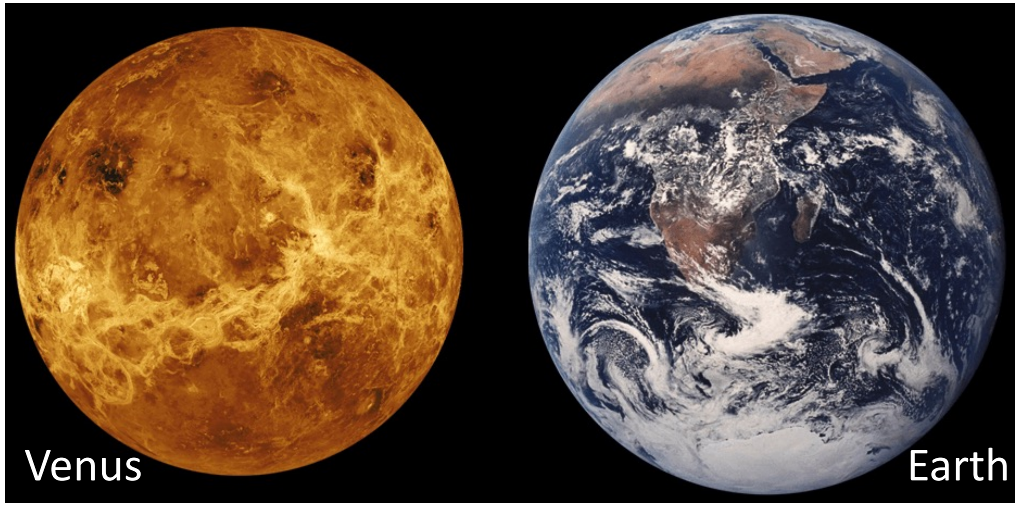
Lecture III
Tectonic-scale climate change

From Ruddiman's EARTH'S CLIMATE – PAST, PRESENT AND FUTURE

Why is Earth habitable?

- Just at the right distance from the sun
- But Sun has warmed by 25-30% over the last 4.5 billion years – so how is it that the Earth remained habitable for most part during this time?
- **Earth’s internal thermostat** that prevented from Oceans to get evaporated or Earth turn into a snowball

Why is Earth habitable and Venus not?



- Mean surface temperature
  Venus: 460°C Earth: 15 °
- Distance from Sun
  72% as far as Earth does
- Solar radiation varies inversely with (distance)^2

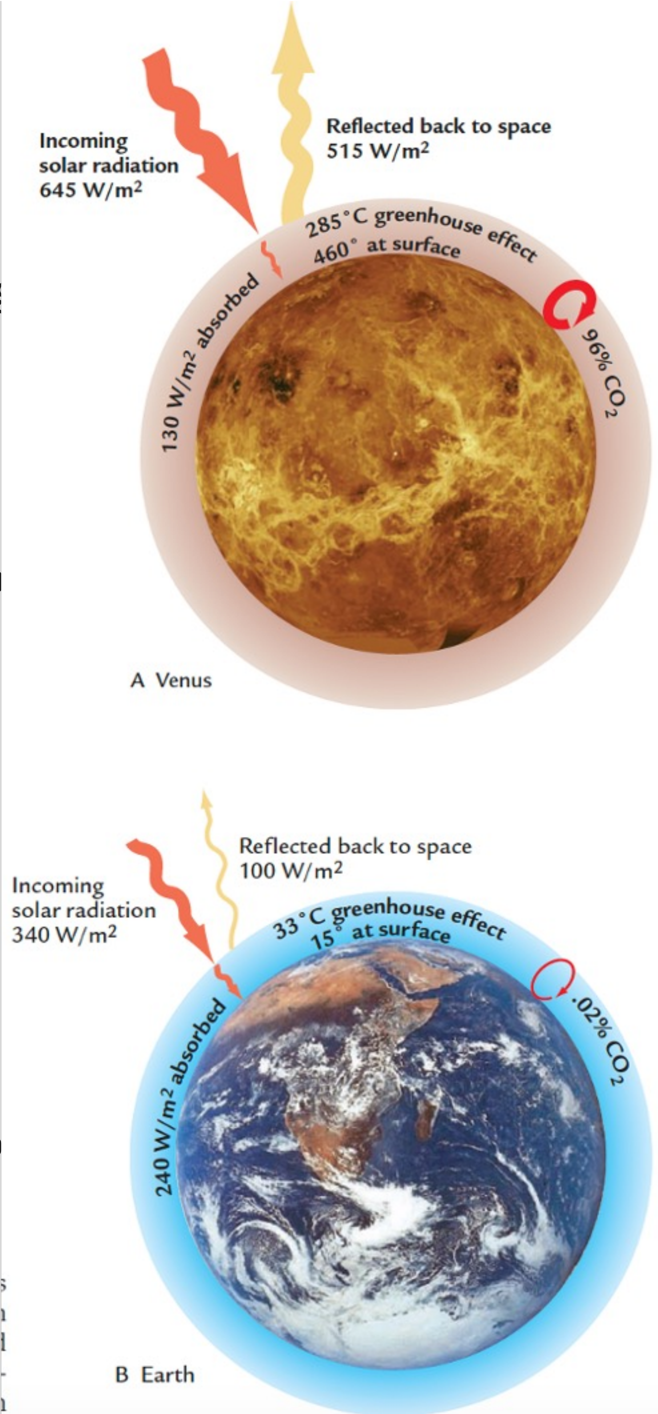
$$\frac{Earth}{Venus} \quad \frac{(1)^2}{(0.72)^2} = \frac{1}{0.518} = 1.93$$

Venus receives twice as much solar radiation than Earth!
However….

Thick sulphuric acid clouds reflect 80% of the total incomin radiation
While Earth's cloud reflect just 26%
Therefore Venus receives ~half the solar radiation than Earth so Venus should be colder!!!

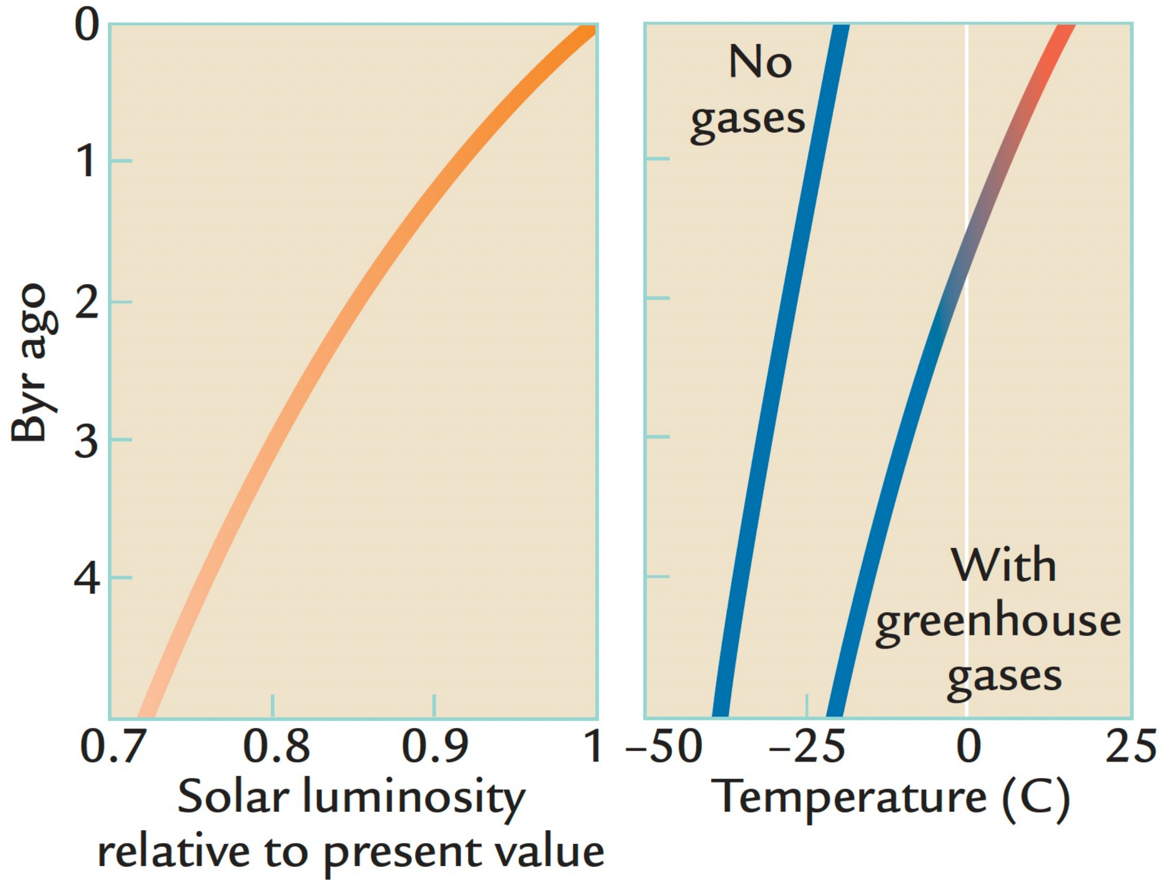
Correct answer is the **atmospheric composition**.

Earth and Venus both have nearly equal amounts of carbo but stored in very different reservoirs
Earth: in rocks
Venus: in atmosphere



The faint Sun paradox

Astrophysical models of the Sun's evolution indicate it was 25% to 30% weaker early in Earth's history (left). Climate model simulations show that the weaker Sun would have resulted in a completely frozen Earth for more than half of its early history if the atmosphere had the same composition as it does today (right).

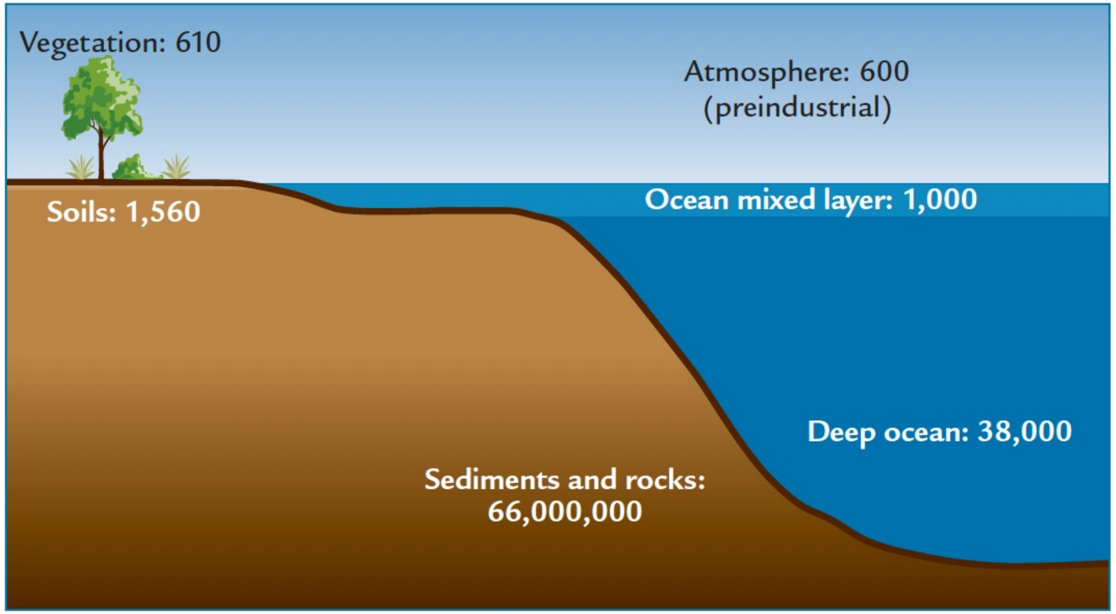


THERMOSTAT at work!!!

