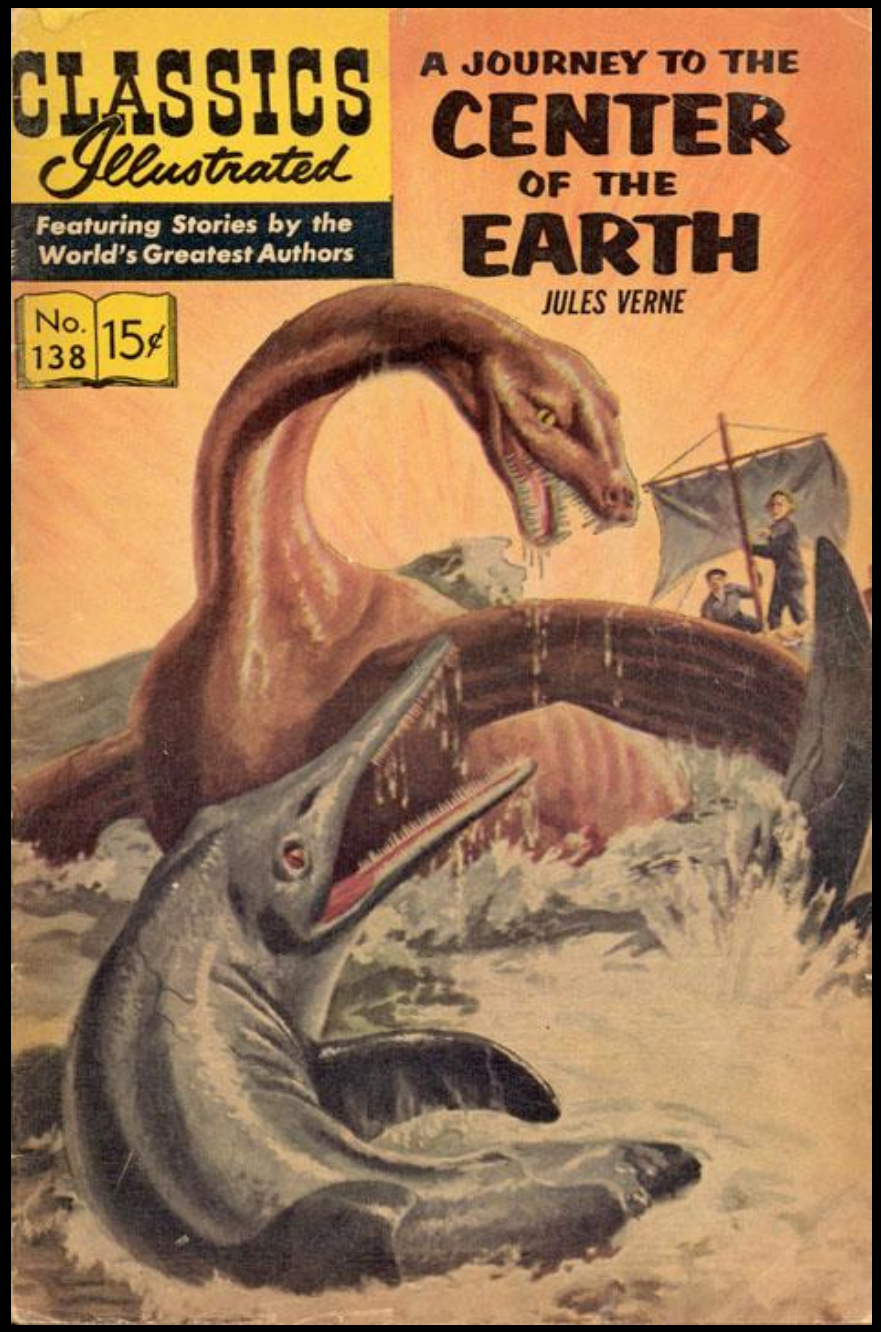



Figure 4-1
*Earth's Climate: Past and Future, Second Edition*


Several global glaciations occurred during the past 550 my

What caused them?

forget greenhouse gases and blame it on continental drift (?)



