

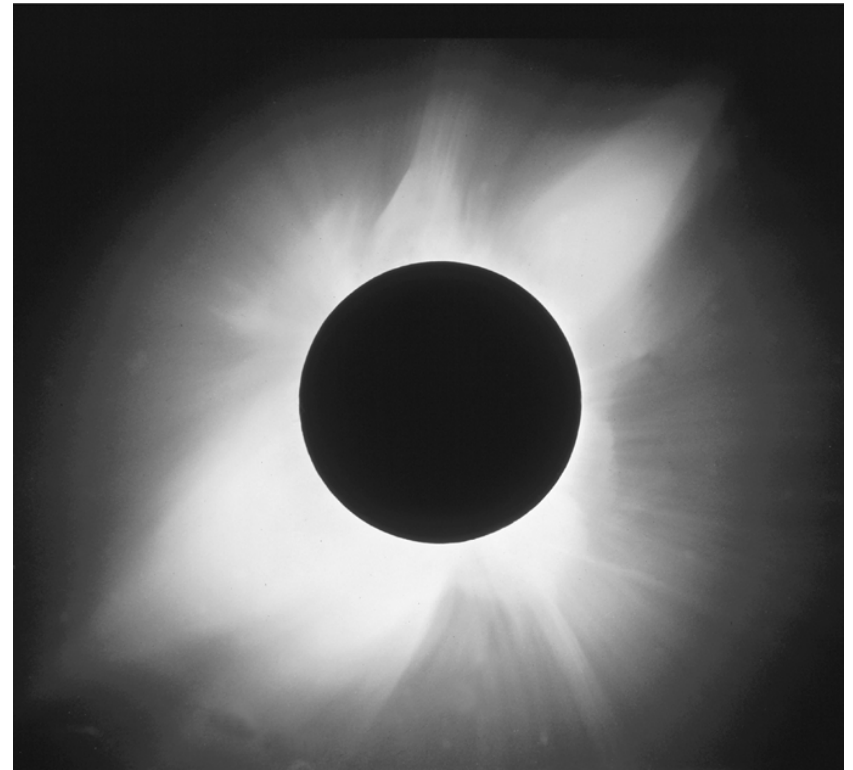
# Chapter 12: Long-Term Climate Regulation

Carl Sagan and George Mullen posed the “Faint Young Sun” Paradox in 1972.



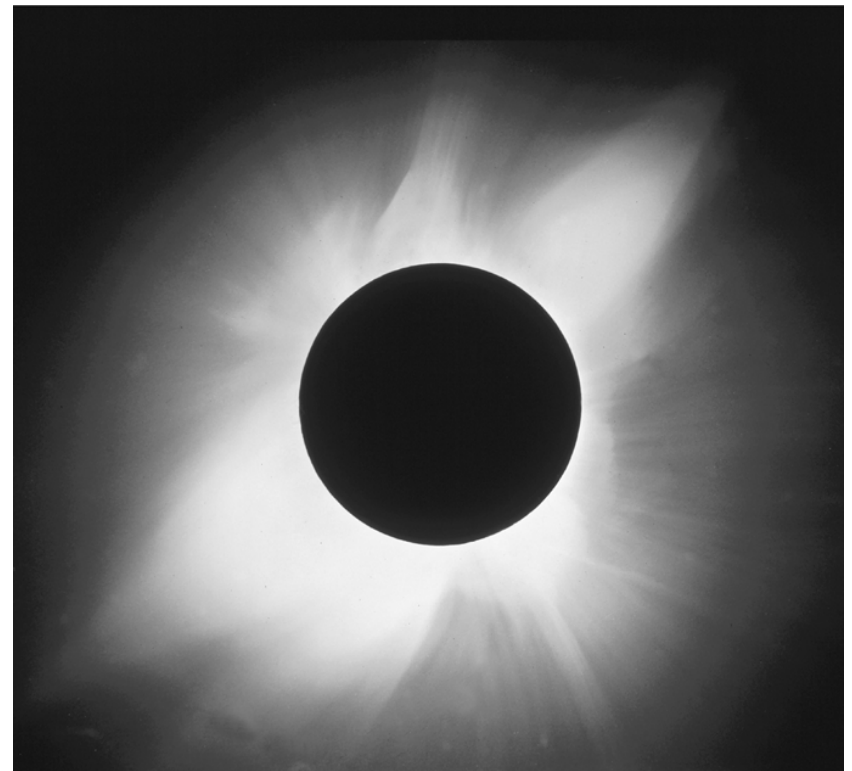
# What about the details?