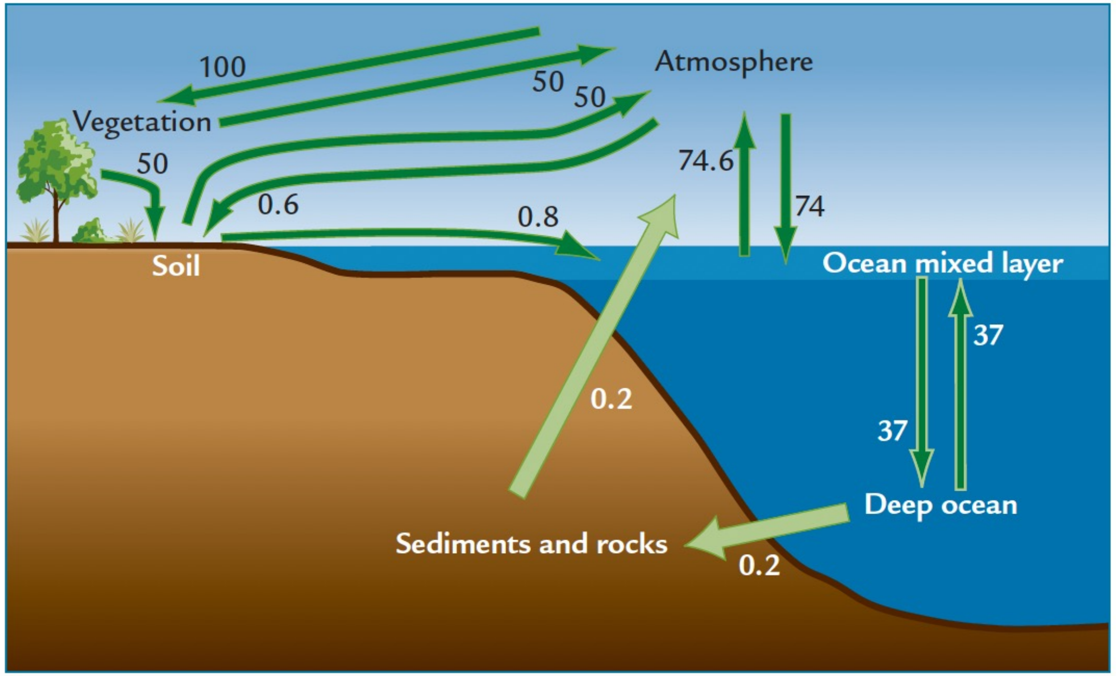
The Carbon cycle

Carbon exchanges between various reservoirs varied at various timescales.

So what worked at Tectonic scales?



A Major carbon reservoirs (gigatons)

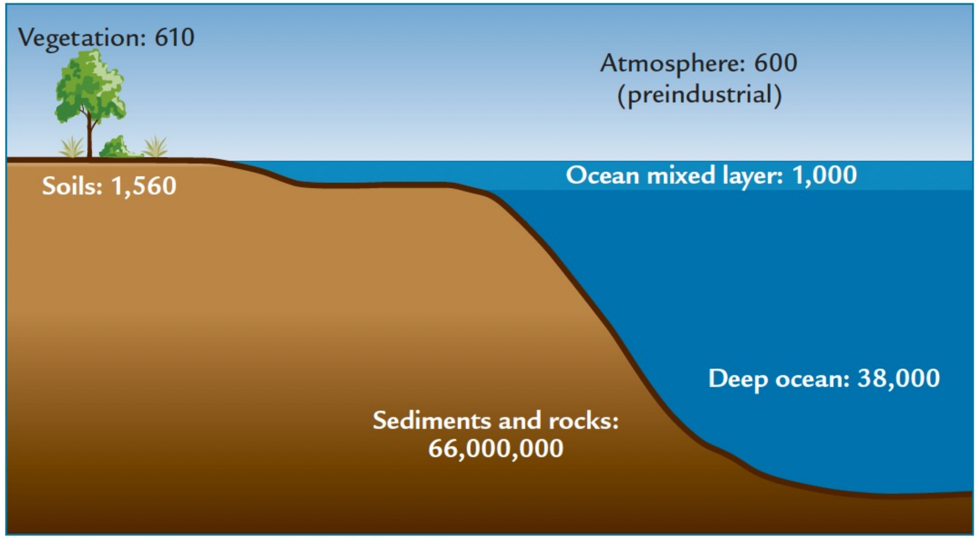


B Carbon exchange rates (gigatons/year)

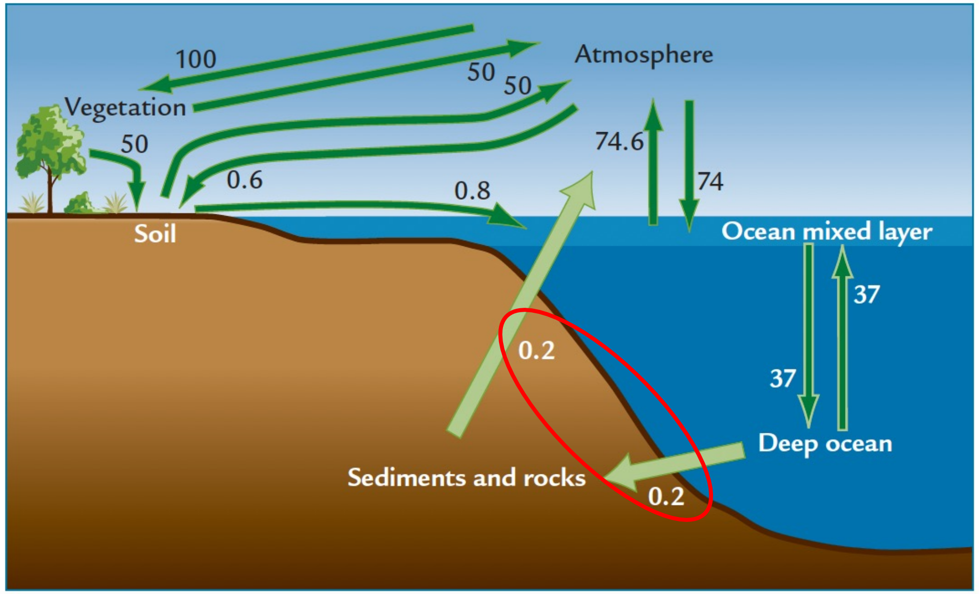
Tectonic scale climate changes

Very gradual climate changes over tens to hundreds of millions of years. Over these very long (tectonic) time scales, the slow carbon exchanges between the rocks and the surface reservoirs are the source of changes in the amount of CO2 in the atmosphere.

This balance between natural input and removal rates helped to keep the size of the "natural" (preindustrial) atmospheric carbon reservoir at ,600 gigatons.

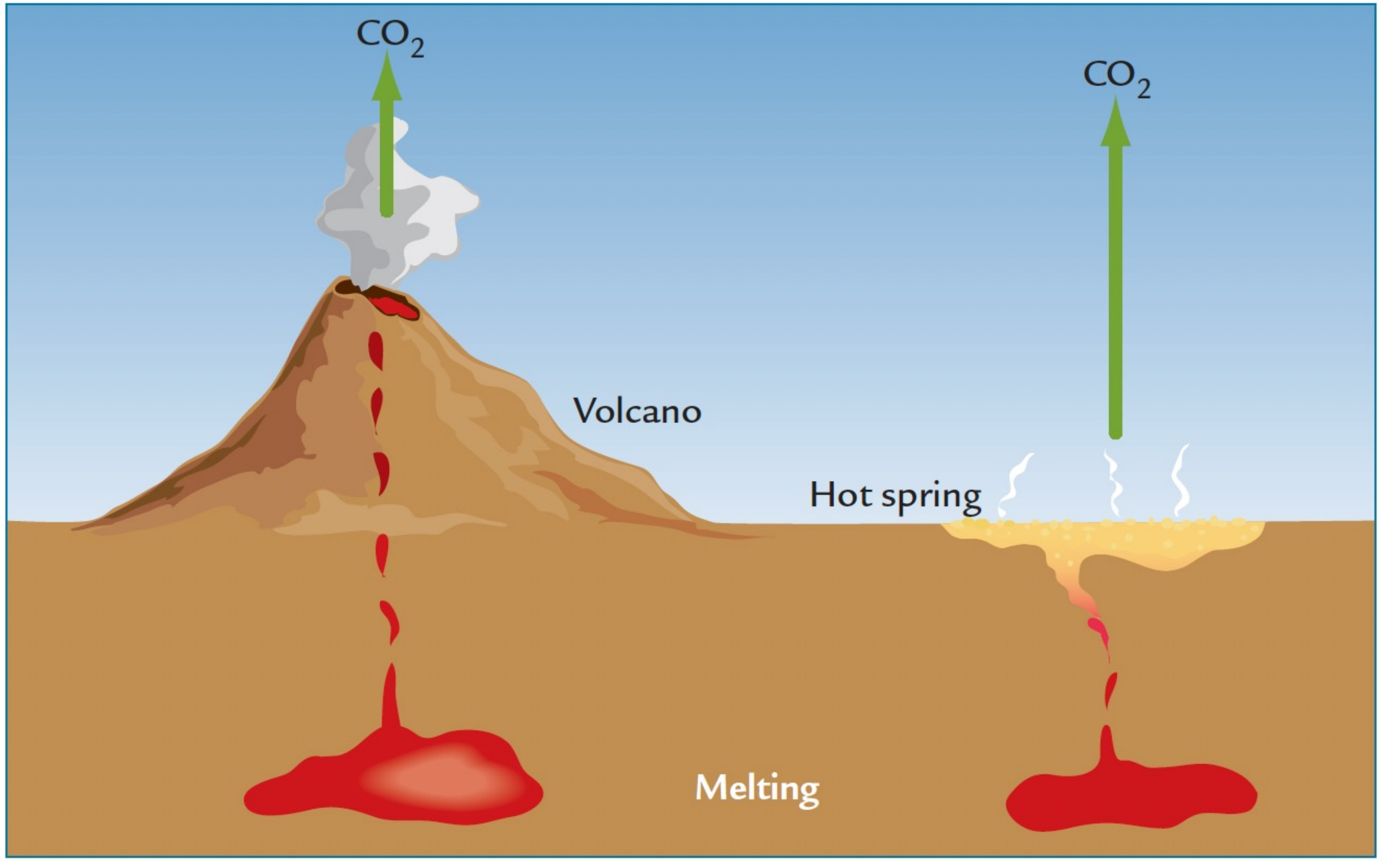


A Major carbon reservoirs (gigatons)



B Carbon exchange rates (gigatons/year)

Volcanic Input of Carbon from Rocks to the Atmosphere



Is this Earth's Thermostat?

Removal of CO_2 from the Atmosphere by Chemical Weathering

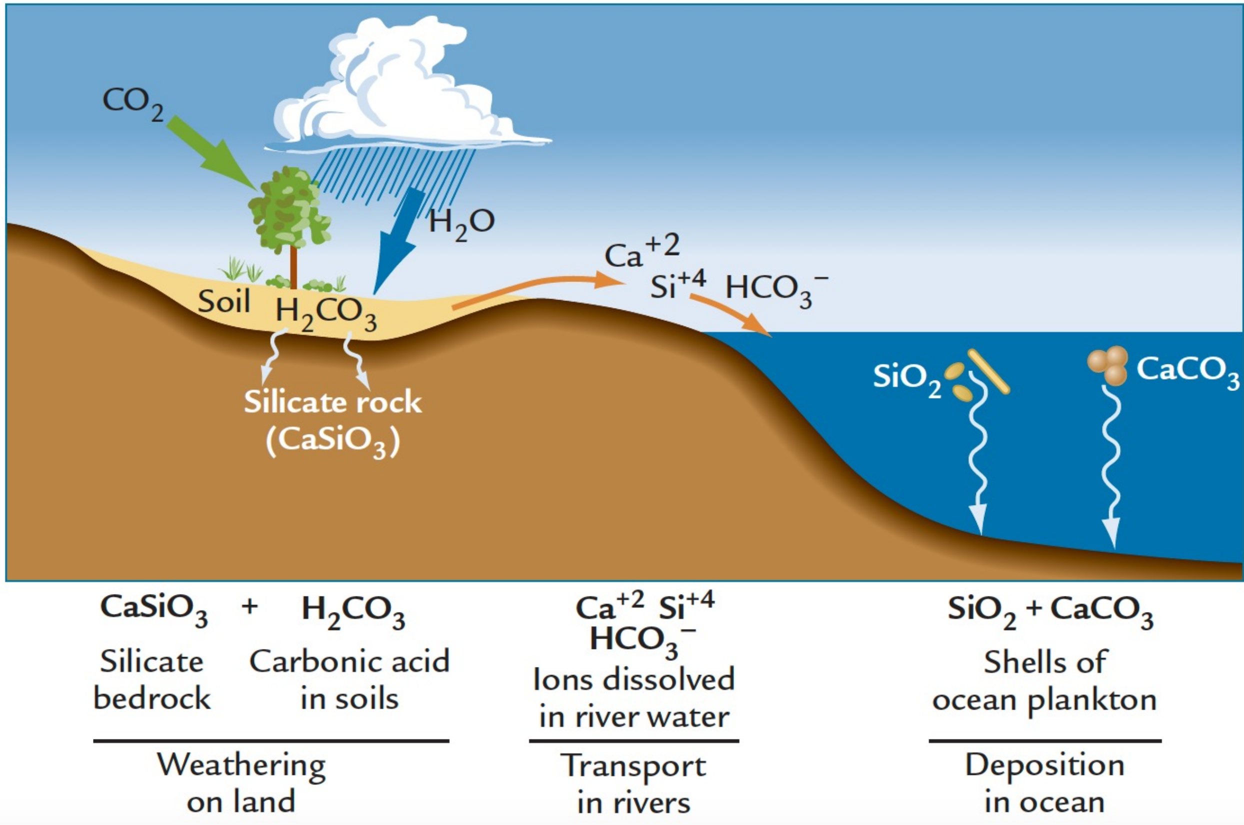
Two major types of chemical weathering occur on continents:

1. ***Hydrolysis***
2. ***Dissolution***

Continental crust consists of rocks such as granite, made of silicate minerals like quartz and feldspar.