# Continental positions since 500 my ago

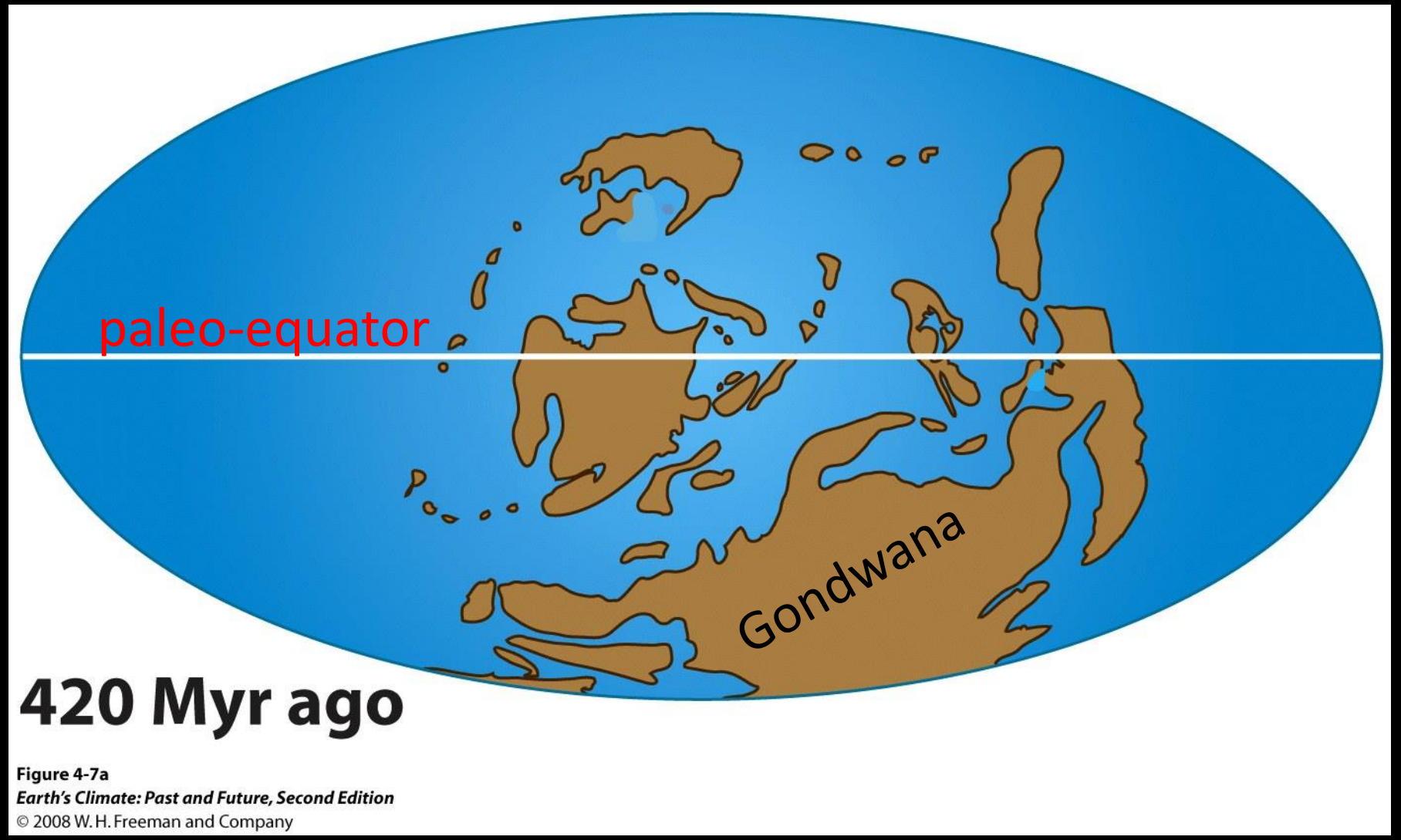



Figure 4-7a
*Earth's Climate: Past and Future, Second Edition*

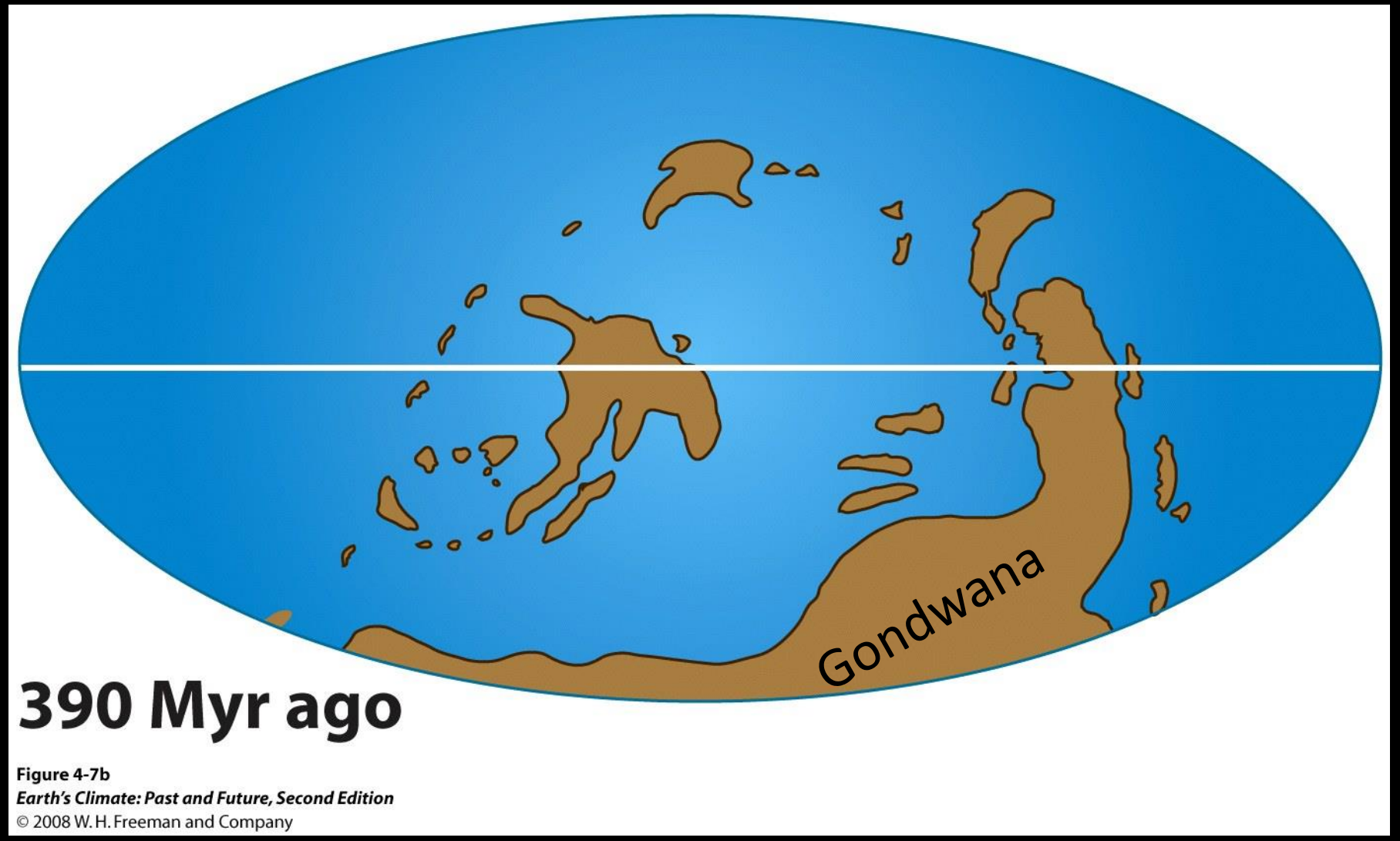



**Figure 4-7b**
***Earth's Climate: Past and Future, Second Edition***

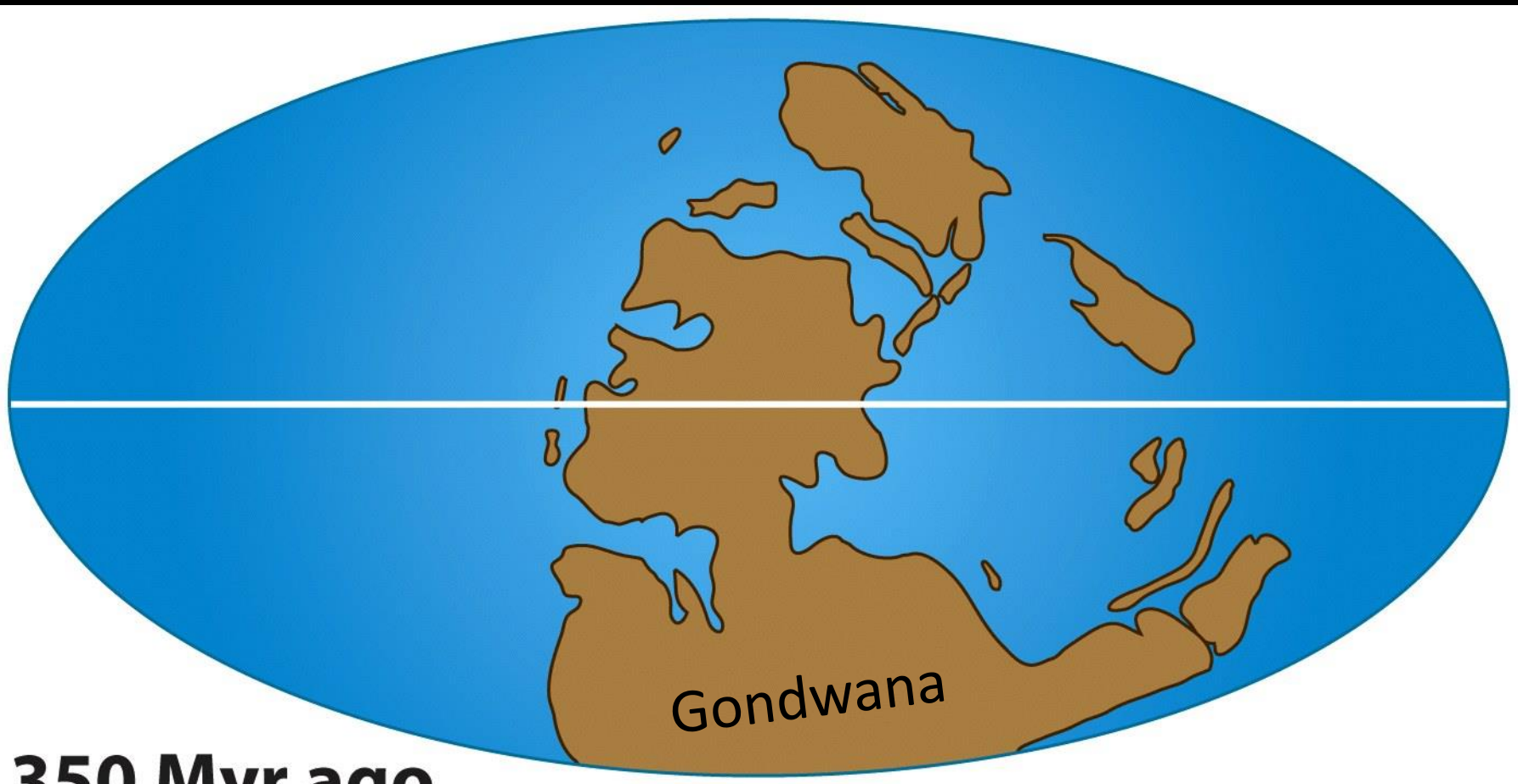



**Figure 4-7c**
***Earth's Climate: Past and Future, Second Edition***

# Gondwana melds with northern continents to form Pangaea

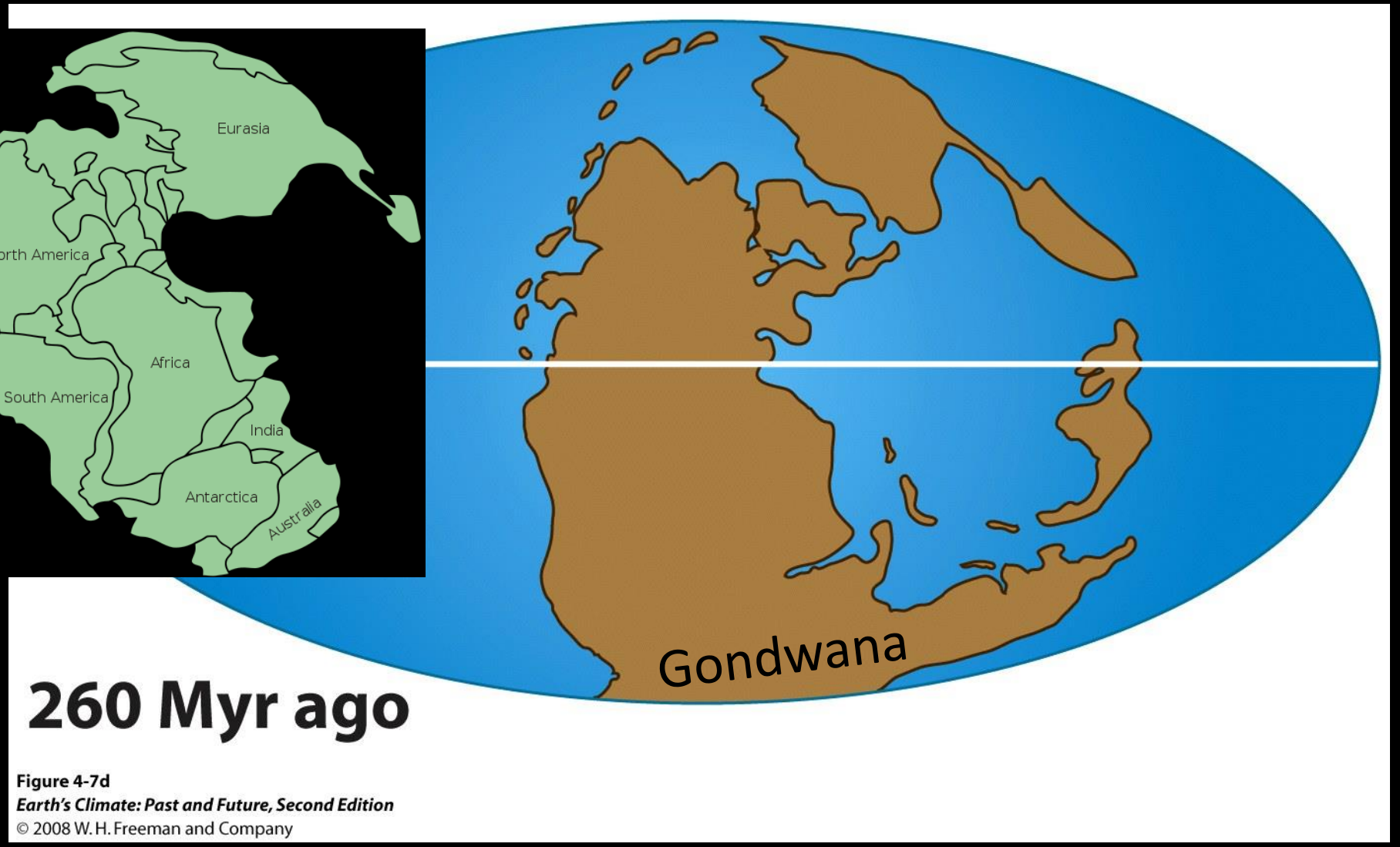



**Figure 4-7d**
***Earth's Climate: Past and Future, Second Edition***

remember

# We had continental glaciation at these times:

440 mya
325-240 mya
35 mya to present*

* technically we are still in an ice age

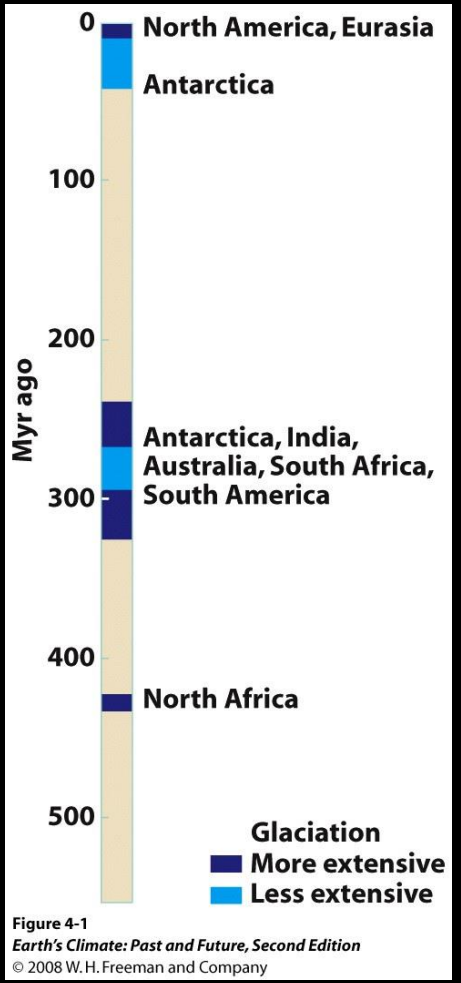


Figure 4-1
*Earth's Climate: Past and Future, Second Edition*

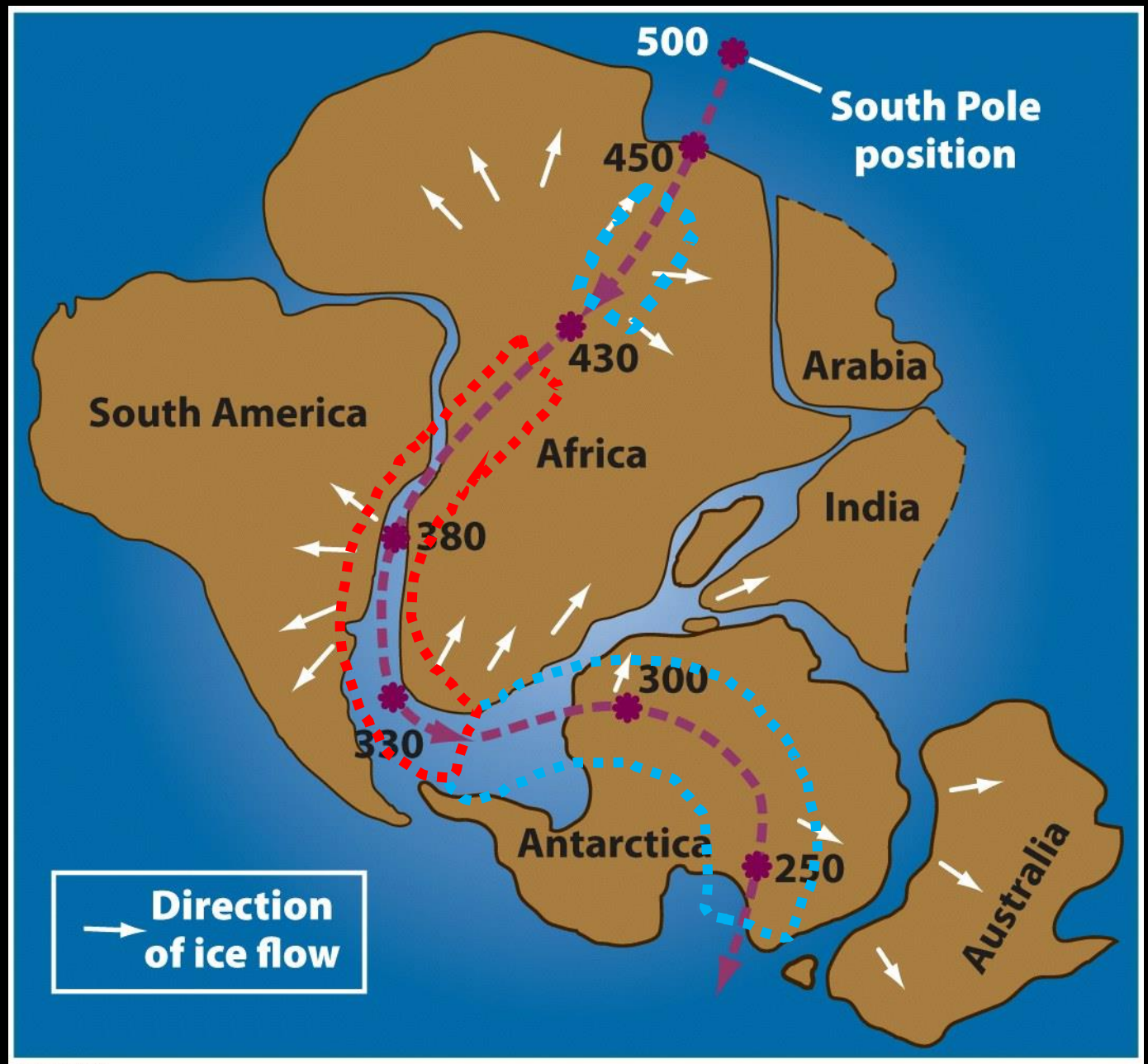



Figure 4-8
*Earth's Climate: Past and Future, Second Edition*