- “Faint young Sun paradox”
- Solution: A greenhouse gas or a lower albedo
- Strong negative feedback over the long term by silicate weathering
- Methane in early atmosphere?



# Was Sun Really Dimmer 4.5 Ga ago?

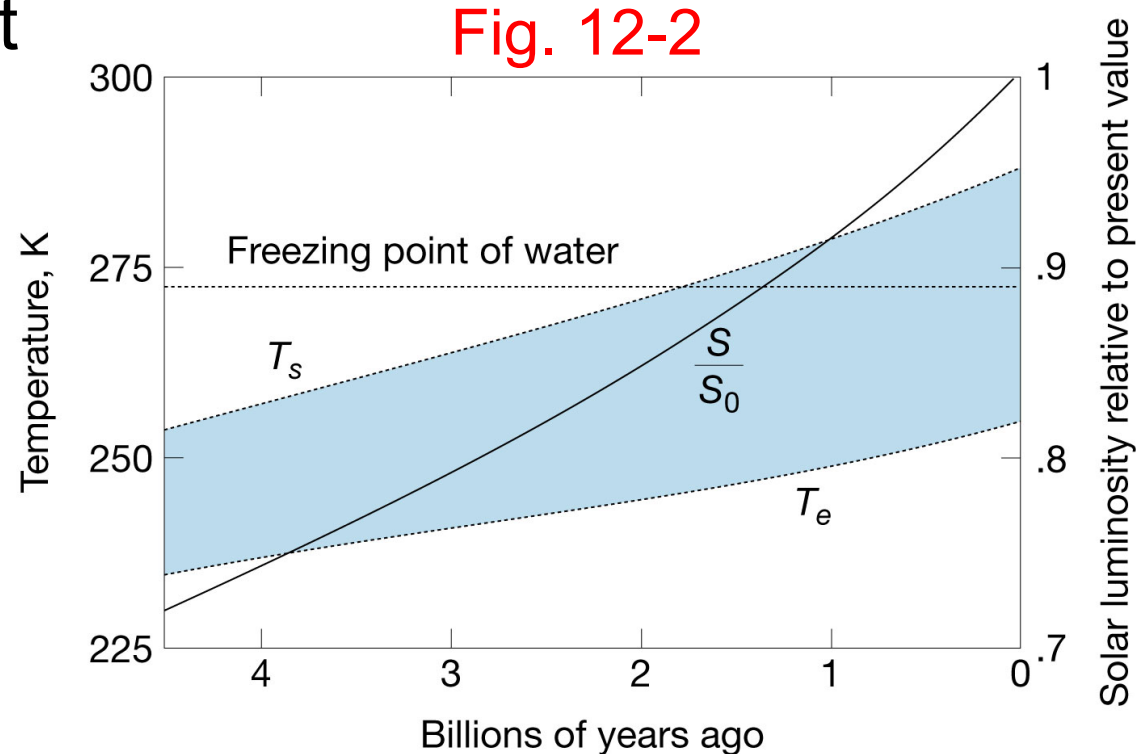
- Understanding of nuclear fusion is, scientifically speaking, relatively simple and robust
- Was Sun more massive previously?
- How would it lose mass?



Solar wind: 10,000 times too slow to account for 1% mass loss

# “Faint Young Sun” Revisited

- Solid: Solar output over time
- Bottom dashed: Effective radiating temperature  $T_e$
- Top: Greenhouse effect assuming 340 ppm  $\text{CO}_2$



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Conclusion: Earth was too cold for liquid surface water until 1.9 Ga, but we have good evidence otherwise for 3.8 Ga or older! This requires AN ADDITIONAL FACTOR

# Proposed Explanations:

- Albedo lower
- Greater greenhouse effect earlier
- Another source of heat

Geothermal heat: Radioactive decay in Earth keeps the interior hot, and was greater on early Earth (simply because our initially-supplied radioactive material had not decayed yet!)

...but the “deficit” is about  $70 \text{ W/m}^2$ , and geothermal only supplies  $0.06 \text{ W/m}^2$  today...and maybe up to  $0.3 \text{ W/m}^2$  on early Earth!

...geothermal vents? Stromatolites? C-isotope fractionation?