Silicate minerals typically are made up of positively charged cations (Na+, K+, Fe+, Mg+, Al+, and Ca+) that are chemically bonded to negatively charged SiO4 (silicate) structures.

Part of the weathered rock is chemically converted to clay minerals (compounds of Si, Al, O, and H) in soils.



Chemical weathering also produces several types of dissolved ions and ion complexes, including HCO3-, CO3(2-), H2SiO4-, H+. These ions are carried by rivers to the ocean, where most are incorporated in the shells of planktic organisms

Removal of CO_2 from the Atmosphere by Chemical Weathering

Two major types of chemical weathering occur on continents:

1. ***Hydrolysis***
2. ***Dissolution***

$$\underset{\text{Rain}}{H_2O} \quad + \quad \underset{\text{From atmosphere}}{CO_2}$$

$$\searrow \quad \swarrow$$

$$\underset{\text{Limestone rock}}{CaCO_3} + \underset{\text{In soils}}{H_2CO_3} \rightarrow \underset{\text{Shells of organisms}}{CaCO_3} + H_2O + \underset{\text{Returned to atmosphere}}{CO_2}$$

Which process is faster?? Hydrolysis or Dissolution?

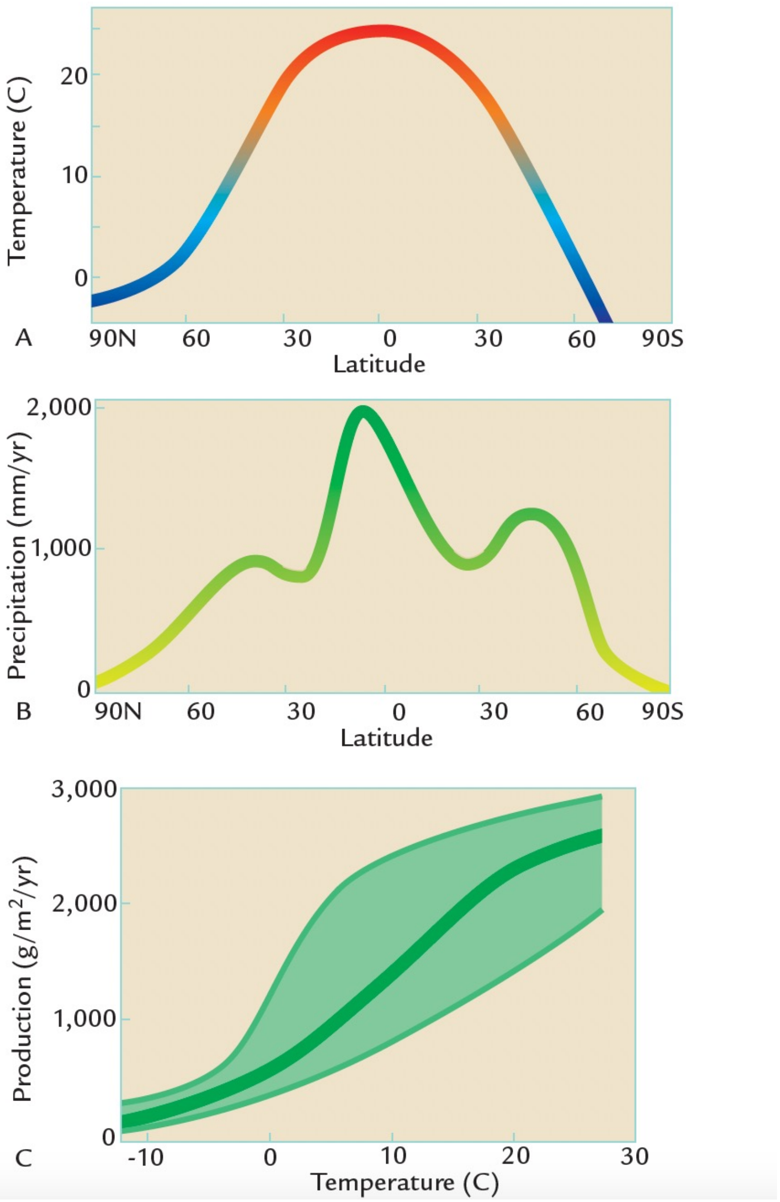
Dissolution of limestone proceeds at much faster rates than hydrolysis of silicates.

Climatic Factors that Control Chemical Weathering

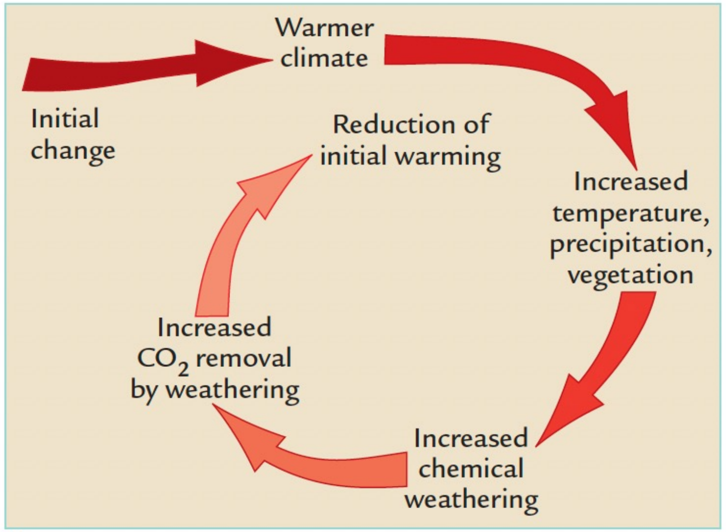
1. *TEMPERATURE: Silicate weathering rates double for each 10◦C increase in temperature across the roughly 30 ◦ C range of mean annual temperatures found on Earth’s surface.*

2. PRECIPITATION: Increased rainfall boosts the level of groundwater held in soils, and the water combines with CO_2 to form carbonic acid and enhance the weathering process.

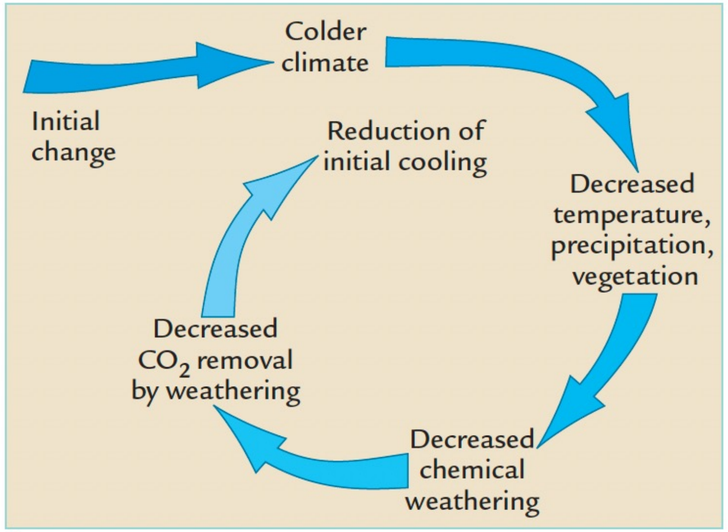
3. VEGETATION: Plants extract CO_2 from the atmosphere through the process of photosynthesis, and deliver it to soils, where it combines with groundwater to form carbonic acid.



So, Is Chemical Weathering Earth's Thermostat?



A



B

How do we apply this concept to the mystery of the faint young Sun paradox?

Faint young sun paradox

We need to account for a global thermostat that made it

→ warmer early in Earth's history to counter the weakness of the early Sun,
→ cooling effect as the strengthening Sun provided greater heat.

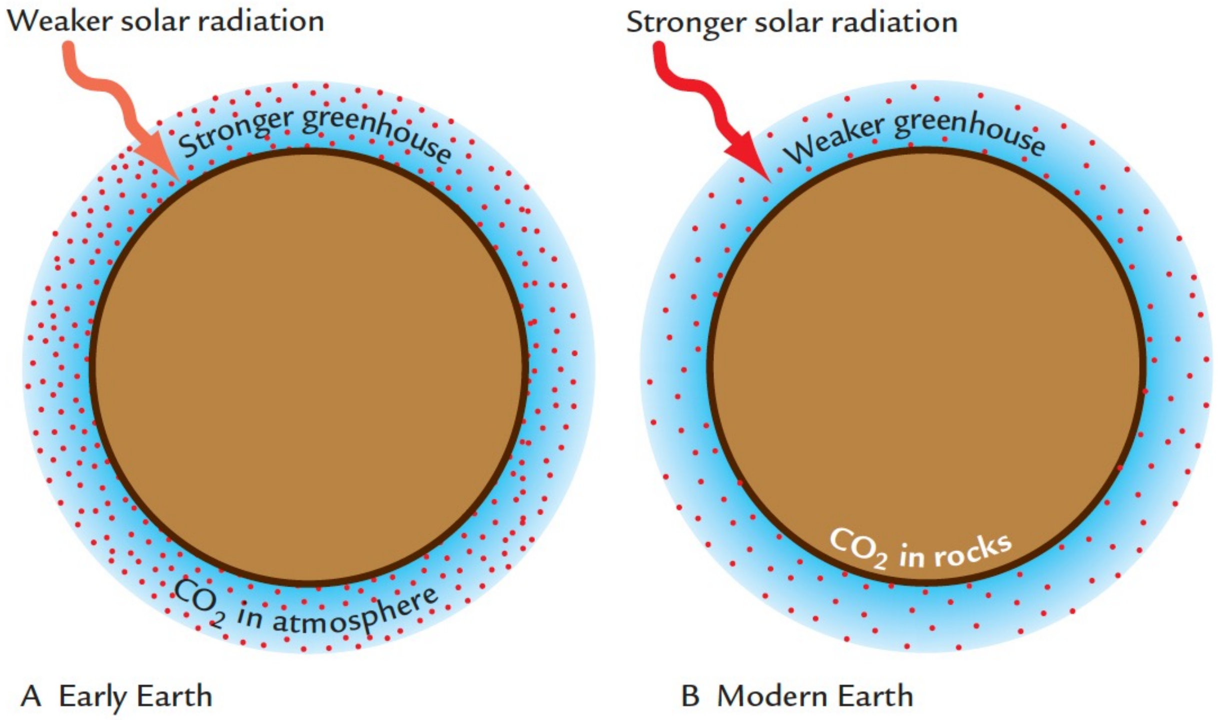


FIGURE 4-8
Earth's thermostat
A plausible explanation of the faint young Sun paradox is that the weakness of the early Sun was compensated for by a stronger CO_2 greenhouse effect in the atmosphere (A). Later, when the Sun strengthened, increased chemical weathering deposited the excess atmospheric greenhouse carbon in rocks, and the weakened greenhouse effect kept Earth's temperatures moderate (B). (ADAPTED FROM W. BROECKER AND T.-H. PENG, *GREENHOUSE PUZZLES* [NEW YORK: ELDIGIO PRESS, 1993].)

Plate tectonics

The lithosphere consists of a dozen tectonic plates, each drifting slowly across Earth's surface.
These plates move at rates ranging from less than 1 up to 10 centimeters per year and average about the same rate of growth as a fingernail.
Over a time span of 100 million years, even slow plate motions of 5 centimeters per year add up to shifts of 5,000 kilometers, enough to create or destroy an entire ocean basin.