Between 425 and 325 mya, continents lay at the South Pole, but no ice sheets formed.

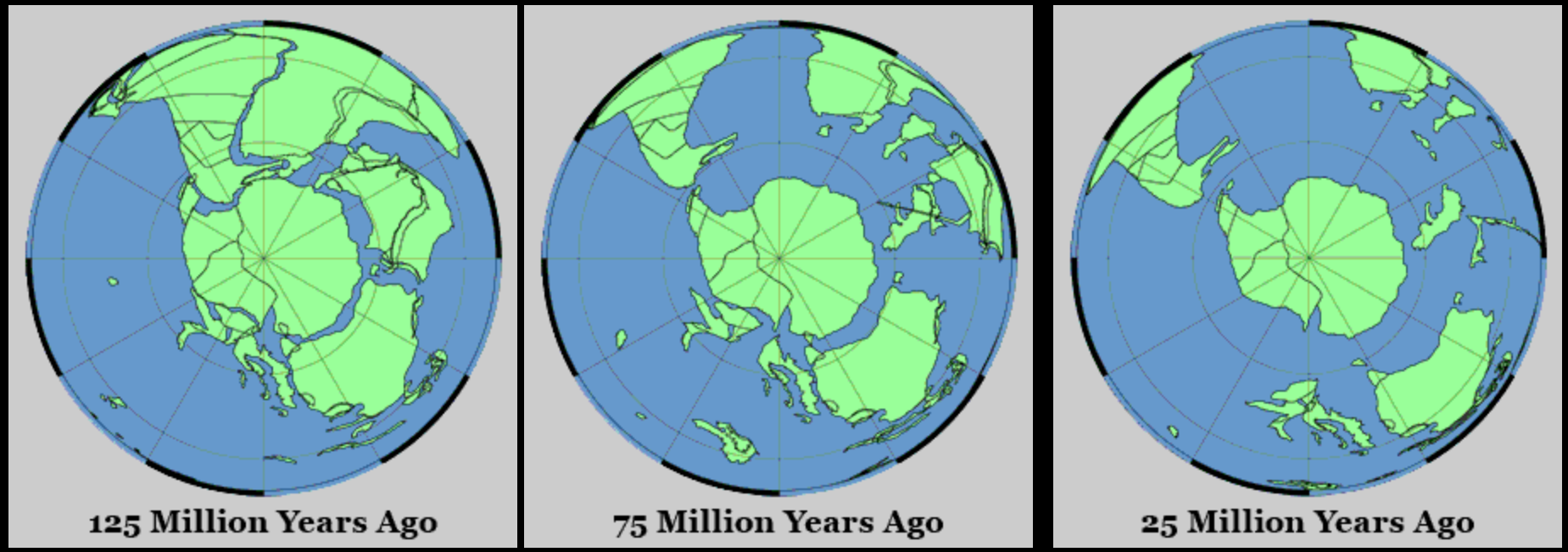
no ice

Shifting position Of South Pole

glaciation

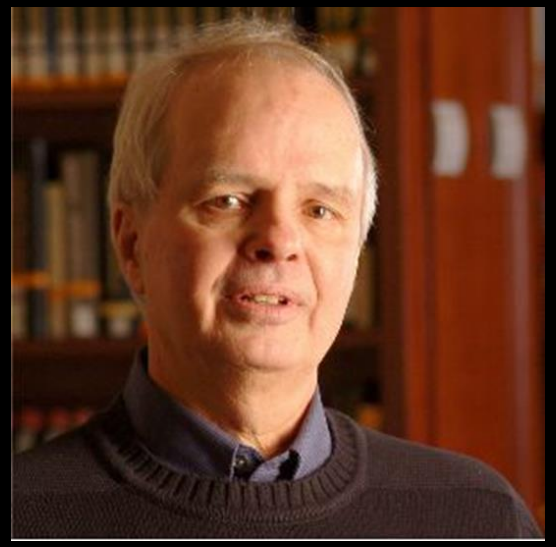
# Gondwana breaking up:

Despite South Pole remaining near/on Antarctica, continental glaciation did not start there until the Miocene.




No ice sheet  No ice sheet  Ice sheet !

# So far, there is evidence both for and against the Polar Position Hypothesis



Ruddiman concludes:

There must be more to it than simply the Polar Position Hypothesis.

It seems to have worked at some times but not at others.

# But does continental arrangement really matter for Earth's climate?

## What happens if we combine the Polar Position Hypothesis with a general circulation model of Earth in the time of Pangaea?

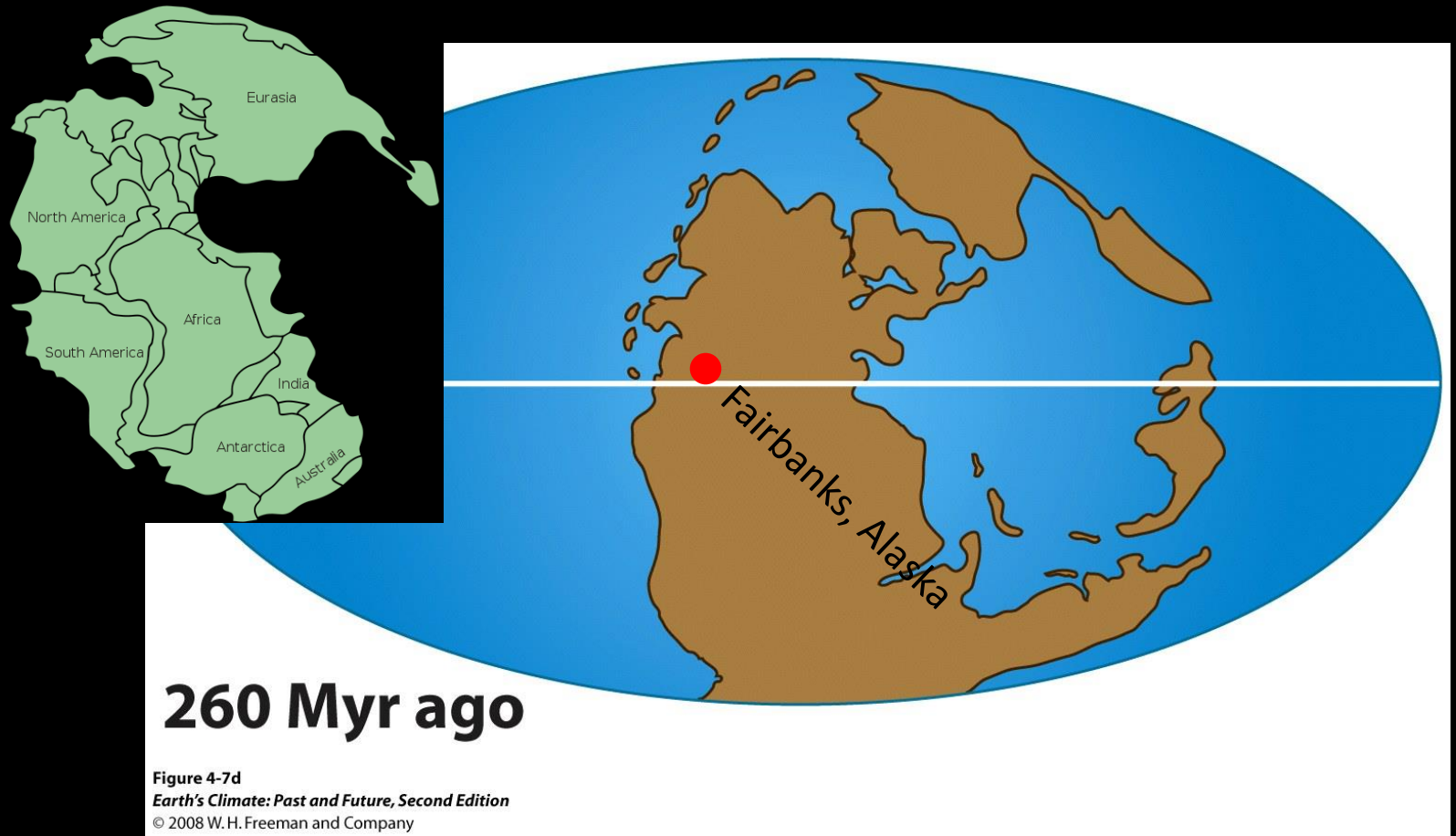



Figure 4-7d
*Earth's Climate: Past and Future, Second Edition*

We need a climate model.