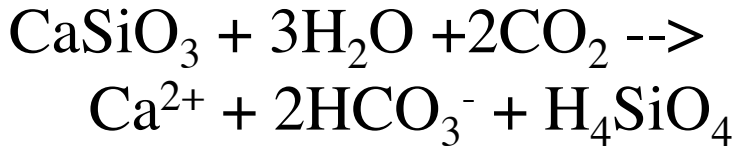
# Albedo?

- **NOT** if cold! (snow, ice)
- With rocks like today, you would have to have albedo near 0 to account for the 30% dimmer Sun - which is impossible
- Some have proposed that absorption by water and black, basaltic rocks on land (not today's more granodiorite-like rocks with forests) could sufficiently decrease albedo – but this remains controversial
- This leaves us with a greater greenhouse effect as the most likely explanation

# Long-term C cycle...

- Silicate weathering: negative feedback

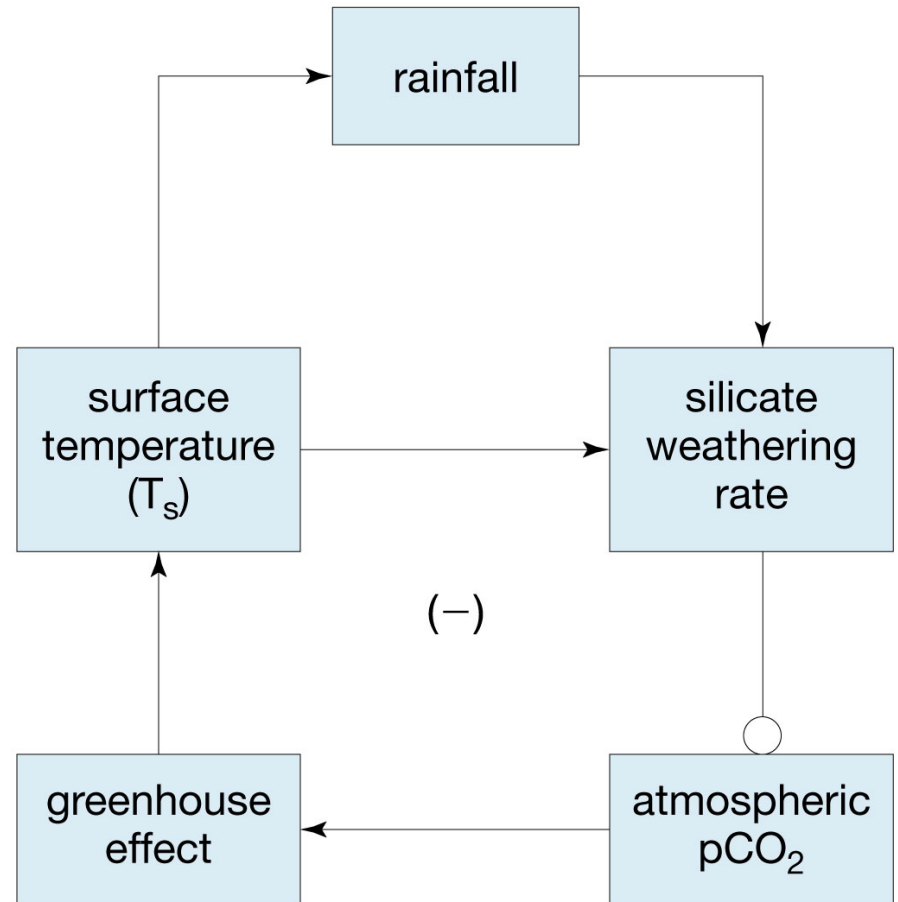
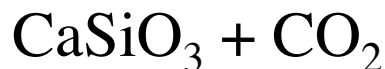
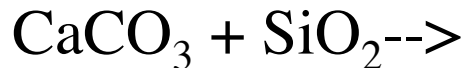
**Silicate rock weathering:**