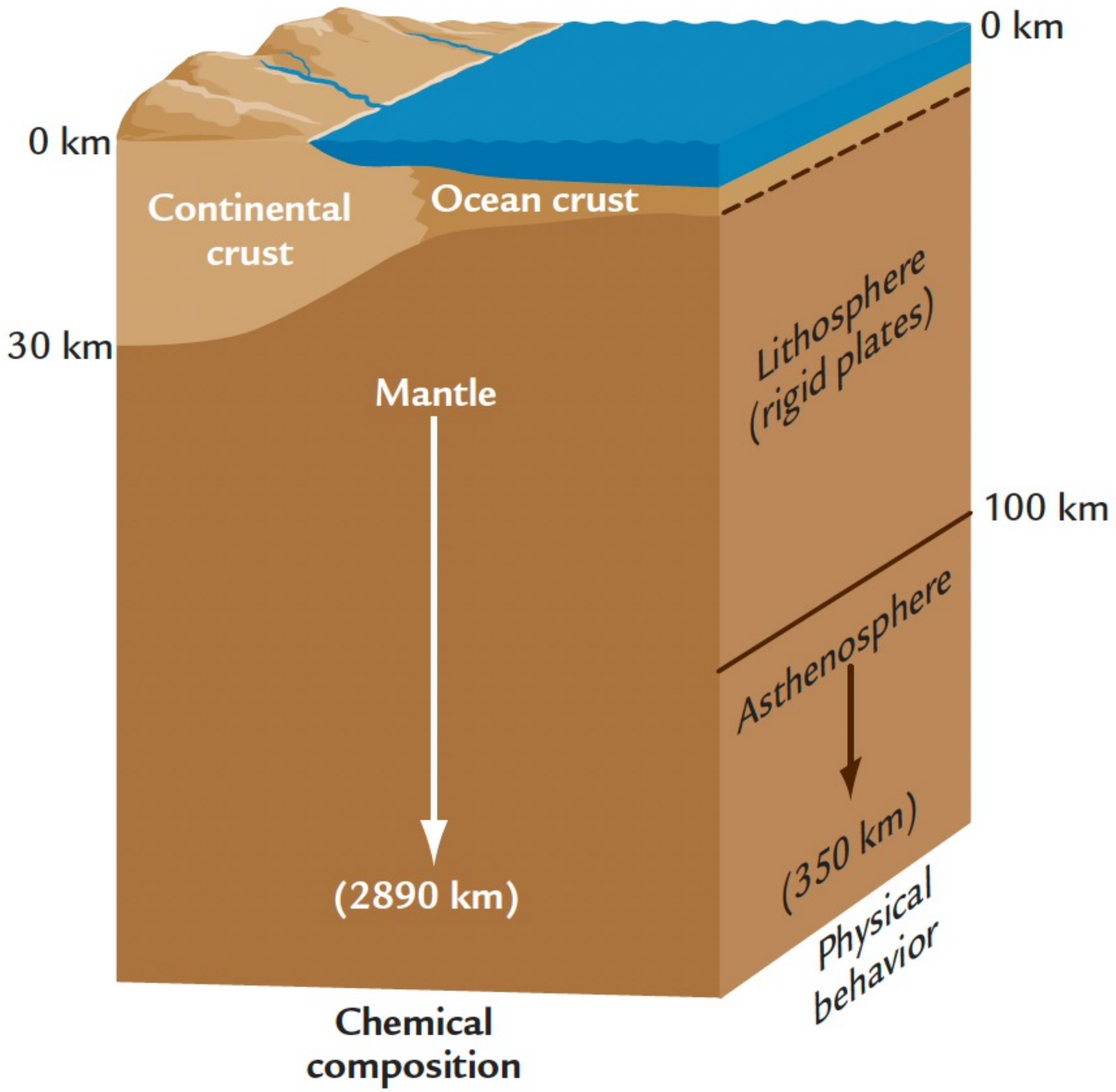
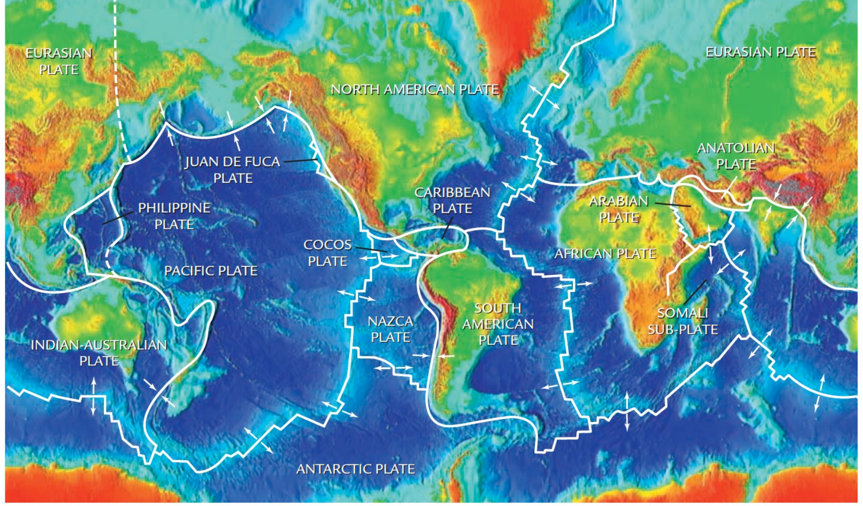


Plate tectonics



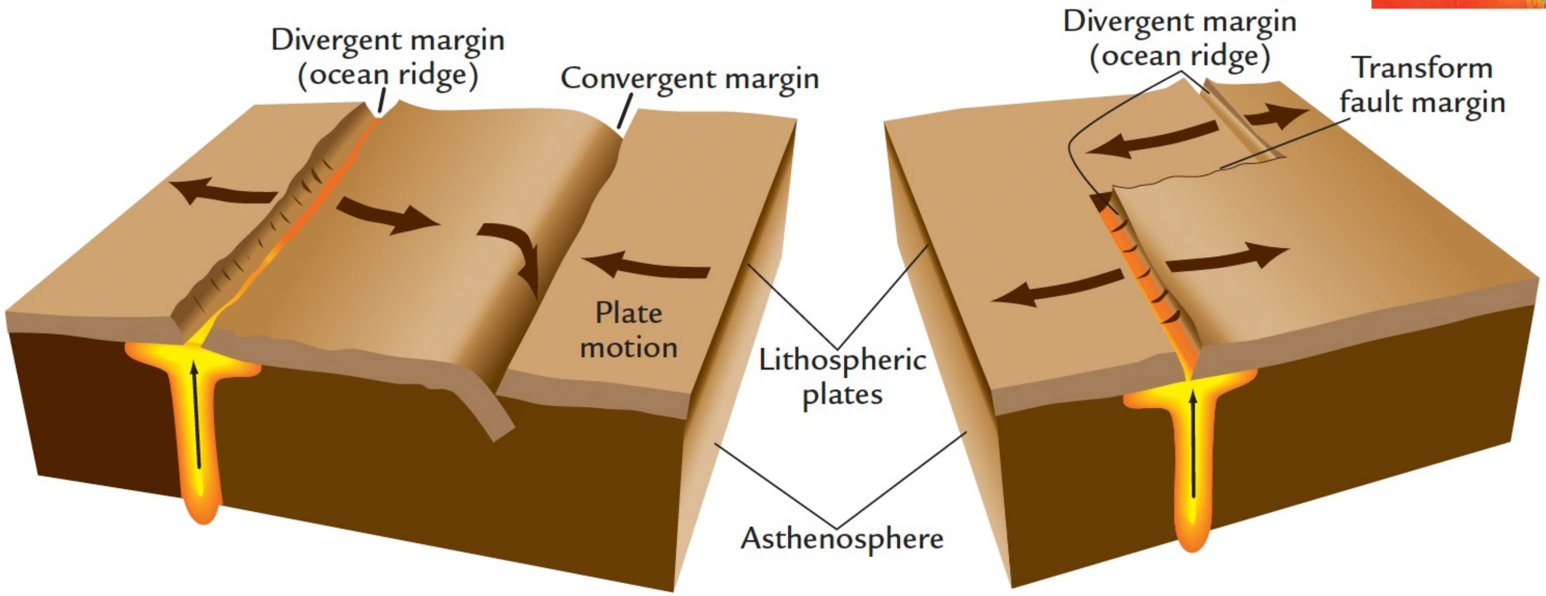
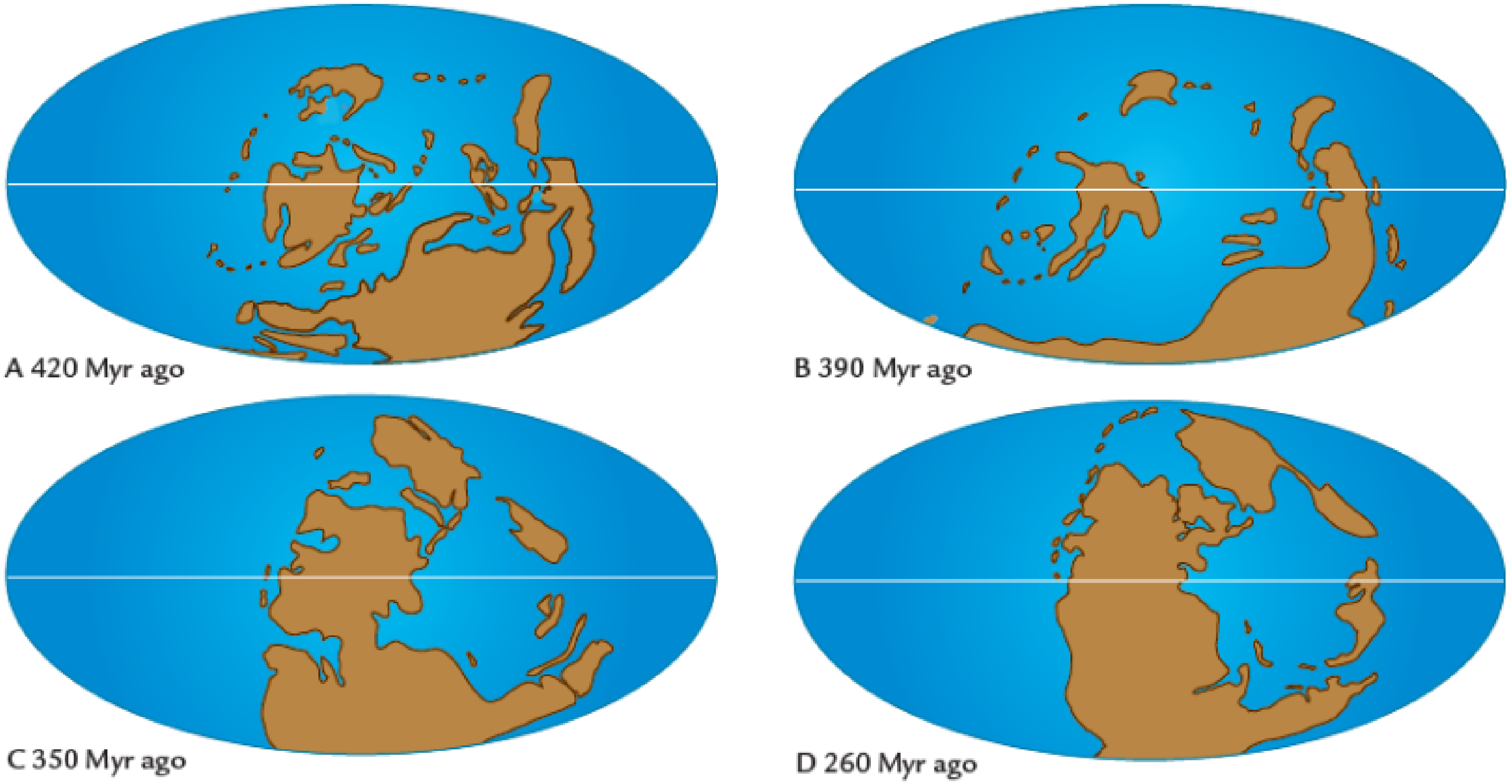


FIGURE 5-4
Plate margins

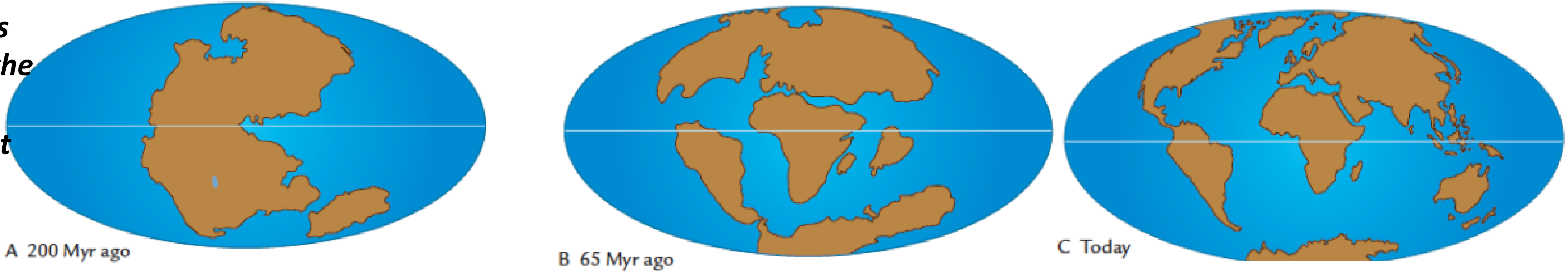
Earth's tectonic plates move apart at ocean ridges (divergent margins), slide past each other at faults (transform fault margins), and push together at convergent margins. (MODIFIED FROM F. PRESS AND R. SIEVER, *UNDERSTANDING EARTH,* 2ND ED., © 1998 BY W. H. FREEMAN AND COMPANY.)