# First step in modeling Pangaea's climate is simplifying its geography

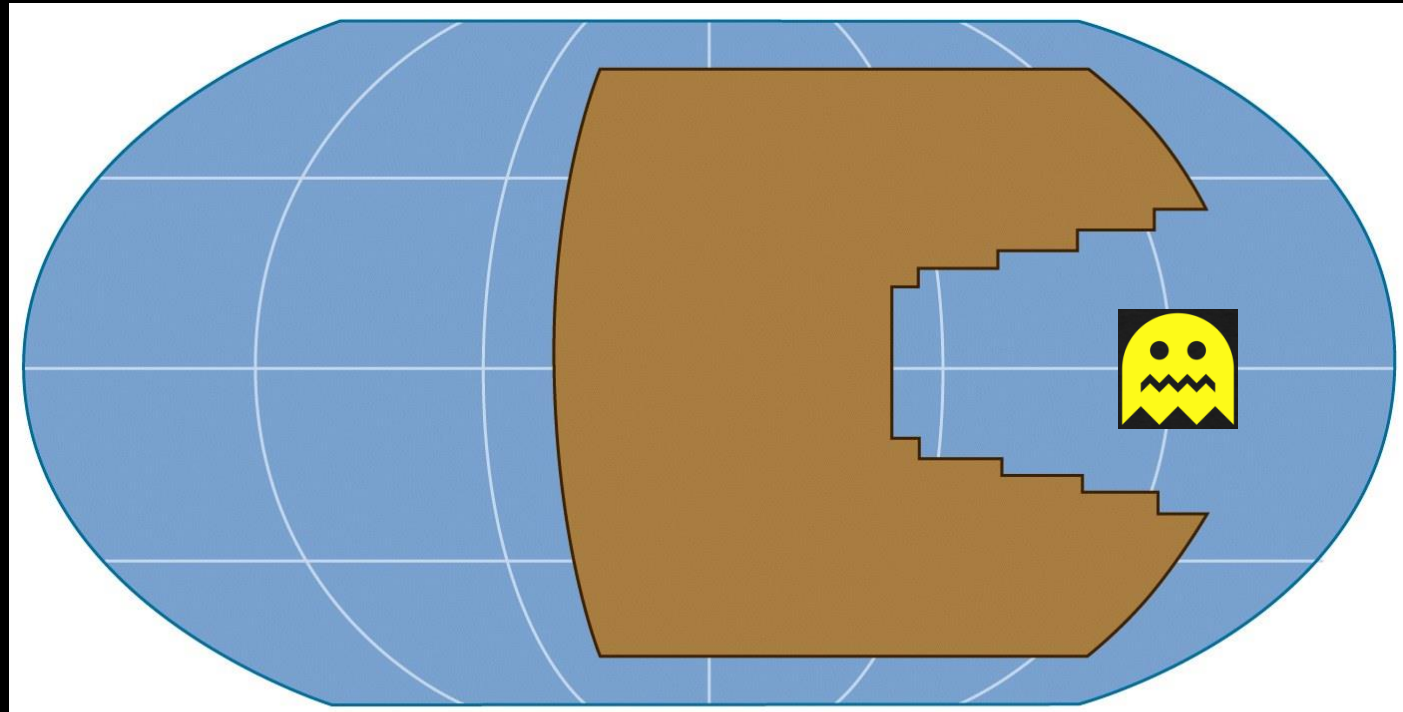



Figure 4-10b
*Earth's Climate: Past and Future, Second Edition*


*Geology*; May 1989; v. 17; no. 5; p. 457-460; DOI: 10.1130/0091-7613(1989)017<0457:SCVOTS>2.3.CO;2

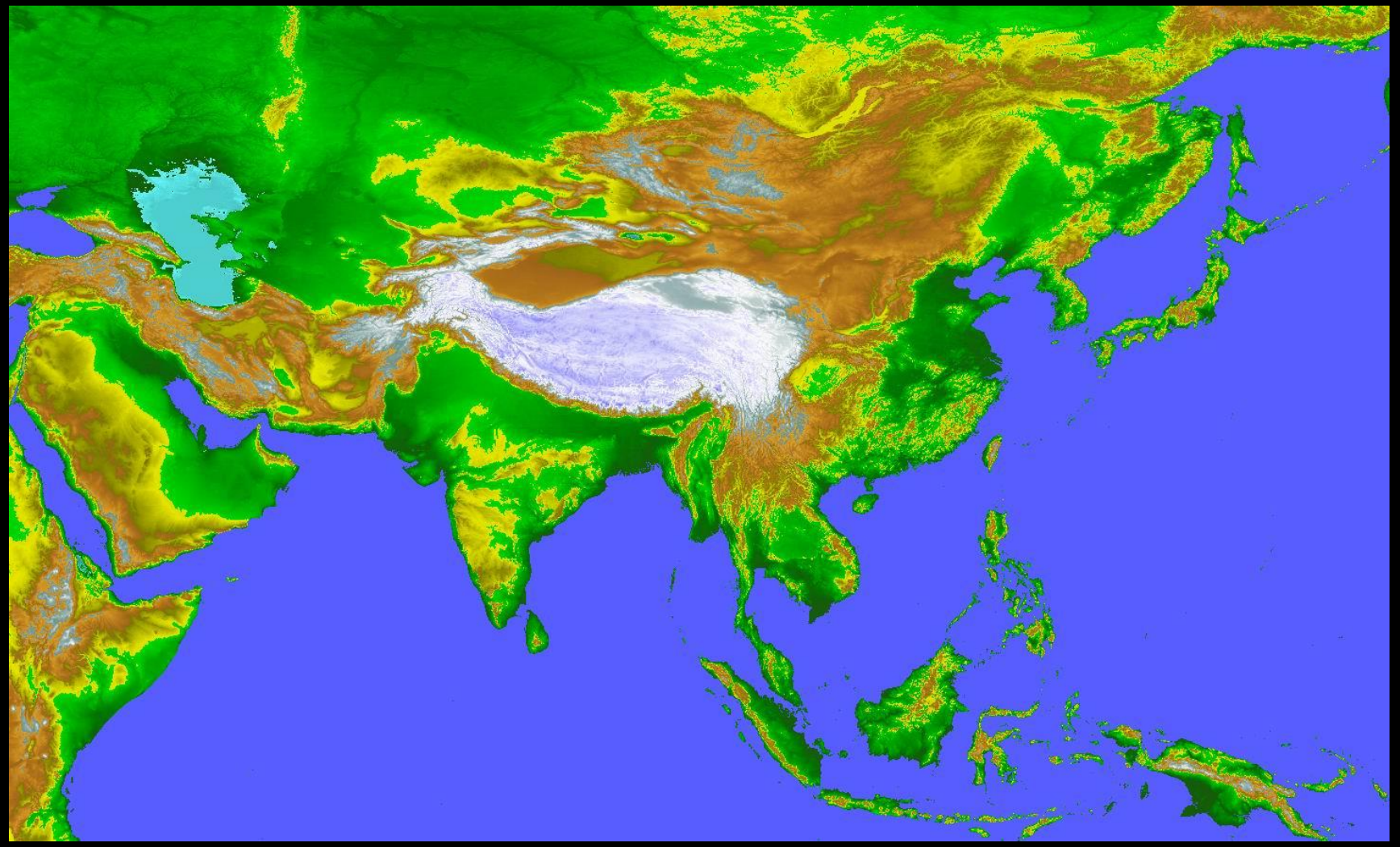
**Seasonal cycle variations on the supercontinent of Pangaea**

**Thomas J. Crowley, Williiam T. Hyde, and David A. Short**

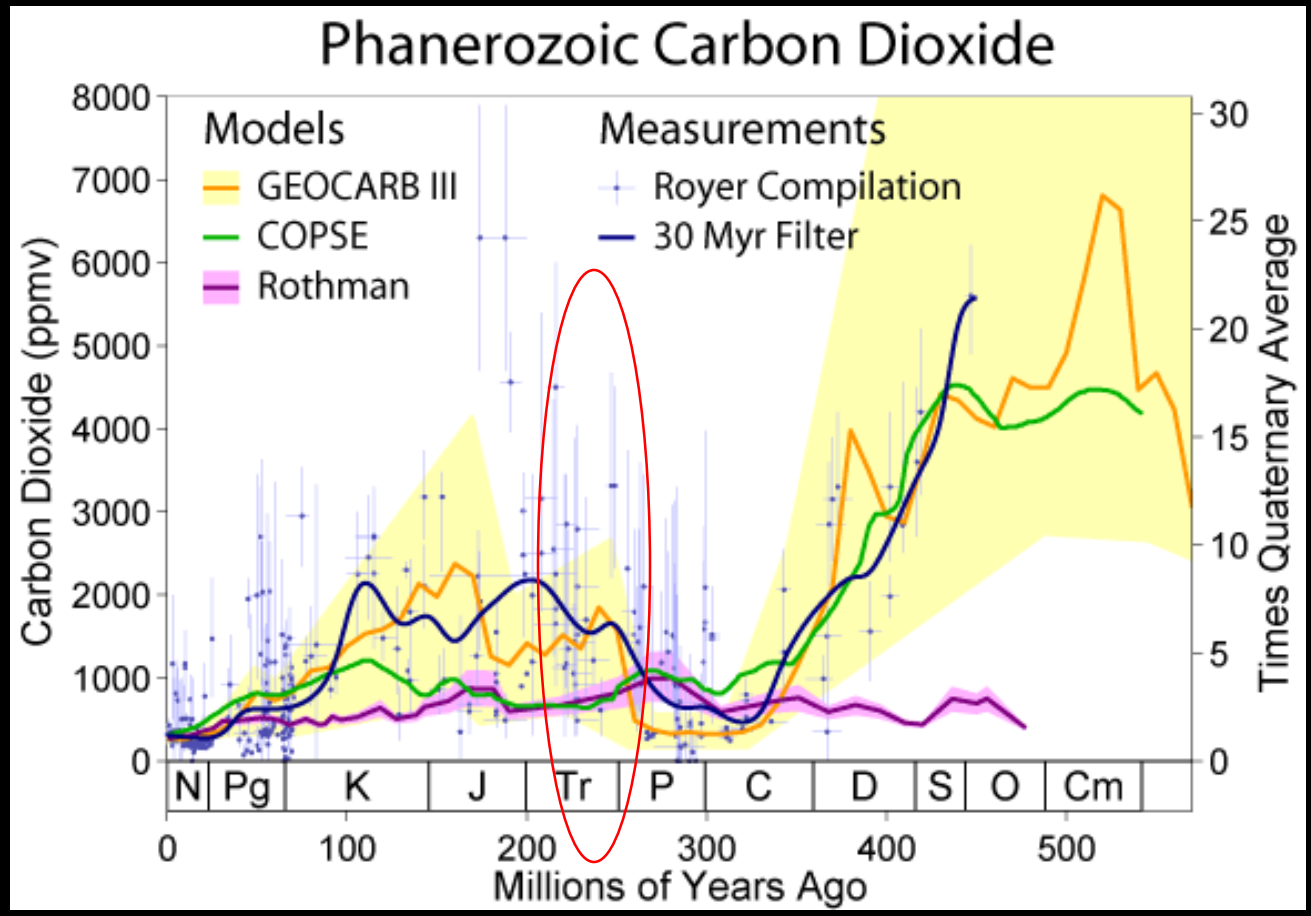
# 2cnd boundary condition decision: Where was sea level?

(this has obvious implications for extent of Pangeaea and continentality of its climates)

# 3rd boundary-condition decision: What ***was*** Pangaea's topography?

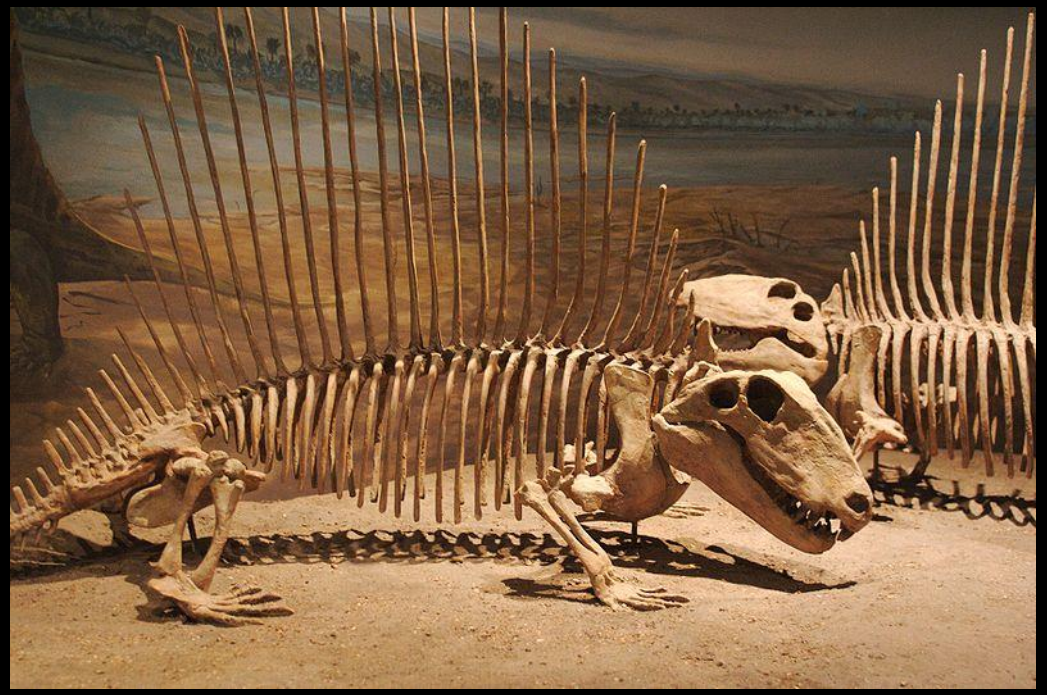


# Fourth assumption: How much $CO_2$ was in Pangaea's atmosphere?




Estimates of CO2 concentrations during the Phanerozoic. Three estimates are based on geochemical modeling: GEOCARB III (Berner and Kothavala 2001), COPSE (Bergmann et al. 2004) and Rothman (2001). These are compared to the carbon dioxide measurement database of Royer et al. (2004) and a 30-Myr filtered average of those data. (Robert Rohde).