**Limestone and chert formation in oceans:**

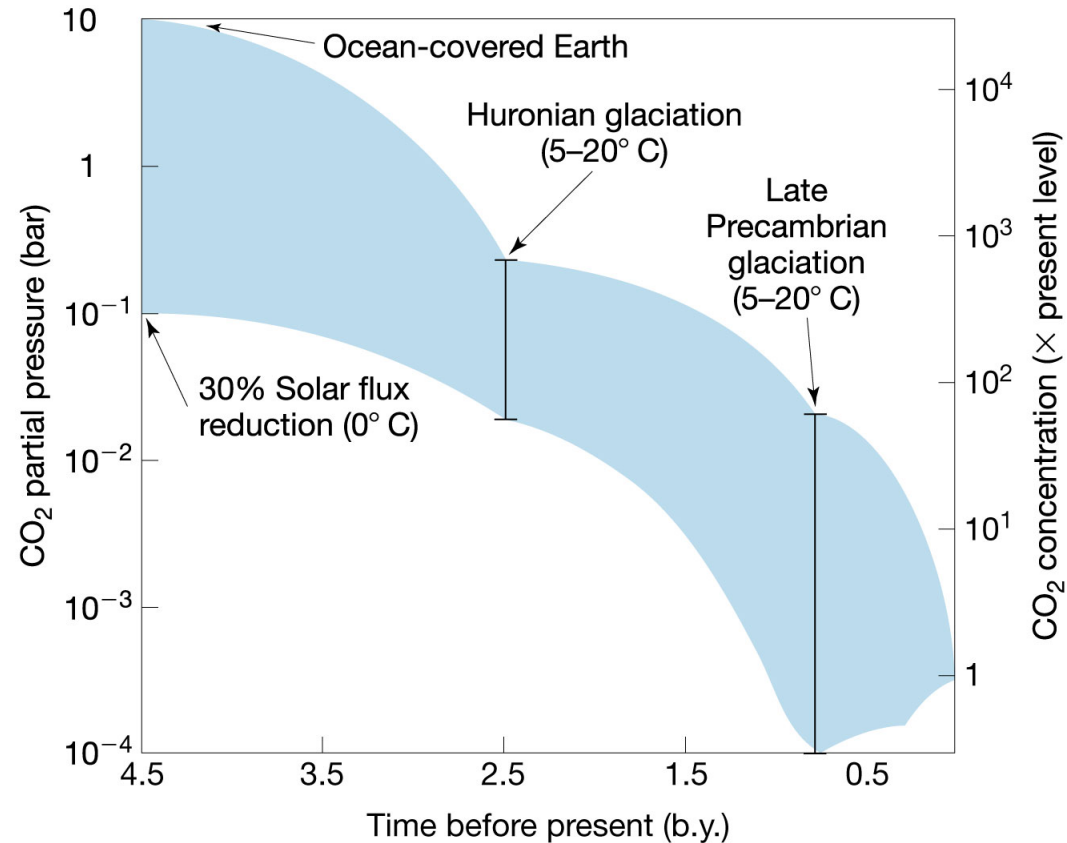


**Plate tectonics returns CO<sub>2</sub> to atm:**



# How much CO<sub>2</sub> needed?

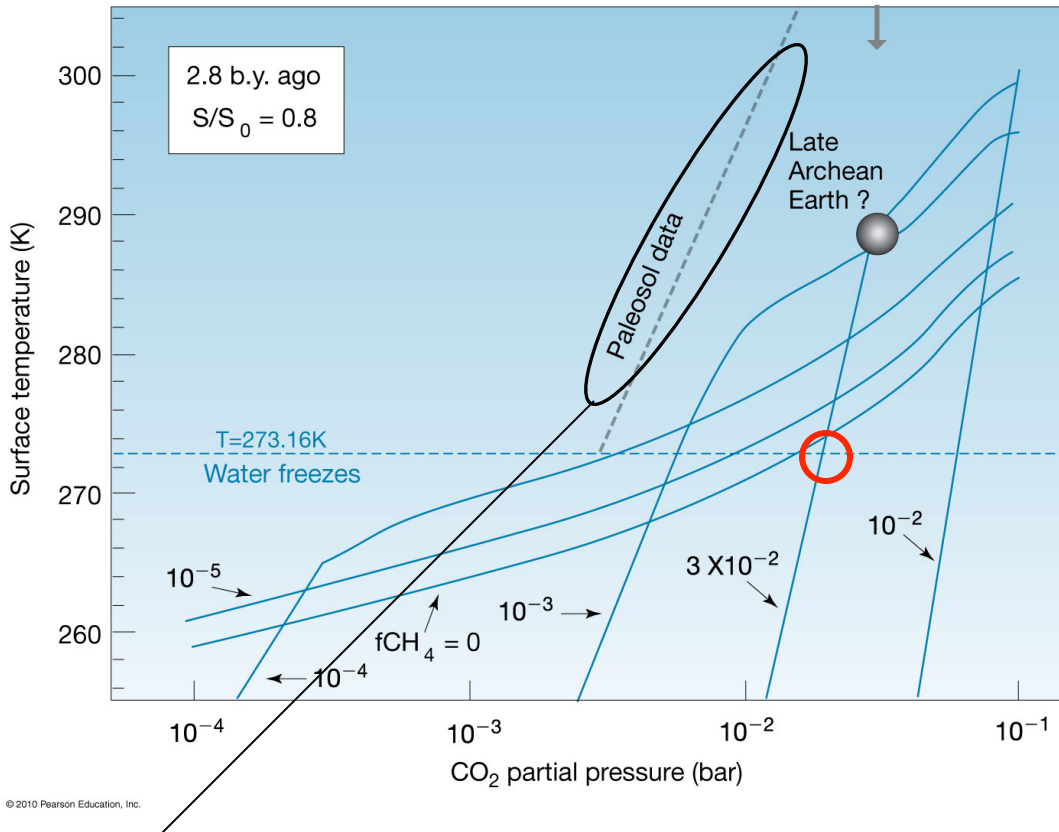
- About 1000 times current levels
- ...but there isn't all that much CO<sub>2</sub> in the atm today, so 1000 times isn't all that much
- We need only about 0.5% of C in limestones to solve the “faint young sun” problem!