Plate tectonics and moving continents

Southern continent Gondwana carried towards continents across NH



Collisions formed the giant continent Pangea



Past Glaciations and continental positions

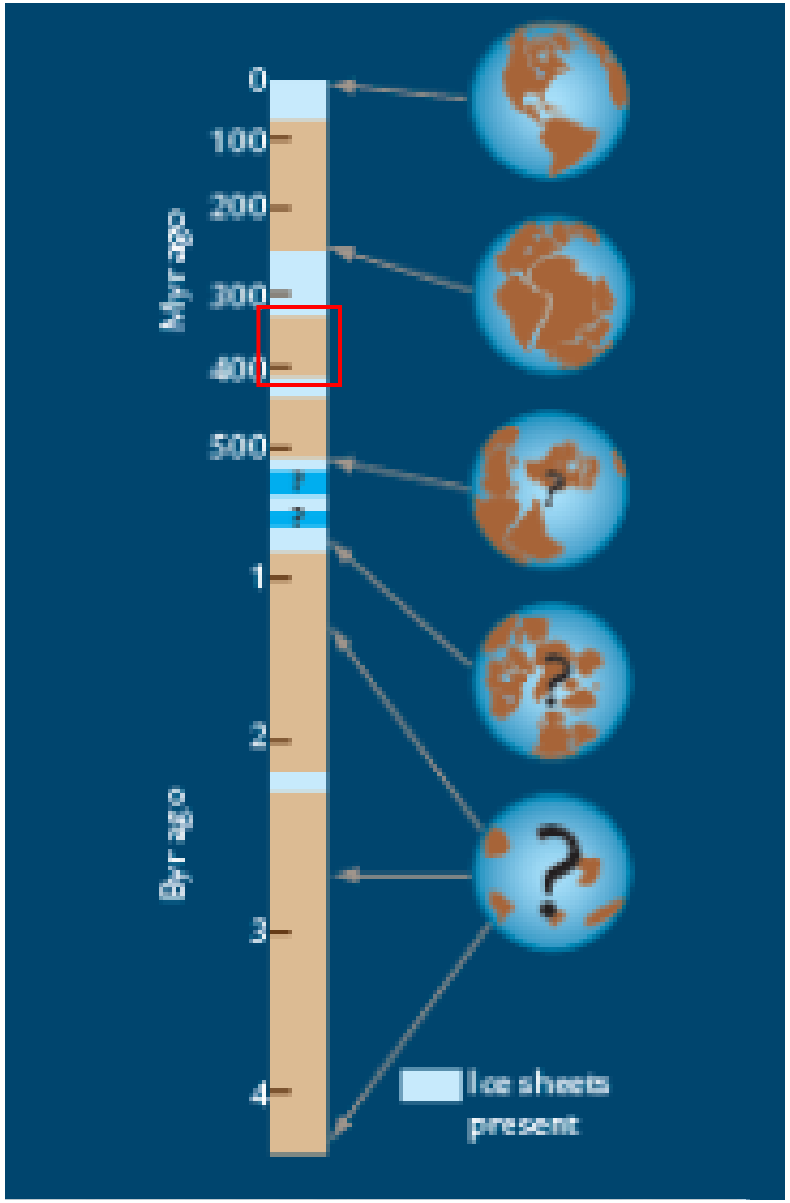
Three major Ice house eras:

- 440 Myr
- 325 to 240 Myr
- Last 35Myr to present

What led to Ice house eras?
Polar position of continents:

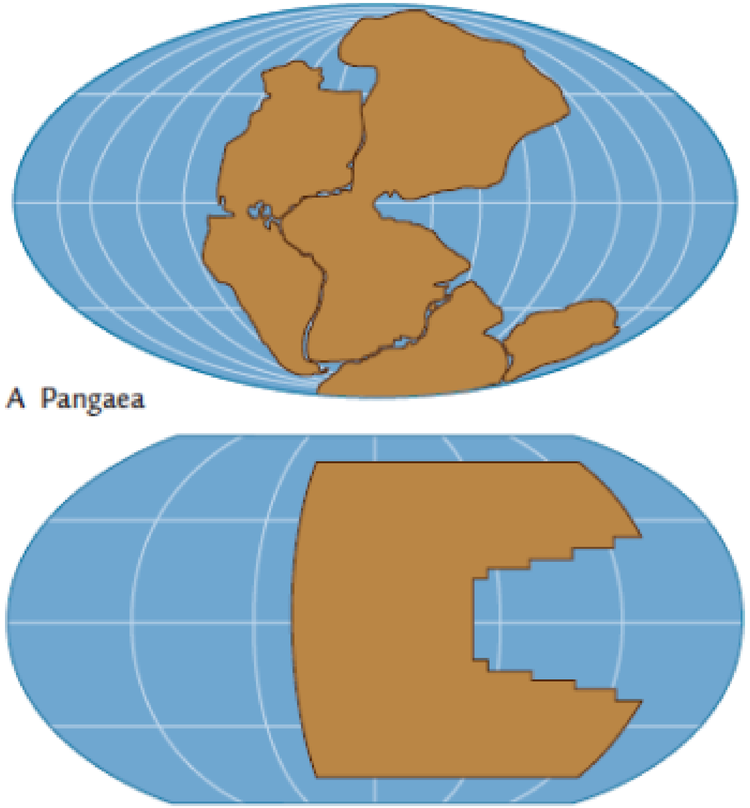
BUT not everytime, such as
425 Myr-325Myr

What prevented the Ice sheets to form then?



How has Earth sustained life over millions of years?

Pangea – 'All earth'



A Pangaea

B Pangaea in model grid

- No ice sheets existed on Pangea at ~200Myr,

even though northern and southern limits lay within the Arctic and Antarctic circles

- Palm like vegetation was found as high as 40 deg N during Pangean times

- Most likely reason for a warmer Pangea is higher CO2

- Model experiments assumed a level of 1650ppm, almost **SIX** times the preindustrial value of 260 parts ppm!!!!

Greenhouse climates

- 100 Ma years ago: well studied, *positions of all the continents are known*

- *climate scientists know much more about Earth's climate100 million years ago, including the fact that it was warm enough at the South Pole to keep large (or possibly any) ice from accumulating.*

What explains the warmth 100 Ma years ago?

What explains the warmth 100 Ma years ago?

- *Around 175 million years ago, the giant single continent of Pangaea began to break apart.*
- *By 100 million years ago, most of the continents had separated from one another, producing a very different-looking Earth consisting of a half-dozen smaller continents.*
- *In addition, global sea level stood at least 80 to 100 meters higher than it does today, and a shallow layer of ocean water flooded continental margins and lowlying interior areas.*
- *The geographic effect of this flooding was to fragment the existing continents into even smaller and areas, making the geography of this greenhouse world even more unlike the single Pangaean landmass of 200 million years ago.*

100 Ma years warming

Geologists call this interval the middle Cretaceous, a word meaning “abundance of chalk,” because marine limestones deposited by the high seas during this interval are common around the world. This interval is important to climate scientists because geologic records contain no evidence of permanent ice anywhere on Earth, even on the parts of the Antarctic continent situated right over the South Pole. Much of this interval seems to have been a warm greenhouse world.

Marine limestone deposits that today form the coasts of southern England and northern France are evidence of higher sea levels 100 Myr ago.

The Cretaceous

The Cretaceous is a geological period that began ~145 million years ago and ended 66 million years ago.

The Early Cretaceous Epoch lasted from 145 million years ago to 100.5 million years ago and the Late Cretaceous Epoch lasted from 100.5 million years ago to 66 million years ago.

CO2 levels even higher than four times the modern level appear to be a major cause of the warmer climate 100 million years ago.

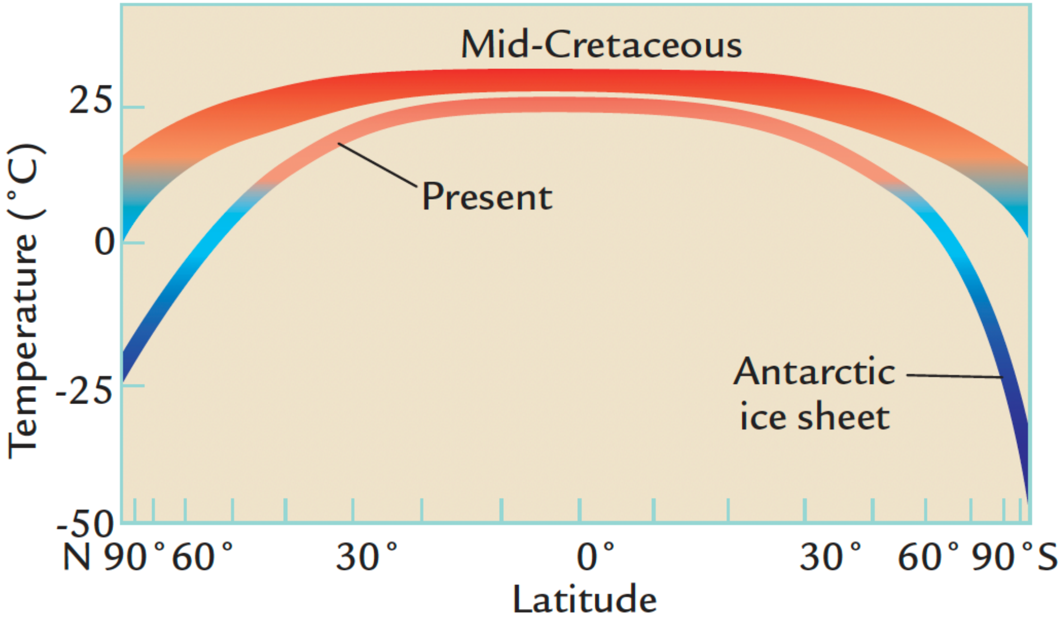


FIGURE 6-3

The Cretaceous target signal

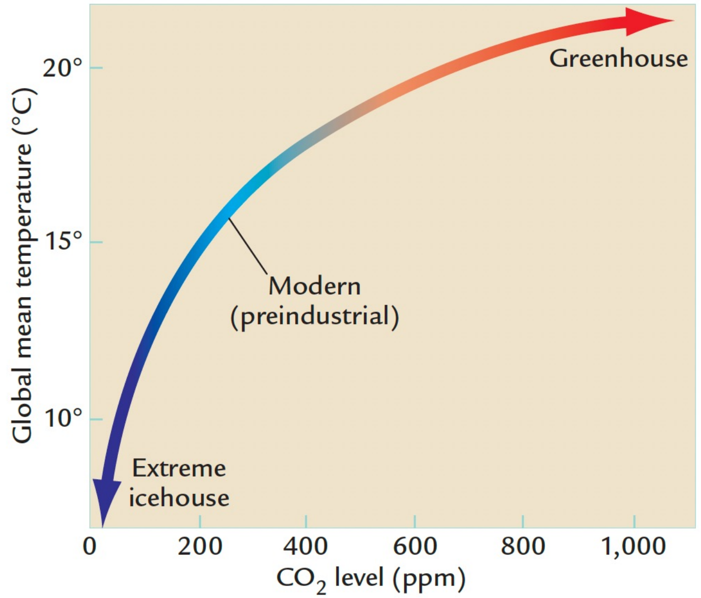
Climate scientists used geologic data (faunal, floral, and geochemical) to compile an initial estimate of temperatures 100 Myr ago. Temperatures were warmer than they are today at all latitudes, especially in polar regions. (ADAPTED FROM E. J. BARRON AND W. M. WASHINGTON, "WARM CRETACEOUS CLIMATES: HIGH ATMOSPHERIC CO_2 AS A PLAUSIBLE MECHANISM," IN *THE CARBON CYCLE AND ATMOSPHERIC CO_2: NATURAL VARIATIONS, ARCHAEAN TO PRESENT*, ED. E. T. SUNDQUIST AND W. S. BROECKER, GEOPHYSICAL MONOGRAPH 32 [WASHINGTON, D.C.: AMERICAN GEOPHYSICAL UNION, 1985].)

Relevance of Past Greenhouse Climate to the Future

Climate scientists have run a series of GCM sensitivity tests using Earth's present geography as a common boundary-condition input to all simulations, but allowing the level of atmospheric CO2 to vary from as low as 100 ppm to as high as 1,000 ppm. The preindustrial ("modern") value of 280 ppm lies in the lower part of this range.

Results:
global average temperature rises with increasing CO2 levels, but the relationship is not linear (directly proportional).

Instead, Earth's temperature reacts strongly to CO2 changes at the lower end of the range, but much less so to changes at the high end of the range.



Earth's temperature reacts strongly to CO_2 changes at the lower end of the range, but much less so to changes at the high end of the range – WHY??

1. Positive feedback effect provided by snow and sea ice:

Icehouse world: CO_2 increases greatly reduce the extent of the bright reflective area of ice, while CO_2 decreases enlarge it.
Greenhouse world: At CO_2 levels near 1,000 ppm, small areas of snow and ice provide little positive feedback to changes in CO_2. As a result, the climate system in a greenhouse world is much less sensitive to changing CO_2 levels.