The modelers decided that because there was frost-sensitive vegetation growing in Pangaea to 40 d N and S and that there were no continental ice sheets, $CO_2$ levels must have been high, 1650 ppm (6x present).



*Dimetrodon*, predatory synapsid mammal-like-reptile of Pangaea

Pangaean ancestor? gingko tree

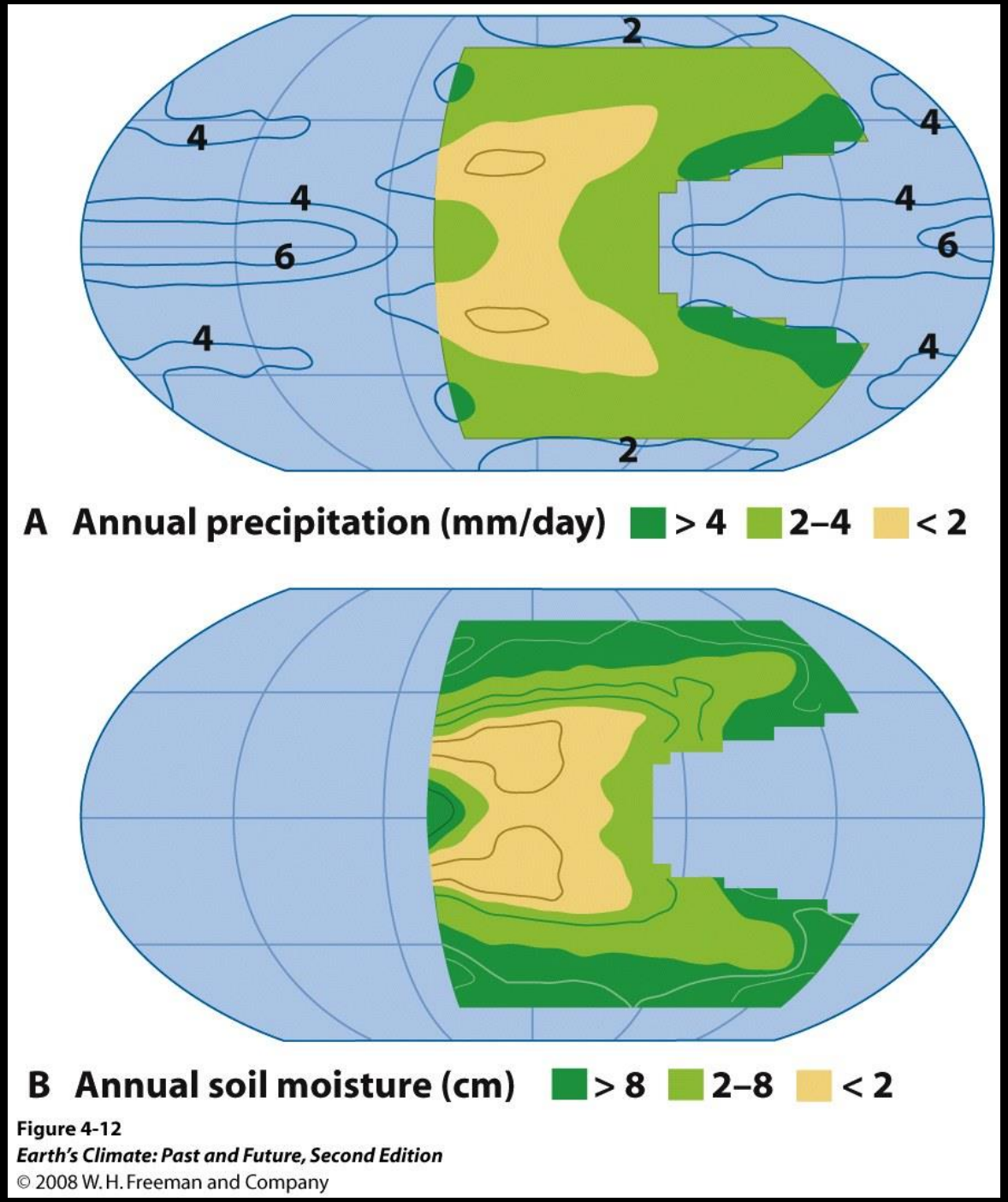



Figure 4-12
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## Model output:

Predicts widespread aridity in interior of Pangaea

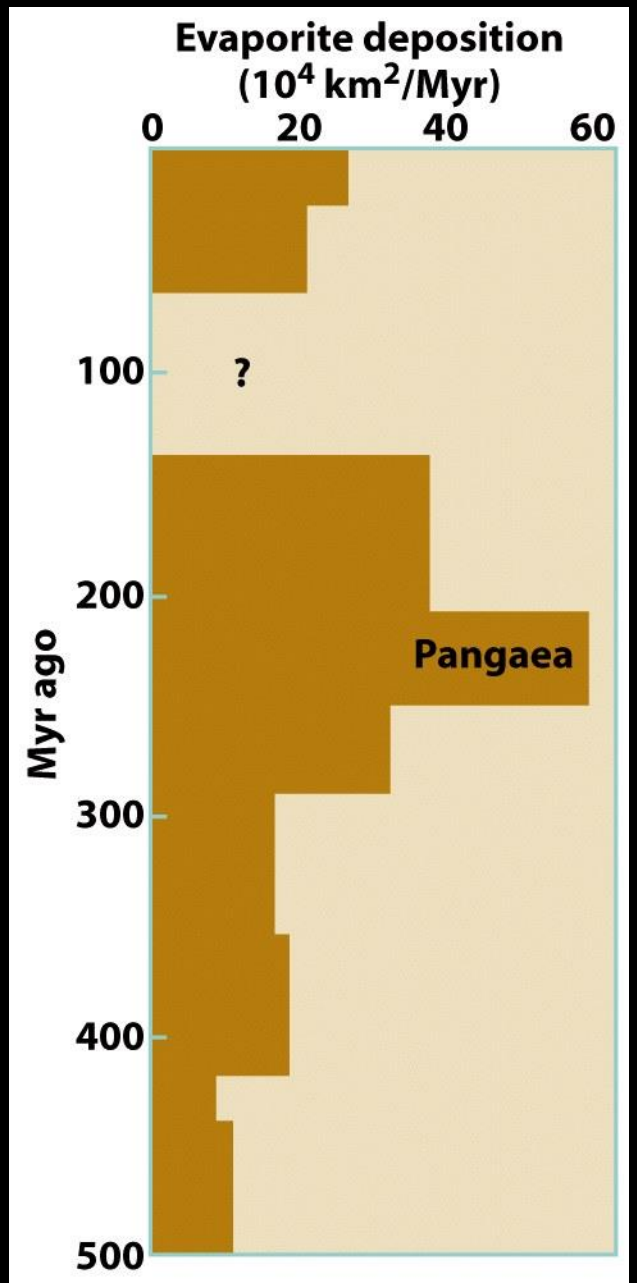


Figure 4-13
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## Geological evidence supports aridity

More salt deposited on Pangaea ca 200 mya than at any other time in Earth's history.