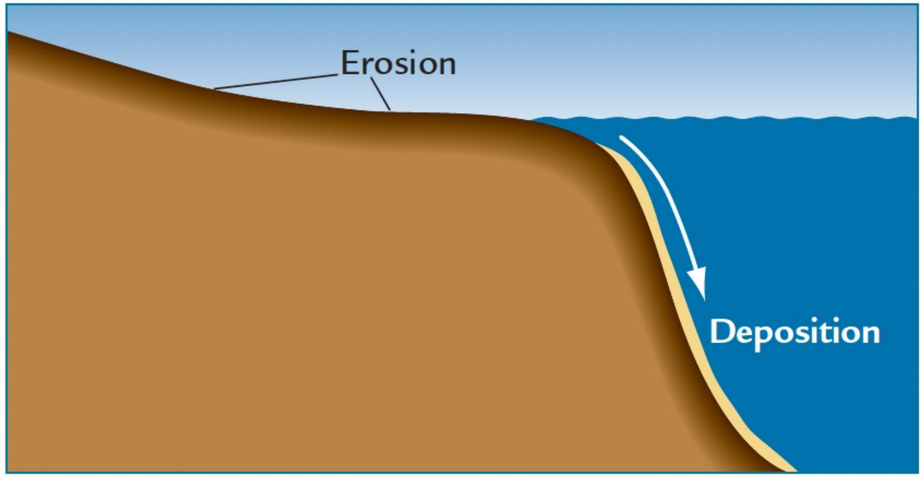
2. CO2 saturation: As CO_2 concentrations rise, the atmosphere gradually reaches the point at which further CO_2 increases have little effect in trapping additional back radiation from Earth's surface.

Past vs future warming

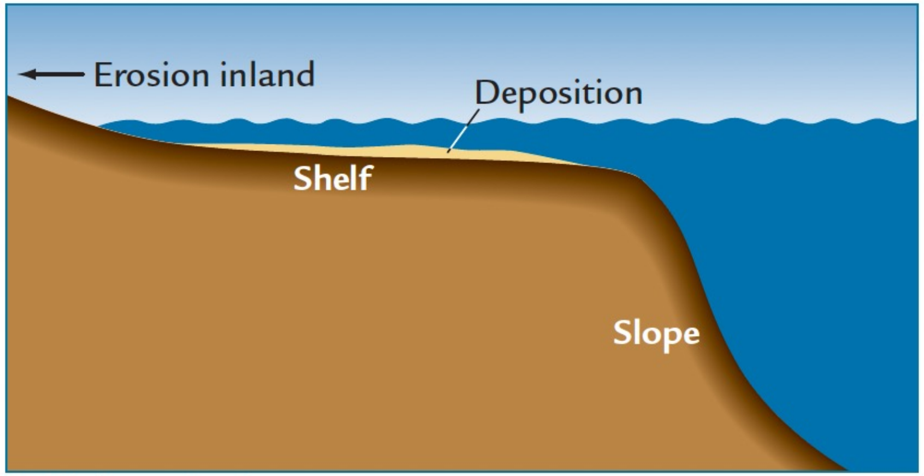
- *In the last 100 years, the CO2 concentration in the atmosphere has risen from 280 ppm to over 400 ppm because of the industrial activities of humans.*
- *Projections for the next two centuries indicate increases to at least 550 ppm, and possibly 1,000 ppm or more, nearly as high as those in the Cretaceous.*
- *We are heading back into a greenhouse world, but this time at a far more rapid rate than anything found in the geologic record.*

Marine transgression and regression

- *Over tectonic time scales, the average level of the world ocean has risen and fallen by 200 meters or more against the margins of the continents. These changes, called* ***marine transgressions and regressions.***
- *Evidence for higher global sea levels in the past comes from the presence of marine sediments deposited simultaneously of coastal margins and in shallow interiors of continents at levels well above present sea level*
- *Deposition of marine sediments on several continents at the same time indicates that the changes in sea level are global in scale and not just local in extent.*

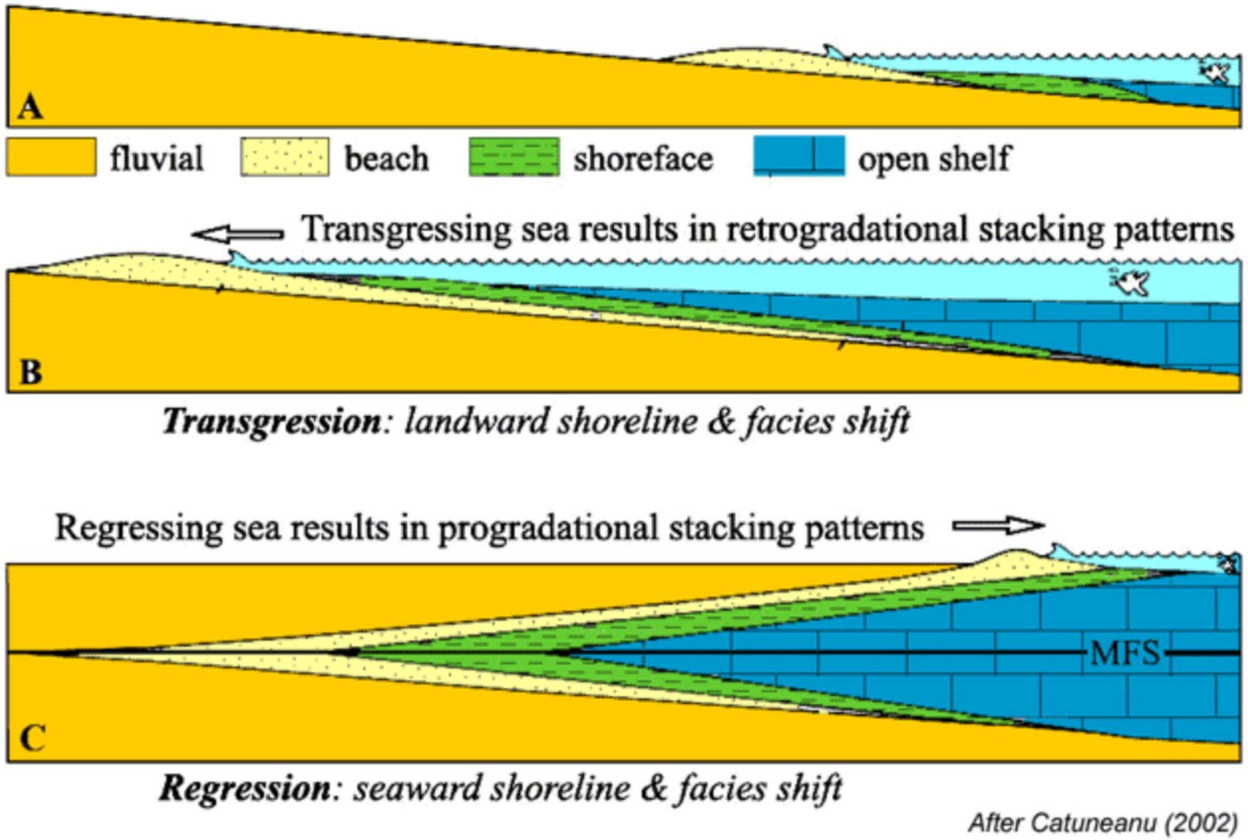


A Low sea level



B High sea level

Marine transgression and regression



Maximum flooding surface

Transgression – landward migration of marine sedimentary environments in response to a rise in sea level
Regression – sea ward migration of marine sedimentary environments in response to a drop in sea level

Catuneanu, Octavian (2002), sequence stratigraphy of clastic systems: concepts, merits, and pitfalls Journal of African Earth Sciences, Volume 35, Issue 1, Pages 1-43.

High cretaceous sea levels

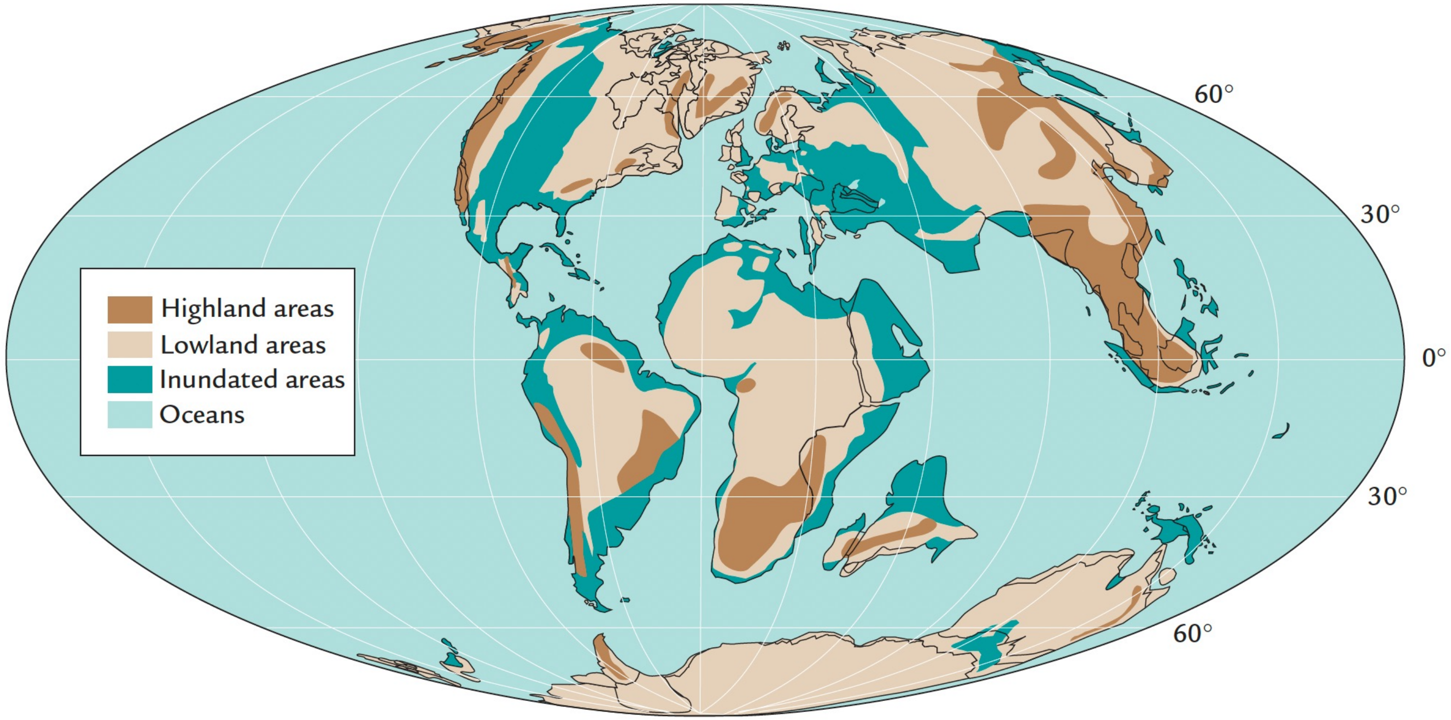


FIGURE 6-1
The world 100 Myr ago

The higher sea levels 80 to 100 million years ago have been attributed to *:*

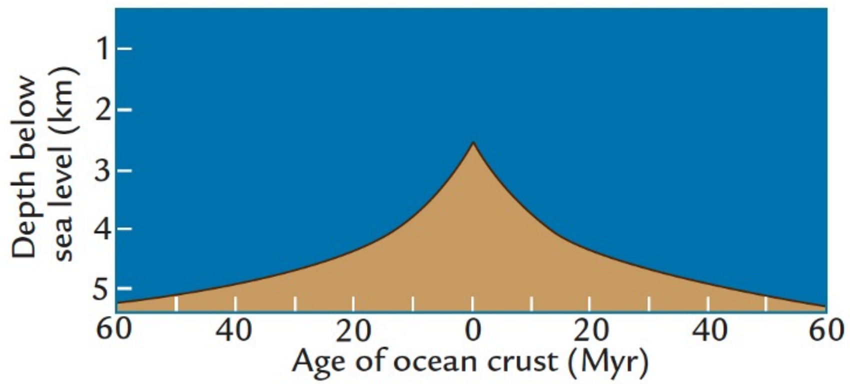
(1) tectonically driven changes that altered the volume of the ocean basins and their capacity to hold water, and

(2) changes in the volume of water in the ocean basins caused by variations in climate.