# Predictions of extreme continentality

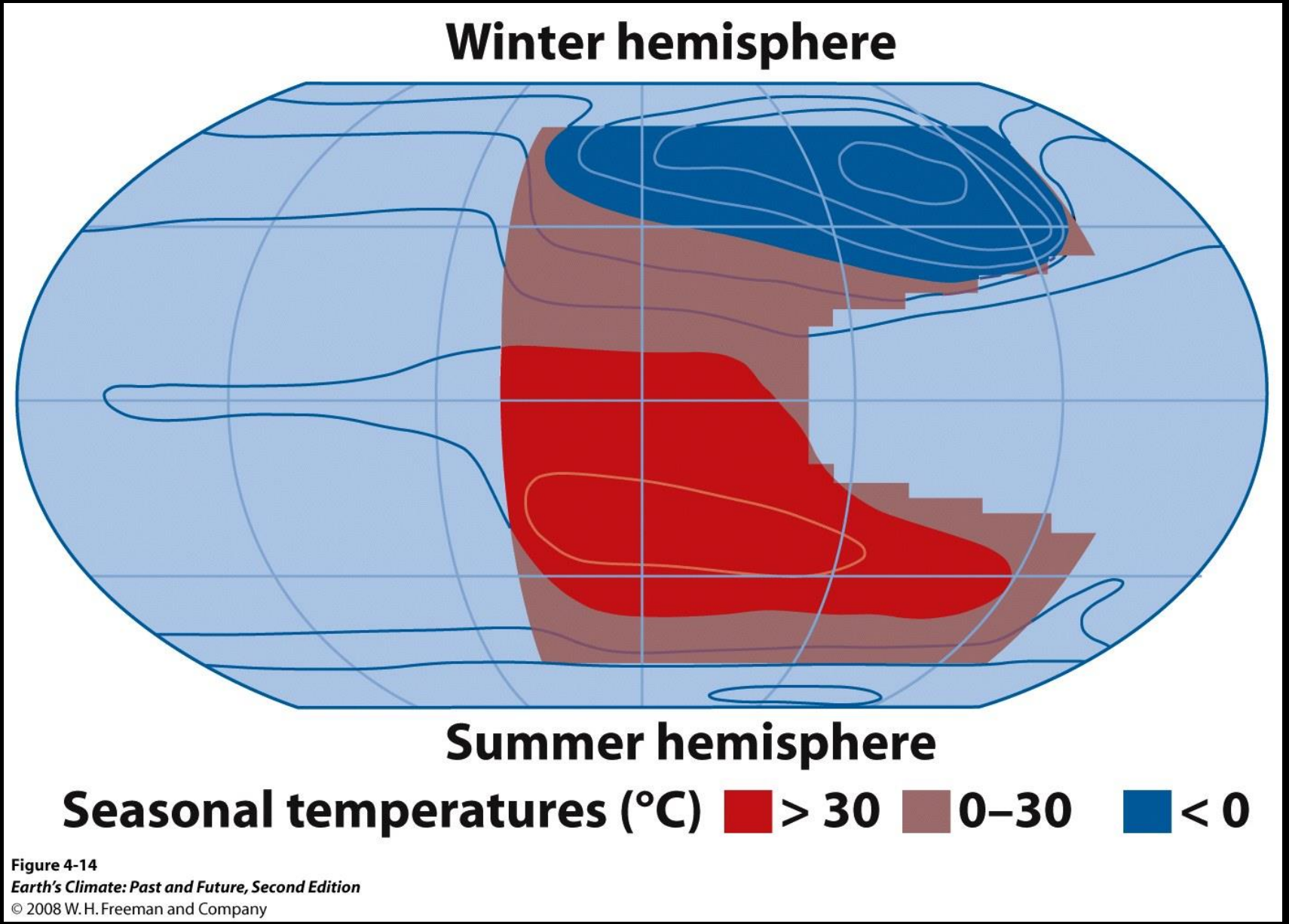


**Figure 4-14**
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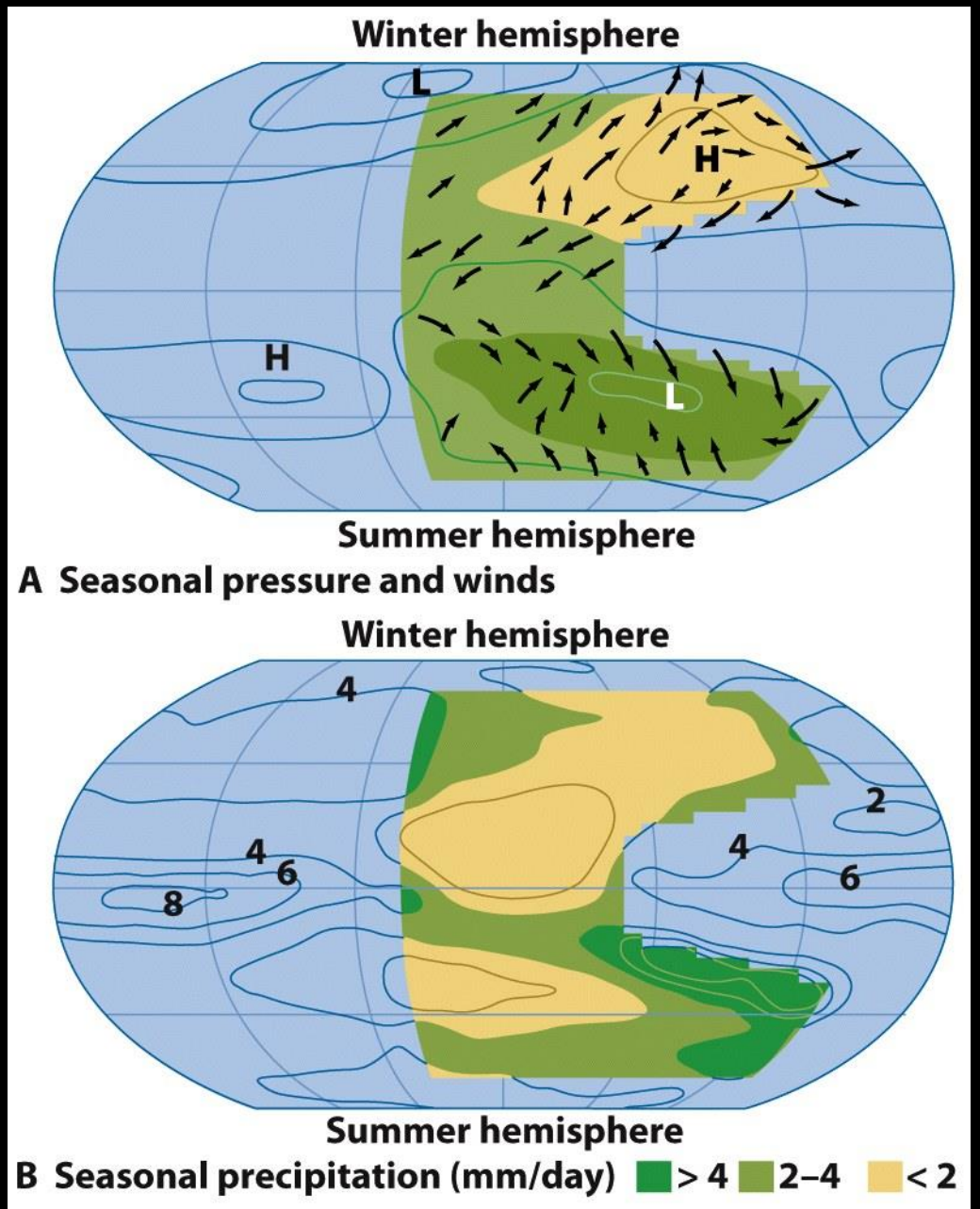


Figure 4-15
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Pangaea probably experienced strong monsoons.

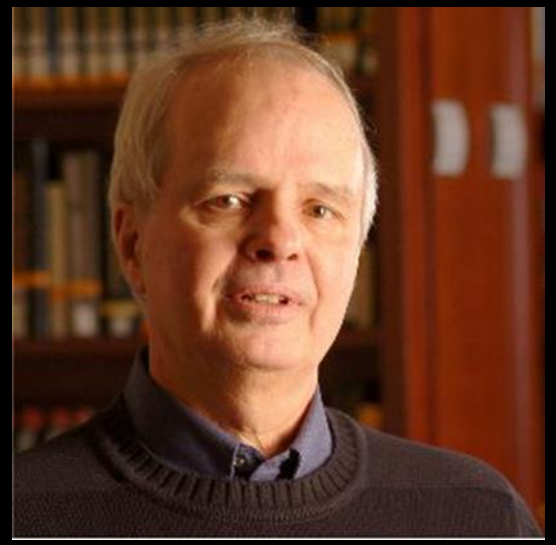
GCMs can only create the super-monsoonal / continental climate if they combine elevated $CO_2$ levels with the clumped continental position.

red beds

# CONCLUDE

Can the positions of tectonic plates determine the timing of ice ages?

Yes, but only in conjunction with changes in $CO_2$ levels (greenhouse effects)



# Polar Position + $CO_2$ changes + ?????

*Meganeura*, dragonfly ancestor with 75-cm wingspan, Carboniferous

So we are back to this question: How can you change $CO_2$ levels over millions of years?

**Where we are:**

$CO_2$ is a crucial driver of Earth's climate

Volcanic hypothesis: *rejected as sole process*

Silicate-weathering hypothesis: highly likely to be important

Polar-position hypothesis: *rejected as sole cause, but may contribute*

NEXT

The BLAG hypothesis

[American Journal of Science, Vol. 283, September, 1983, P. 641-683]

# American Journal of Science

*SEPTEMBER 1983*

## THE CARBONATE-SILICATE GEOCHEMICAL CYCLE AND ITS EFFECT ON ATMOSPHERIC CARBON DIOXIDE OVER THE PAST 100 MILLION YEARS

ROBERT A. BERNER,* ANTONIO C. LASAGA,**
and ROBERT M. GARRELS***

Robert Berner, Yale

# BLAG Hypothesis: spreading-rate hypothesis

"Changes in the rates of sea-floor spreading have controlled rates of recycling of carbon from rock reservoir to atmosphere, and these changes have affected Earth's climate."

# The BLAG (spreading-rate) Hypothesis

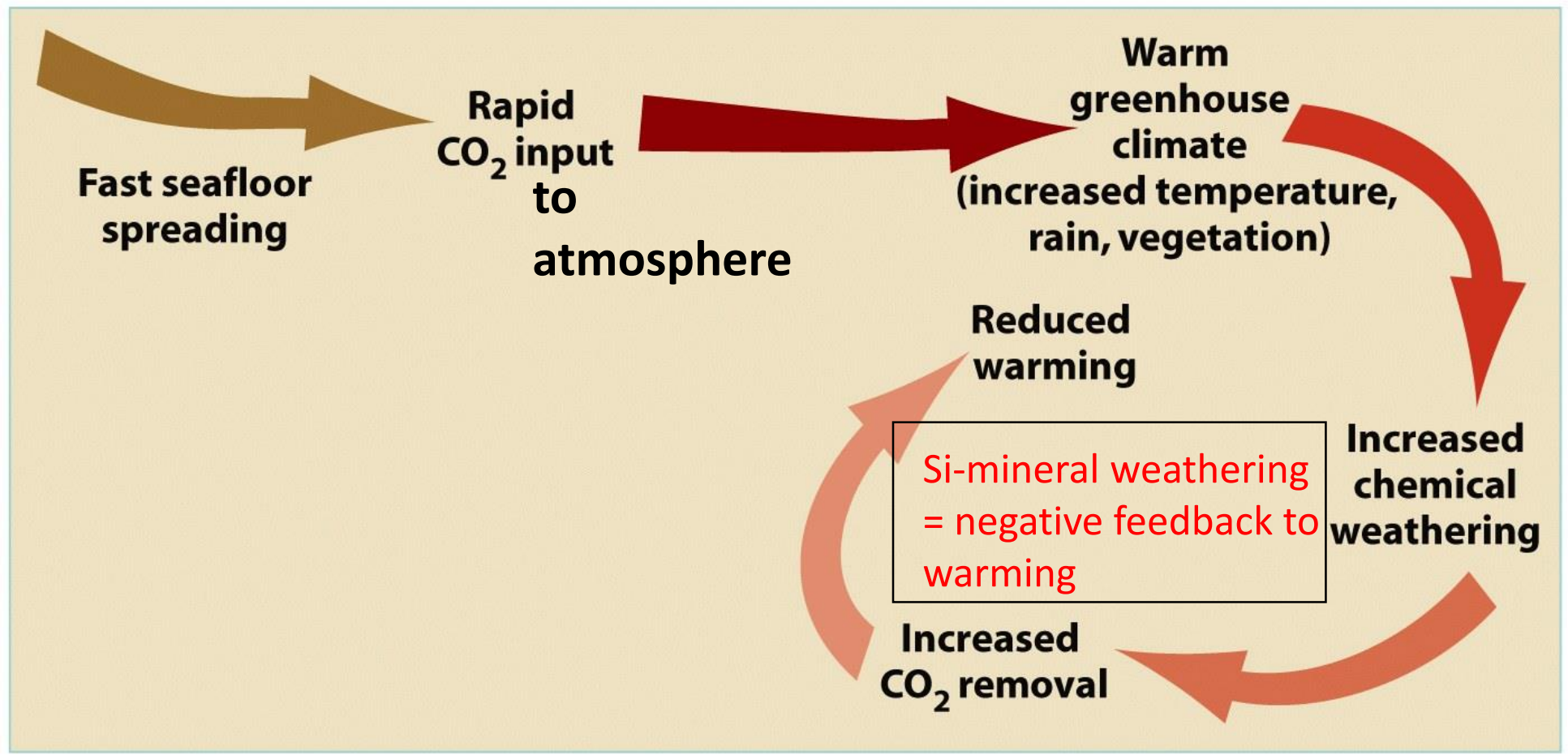



Figure 4-18 part 1
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Note: negative feedback to warming, not to seafloor spreading