I. Changes in the Volume of the Ocean Basins

1. CHANGES IN THE VOLUME OF OCEAN RIDGES:

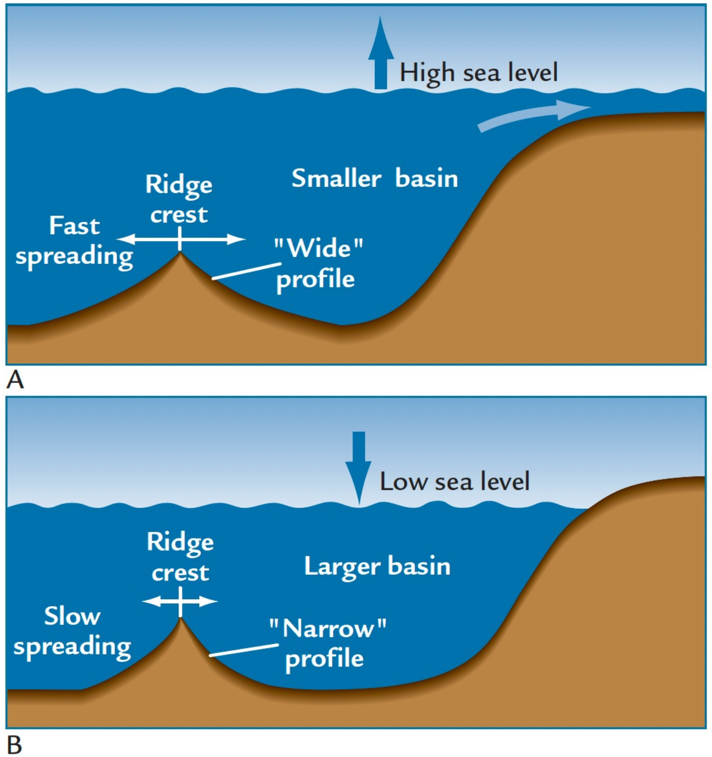
Ocean ridges owe their high elevations to unusual heating from molten material located below the surface of the ocean crust. Heating causes the rocks in the ridges to expand, and expansion of the rock causes the surface of the ocean crust to rise.



$$\underset{\text{(in meters)}}{\text{Ridge depth}} = \underset{\text{(at 0 age)}}{2500\text{ m}} + 350\ \underset{\text{(in millions of years)}}{(\text{crustal age})^{1/2}}$$

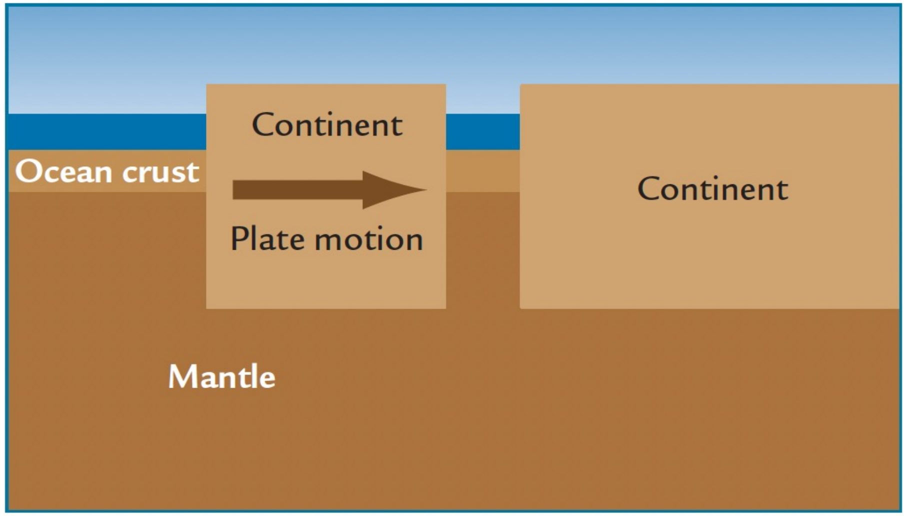
Differing sea floor spreading rates

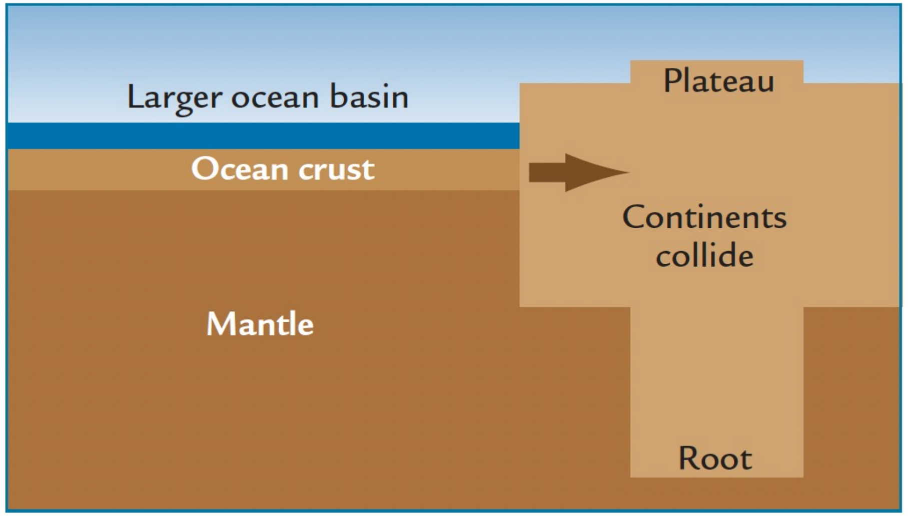
At times like the present, when the globally averaged rate of seafloor spreading is relatively slow, mean ridge profiles are relatively narrow, and little water is displaced onto the continents. At times in the past when the average spreading rate was faster, mean ridge profiles would have been wider, pushing more ocean water up onto the land.



I. Changes in the Volume of the Ocean Basins (contd)

2. COLLISION OF CONTINENTS





- *One major collision began when northern India first made contact with southern Asia some 55 million years ago. This collision, still in progress, has increased the area of the ocean by some 2 million km^2 over the last 55 million years.*
- Viewed in the reverse sense, the absence of continental collisions 80 to 100 million years ago would have kept sea level tens of meters higher than now.

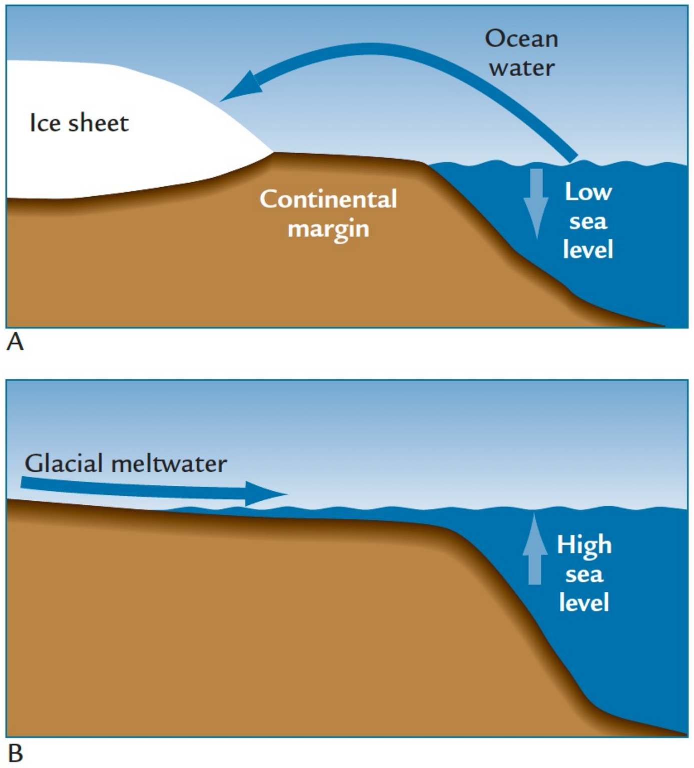
I. Changes in the Volume of the Ocean Basins(contd)

2. TRANSFER OF CONTINENTAL SEDIMENTS TO THE OCEAN

Ocean sediments from major rivers pile up on the seafloor and displace ocean water by reducing the volume of the ocean basins. The Bengal Fan in the northern Indian Ocean is an enormous sediment pile built by eroded sediments from the Himalaya Mountains to the north during the last 55 million years. Other large deposits include debris dumped into the Atlantic Ocean by the Amazon River from South America and by rivers like the Congo flowing from Africa. By some estimates, sediment filling of ocean basins by these eroded deposits can cause sea level increases of as much as 50 meters.

2. Climatic Factors

ICESHEETS



*Together, Antarctica and Greenland ice sheets have extracted a volume of ocean water equivalent to **65 meters of global sea level.***

THERMAL EXPANSION AND CONTRACTION OF SEAWATER

The thermal expansion coefficient of water (the fractional change in its volume per degree of change in temperature) averages about 1 part in 7,000 for each 18C of temperature change.

*Thermal expansion of the warmer ocean that existed 80 to 100 million years ago would have resulted in a global sea level about **7 meters higher than today.***

Estimates of higher Sea Levels 100 Ma years ago

Table 6-1 Factors Contributing to Higher Sea Levels 100 to 80 Million Years Ago

Causes	Total estimated change +100 meters	+150 meters
No major ice sheets	65m higher	65m higher
Thermal expansion of seawater	7m higher	7m higher
No colliding continents	10s of m higher	10s of m higher
Smaller deep-sea fan sedimentation	10s of m lower	10s of m lower
Higher ocean ridge volume	10s of m higher	up to 100m higher

Sea level impact on climate

- *The most likely effect of sea level change on climate is linked to the very different **thermal responses of land and water.** Such that, flooding of the land will tend to moderate nearby extremes of climate and produce milder winters and cooler summers. Withdrawal of the sea should have the opposite effect.*
- *Decades ago, climate scientists thought that sea level might be a factor in the long-term succession of glacial (icehouse) versus nonglacial (greenhouse) climates, or maybe even the main control on these changes. Such that high sea levels caused warm climates by moderating the harsh winters, and low sea levels caused cold climates by permitting the very cold winters typical of continental conditions.*
- So, *coincident timing of high sea level and a largely icefree climate 100 million years ago as compared with the low sea level and glacial climate today fits this explanation.*

Sea level is the major control of long-term glaciation – HYPOTHESIS!

- *Low sea levels and withdrawal of the ocean from continental interiors will lead to more extreme continental climates, including very hot summers. No matter how cold winters become in these continental climates, hot summers should easily melt any snow that accumulated and thereby oppose glaciation.*
- *Conversely, high sea levels should cause cooler, more maritime summers that favor the persistence of snow and ice through the summer ablation season at very high latitudes.*
- *Glaciation is now seen as a major cause of low sea level (because of storage of ocean water in ice sheets) rather than a result.*

The BLAG Hypothesis

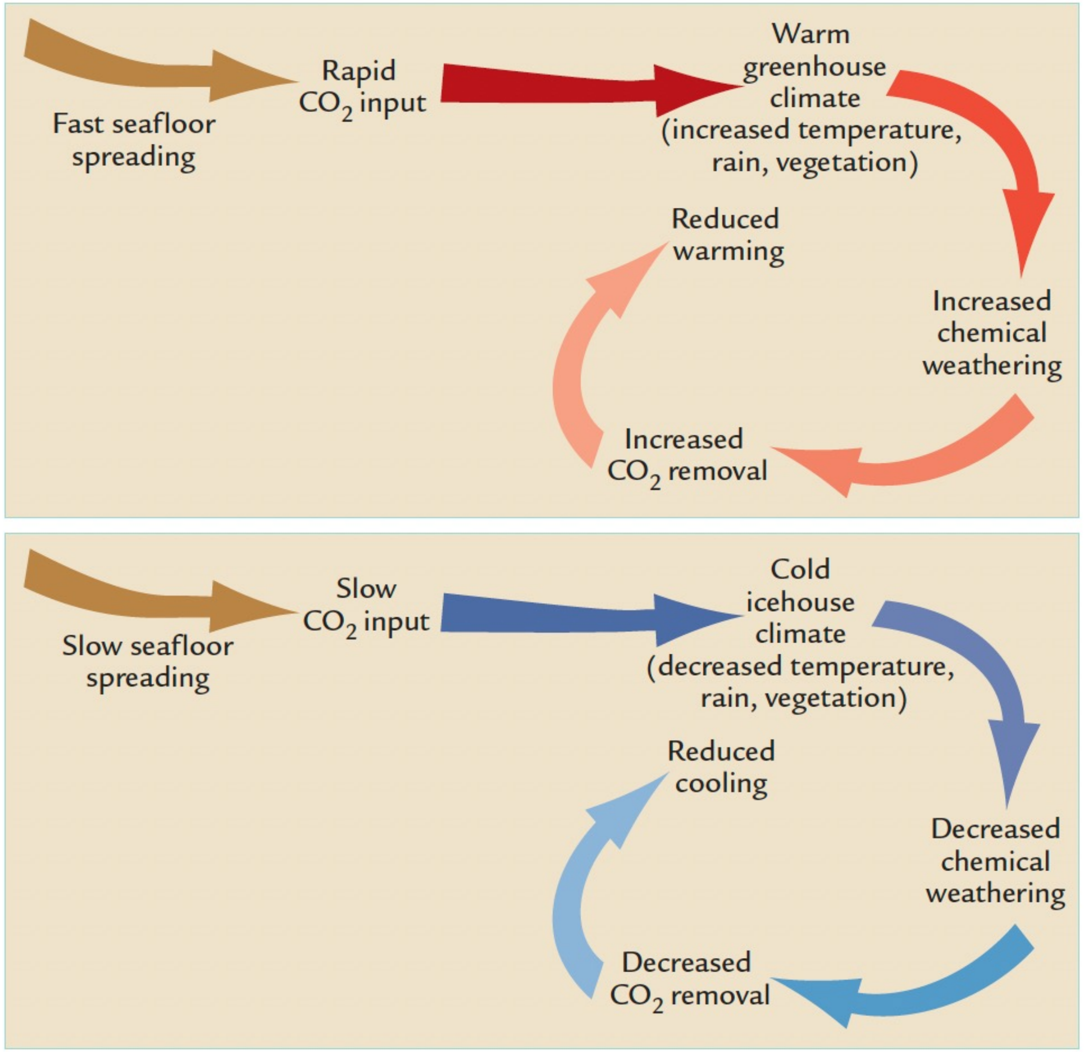


Table 5-2 Evaluation of the BLAG Spreading Rate (CO_2 Input) Hypothesis

Time (Myr ago)	Ice sheets present?	Spreading rates	Hypothesis supported?
100	No	Faster (?)	Yes (?)
0	Yes	Slower (?)	Yes (?)