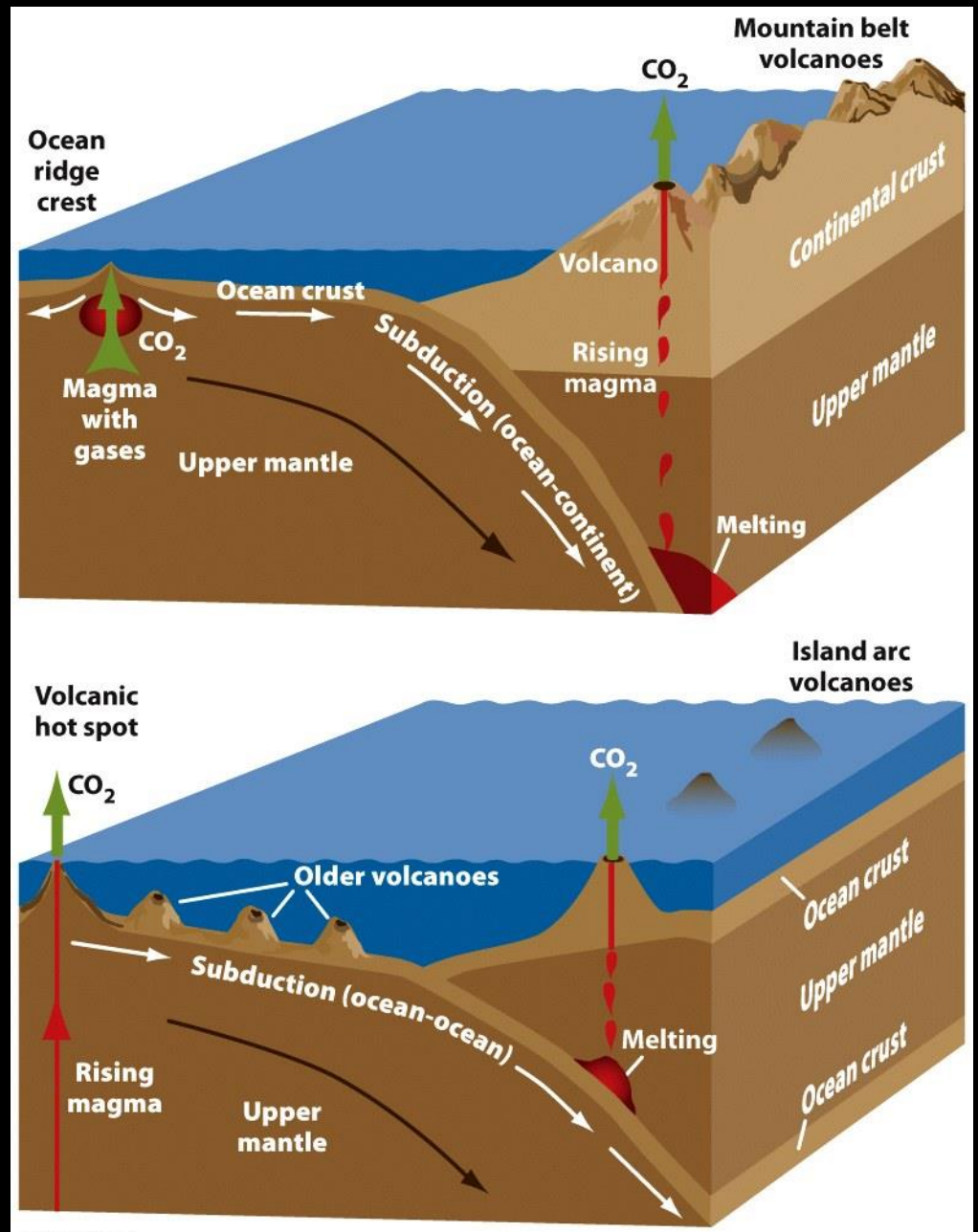
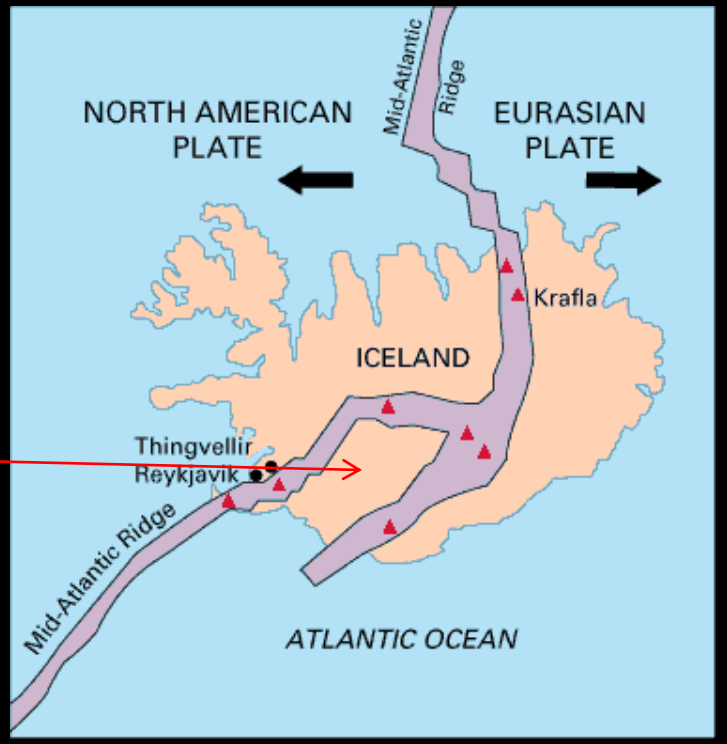



Figure 4-16
*Earth's Climate: Past and Future, Second Edition*


remember: $CO_2$ is recycled from crust to atmosphere at margins of converging plates and at mid-oceanic ridges

# And….we know from paleomagnetic studies of the sea floor that spreading rates vary widely across the Earth today.

Today, Pacific ridge is spreading 10x faster than the mid-Atlantic ridge.



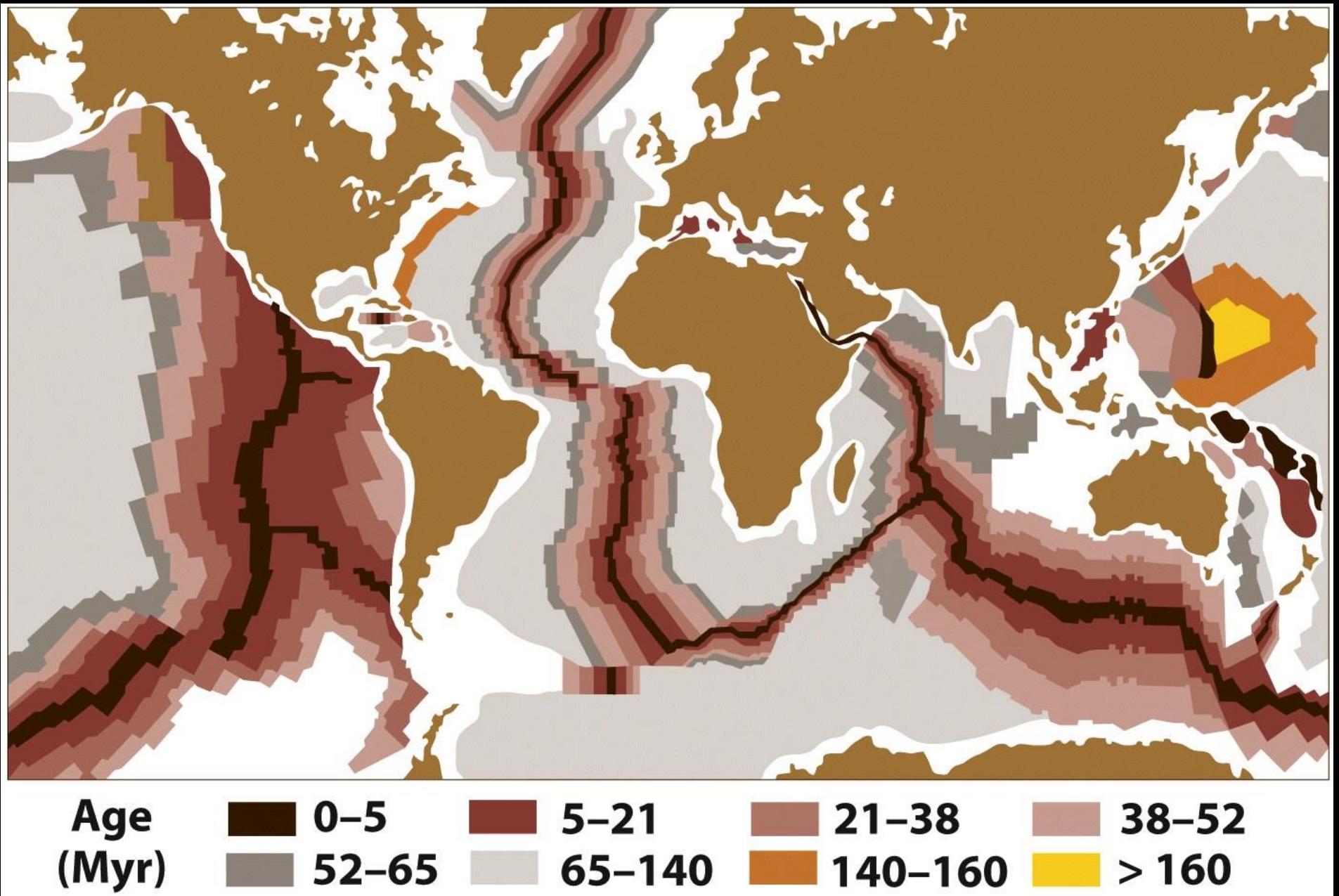



**Figure 4-17**
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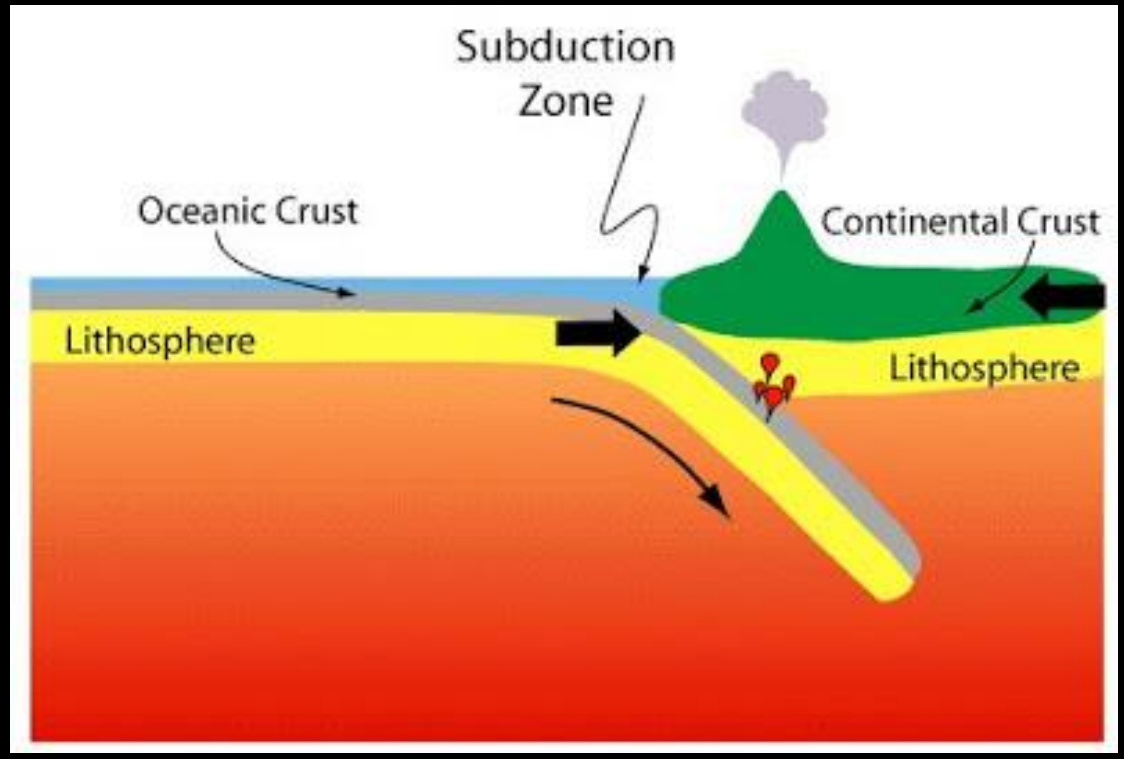
# Melting and transformation in subduction zones

$CaCO_3$ & $SiO_2$ + volcanism → $CaSiO_3$ + $CO_2$ modifies atmosphere's $CO_2$ conc.