FIGURE 5-18
The BLAG (spreading rate) hypothesis
This hypothesis predicts that atmospheric CO_2 concentrations and global climate are driven by the global mean rate of seafloor spreading, which controls the rate of CO_2 input at ocean ridge crests and subduction zones. The spreading rate hypothesis also invokes chemical weathering as a negative feedback that partially counters changes in atmospheric CO_2 and global climate initiated by varying rates of seafloor spreading.

Tectonic Control of CO2 Removal: The Uplift Weathering Hypothesis

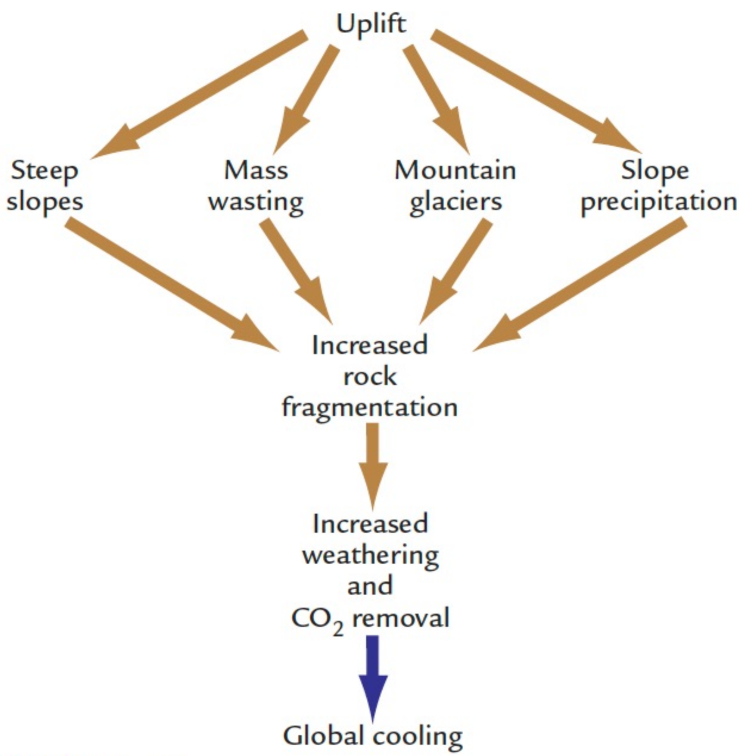


FIGURE 5-23
Uplift weathering hypothesis
Active tectonic uplift produces several tectonic and climatic effects that cause strong weathering of freshly fragmented rock. This process removes CO_2 from the atmosphere and cools global climate.

Table 5-3 Evaluation of the Uplift Weathering (CO_2 Removal) Hypothesis

Time (Myr ago)	Ice sheets present?	Continents colliding?	Hypothesis supported?
325–240	Yes	Yes	Yes
240–35	No	No	Yes
35–0	Yes	Yes	Yes

The Asteroid Impact (65 Million Years Ago)

Impact events such as the one at the Cretaceous-Tertiary boundary have clearly had apocalypse-like effects on the environment, including mass extinctions of organisms, transforming life on Earth. Despite this environmental apocalypse, the background state of the climate system 65 million years ago seems to have been changed little or not at all.

ASSIGNMENT TOPIC!

Greenhouse Episode 55 Million Years Ago: Another Thermostat Malfunction?

- *The warm greenhouse world was still in existence when a relatively brief episode of even warmer climate began near 55.5 million years ago. Because this warm episode falls near the boundary between the geologic epochs known as the Paleocene and the Eocene, it is called the* ***PETM (Paleocene-EoceneThermal Maximum).***

FROM GREENHOUSE TO ICEHOUSE

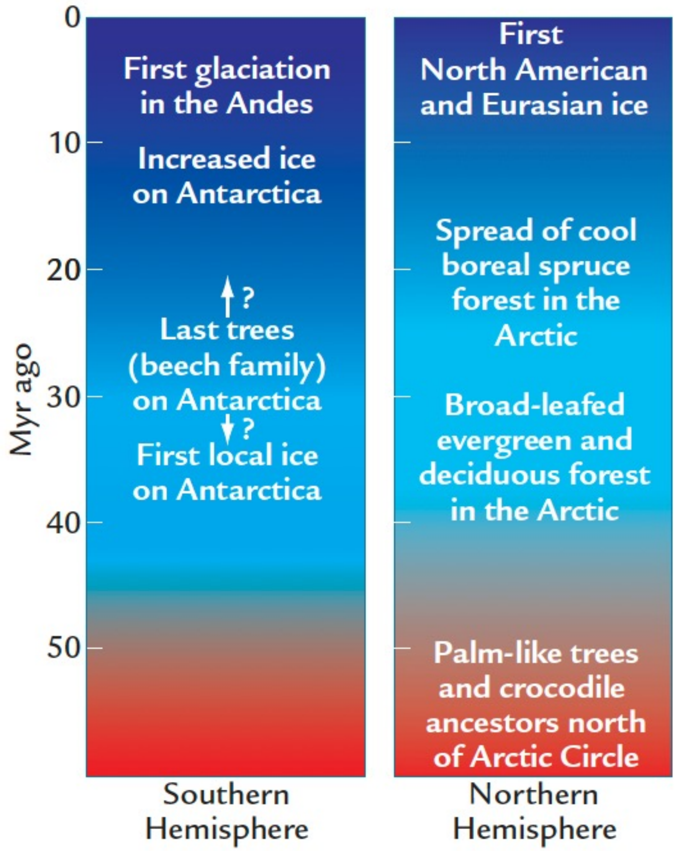


FIGURE 7-1

Global cooling for 50 Myr

Gradual cooling during the last 50 Myr is demonstrated by the first appearance of mountain glaciers and continental-scale ice sheets, and by a progressive trend toward cold-adapted vegetation in both hemispheres.

Evidence from Oxygen Isotope Measurements

$$\Delta\delta^{18}O_c = \Delta\delta^{18}O_w \times 0.23\Delta T$$

This signal begins to trend erratically toward more positive values near
→ 50 million years ago, and
→ 35 million years ago
→ 13 million years ago, and
→ last 3 million years.

Combination of (1) cooling of the deep ocean, and (2) growth of ice sheets on land.

Both of these factors are critical aspects of the transition from a greenhouse to an icehouse climate.

How much has the deep water cooled since 50 Ma?

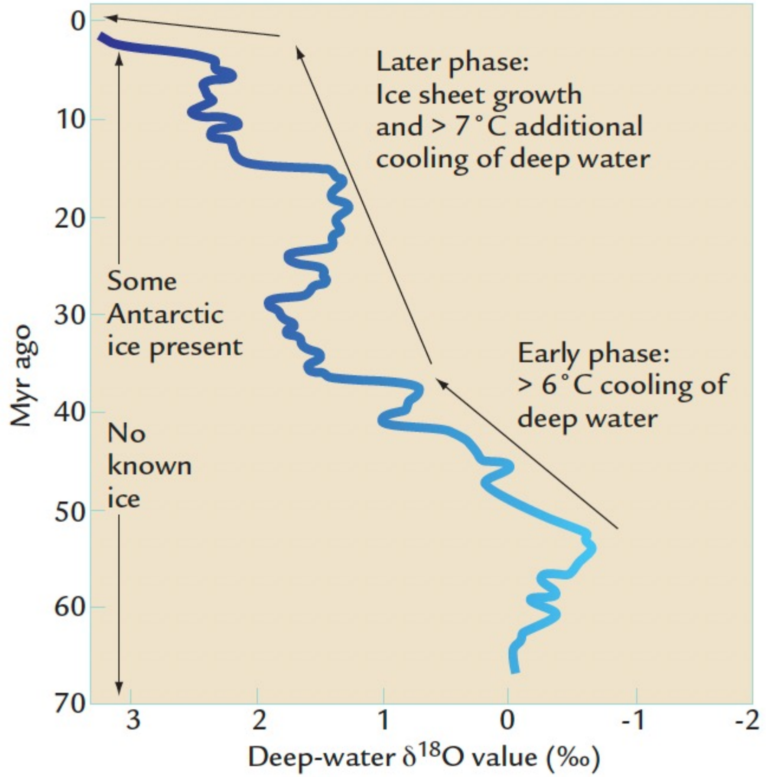


FIGURE 7-7

Long-term $\delta^{18}O$ trend

Measurements of $\delta^{18}O$ in benthic foraminifera show an erratic long-term trend toward more positive values. From 50 to 35 Myr ago, the increase in $\delta^{18}O$ was caused by cooling of the deep ocean. After 35 Myr ago, it reflects further ocean cooling and formation of ice sheets on Antarctica. (ADAPTED FROM K. G. MILLER ET AL., "TERTIARY OXYGEN ISOTOPE SYNTHESIS: SEA LEVEL HISTORY AND CONTINENTAL MARGIN EROSION," *PALEOCEANOGRAPHY* 2 [1987]: 1–19.)

Evidence from Mg/Ca Measurements

How much has the deep water cooled since 50 Ma?

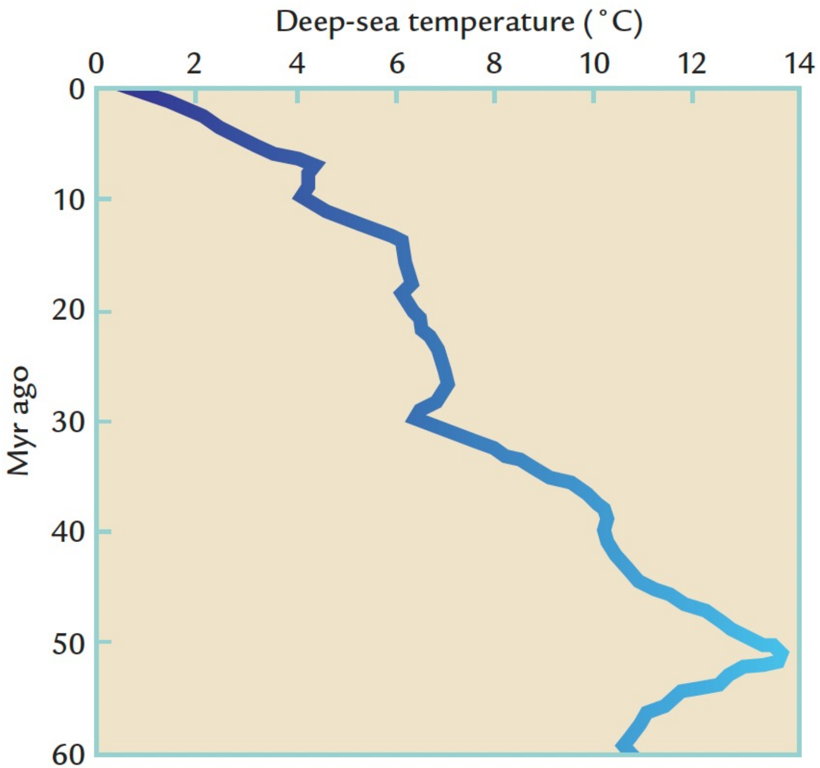


FIGURE 7-8

Long-term Mg/Ca trend

Measurements of Mg/Ca ratios in benthic foraminifera indicate a progressive cooling of deep water over the last 50 Myr. (ADAPTED FROM LEAR ET AL., "CENOZOIC DEEP-SEA TEMPERATURES AND GLOBAL ICE VOLUMES FROM MG/CA IN BENTHIC FORAMINIFERAL CALCITE," *SCIENCE* 287 [2000]: 269–272.)

What caused glaciation during the last 50 Ma?