ocean sediment — new silicate rock — greenhouse effects



# 10’s of millions years to billions? of years

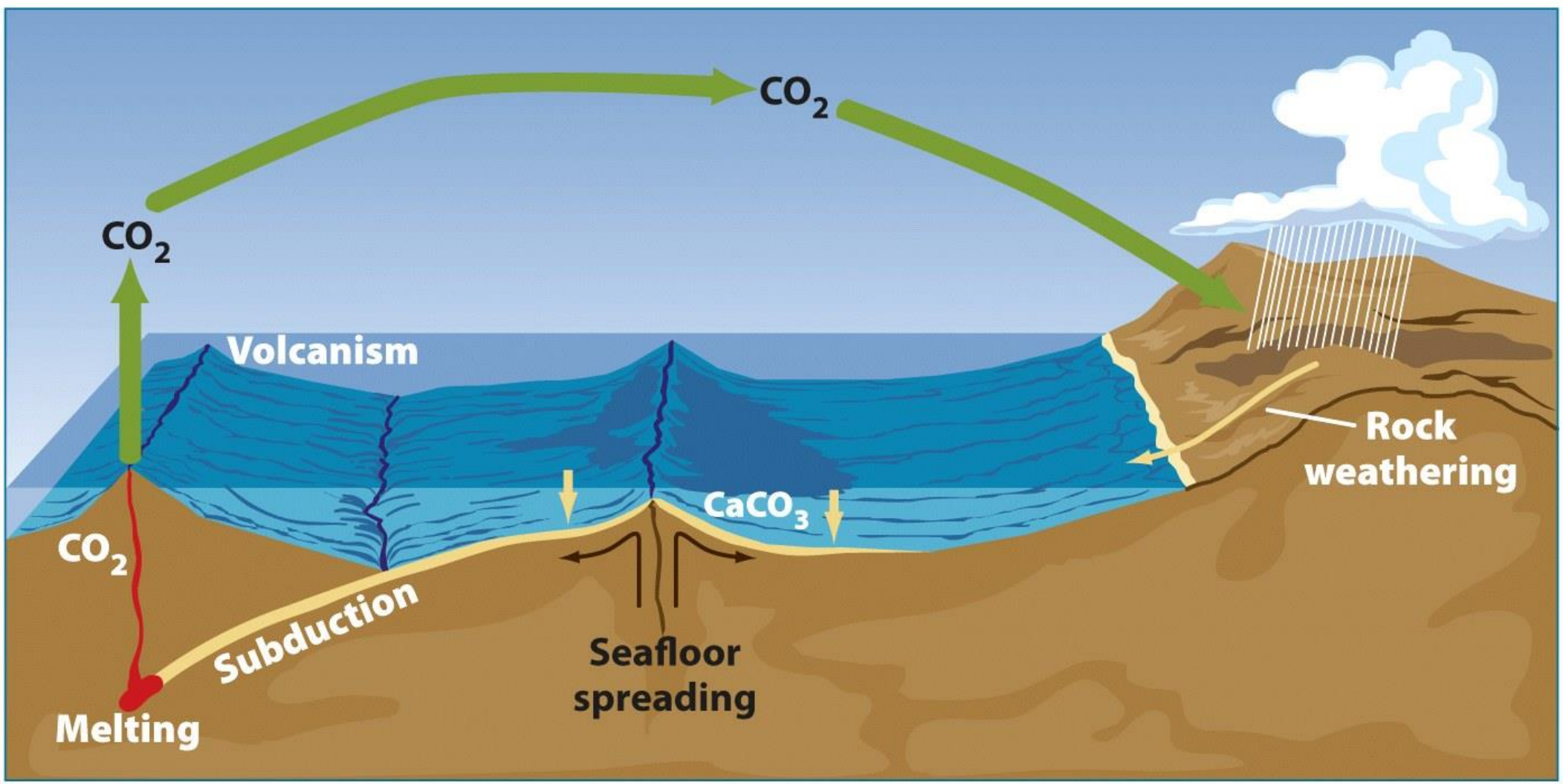



**Figure 4-19**
***Earth’s Climate: Past and Future, Second Edition***

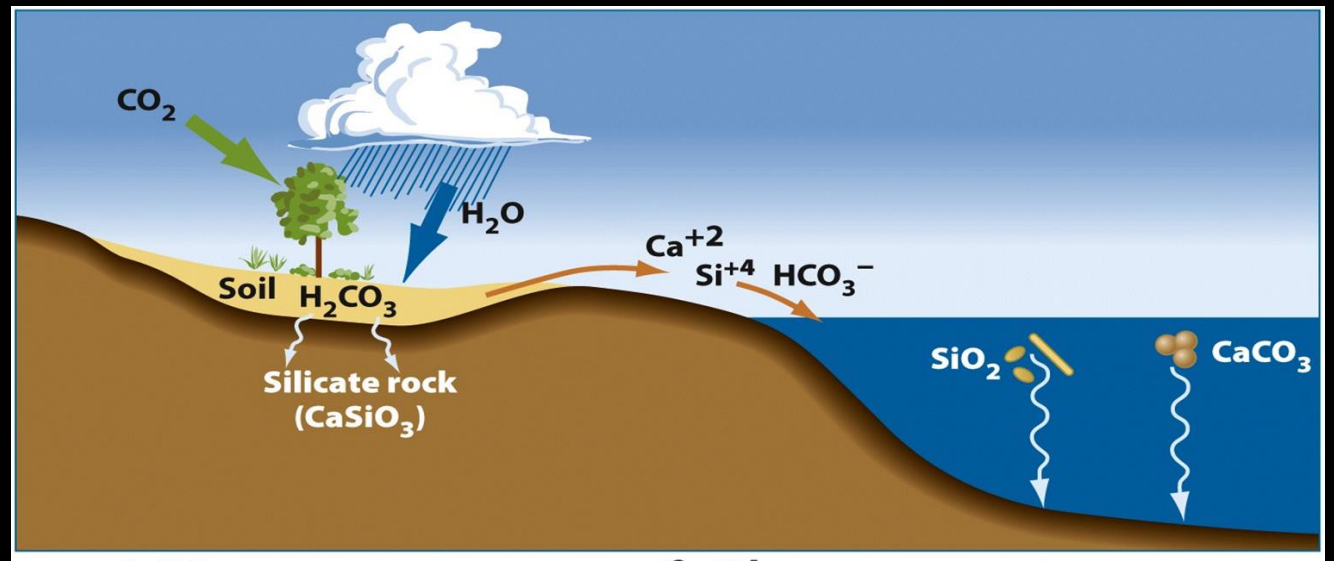
We are looking for Earth's thermostat.

$CO_2$ + *What Else?*

# How do plate tectonics interact with silicate weathering to affect climate?


Is $CO_2$ the global thermostat,
and tectonics the finger that pushes it?

# The BLAG hypothesis:




$CaSiO_3$ + $H_2CO_3$

Silicate bedrock + Carbonic acid in soils

Weathering on land

$Ca^{+2}$ $Si^{+4}$ $HCO_3^-$

Ions dissolved in river water

Transport in rivers

$SiO_2 + CaCO_3$

Shells of ocean plankton

Deposition in

Figure 3-5
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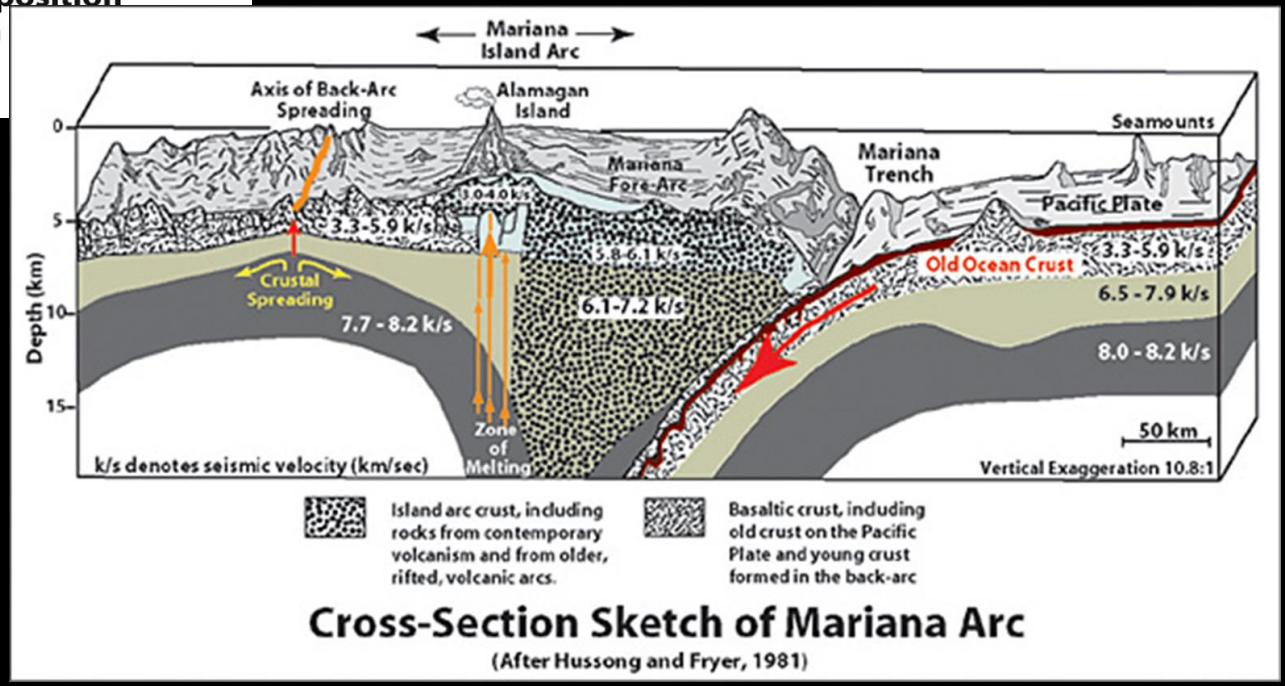
PLUS ?



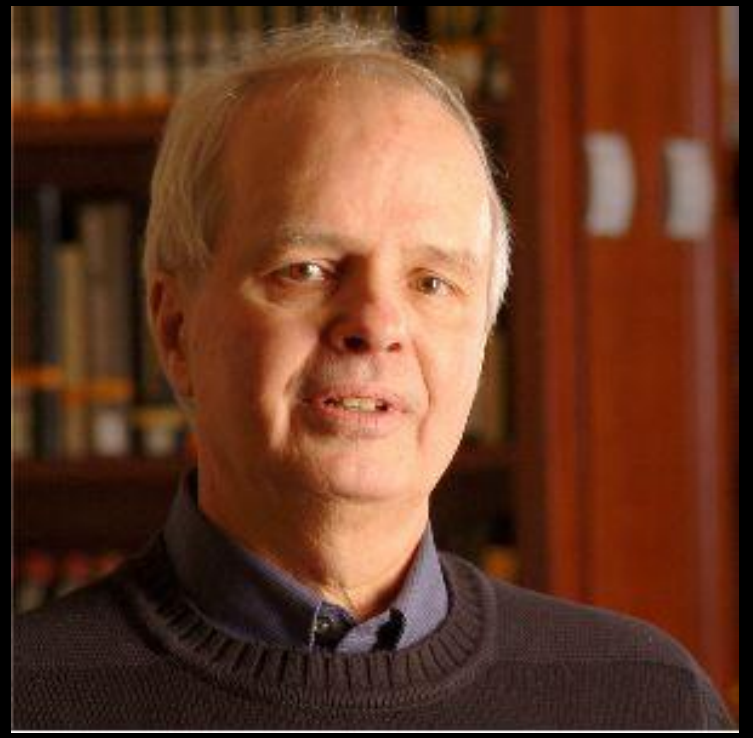

**Cross-Section Sketch of Mariana Arc**

(After Hussong and Fryer, 1981)

## Ruddiman:

The oldest oceanic crust is only ca. 170 my old.

So we cannot evaluate BLAG earlier in Earth's history (e.g., Pangaean climate).



Ruddiman:

Furthermore, about ½ of the oceanic crust older than 50 my old has been lost, so we are limited as to when we can get accurate estimates of spreading rates.

So testing of the BLAG H is inconclusive.