...at 10 bars, the Earth would have been 80°-90°C - which is another potential reason early life was hyperthermophiles!



# Other greenhouse gasses? Methane



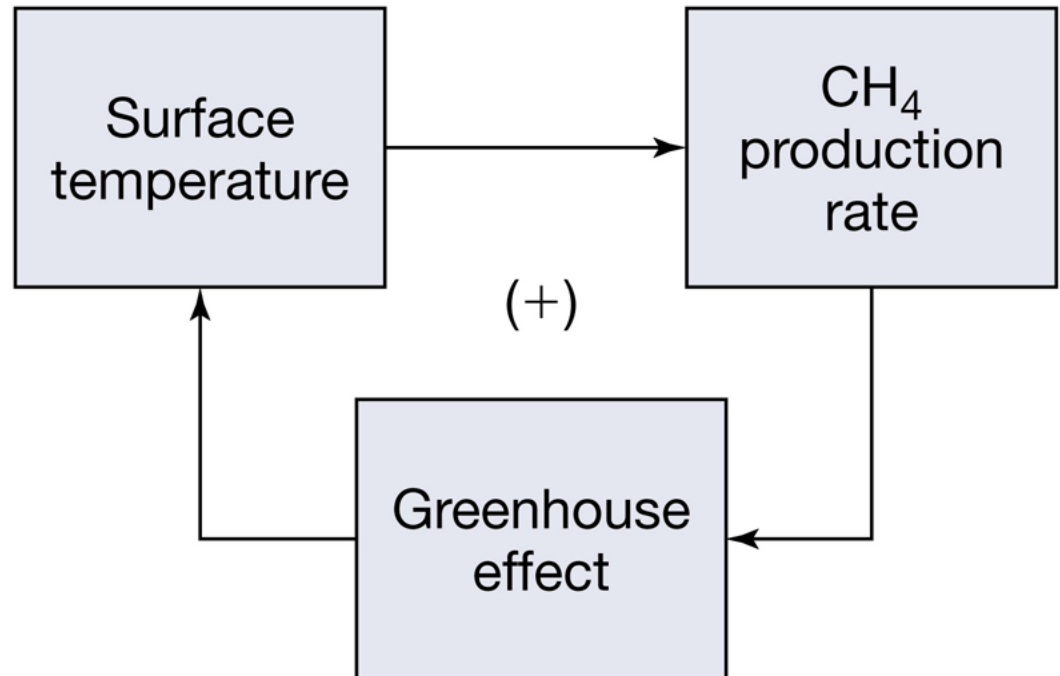
- Methanogenic bacteria:  
 $\text{CO}_2 + 4\text{H}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O}$
- Could have caused ~1000 ppm methane in early (no or little oxygen) atmosphere
- With this much methane, we would not need **any** more CO<sub>2</sub> in atm than today to overcome the “faint young sun” paradox

Lack of siderite (FeCO<sub>3</sub>) in Archean paleosols limits  
The amount of CO<sub>2</sub> that could have been in the early atm

# But a problem...+ feedback!

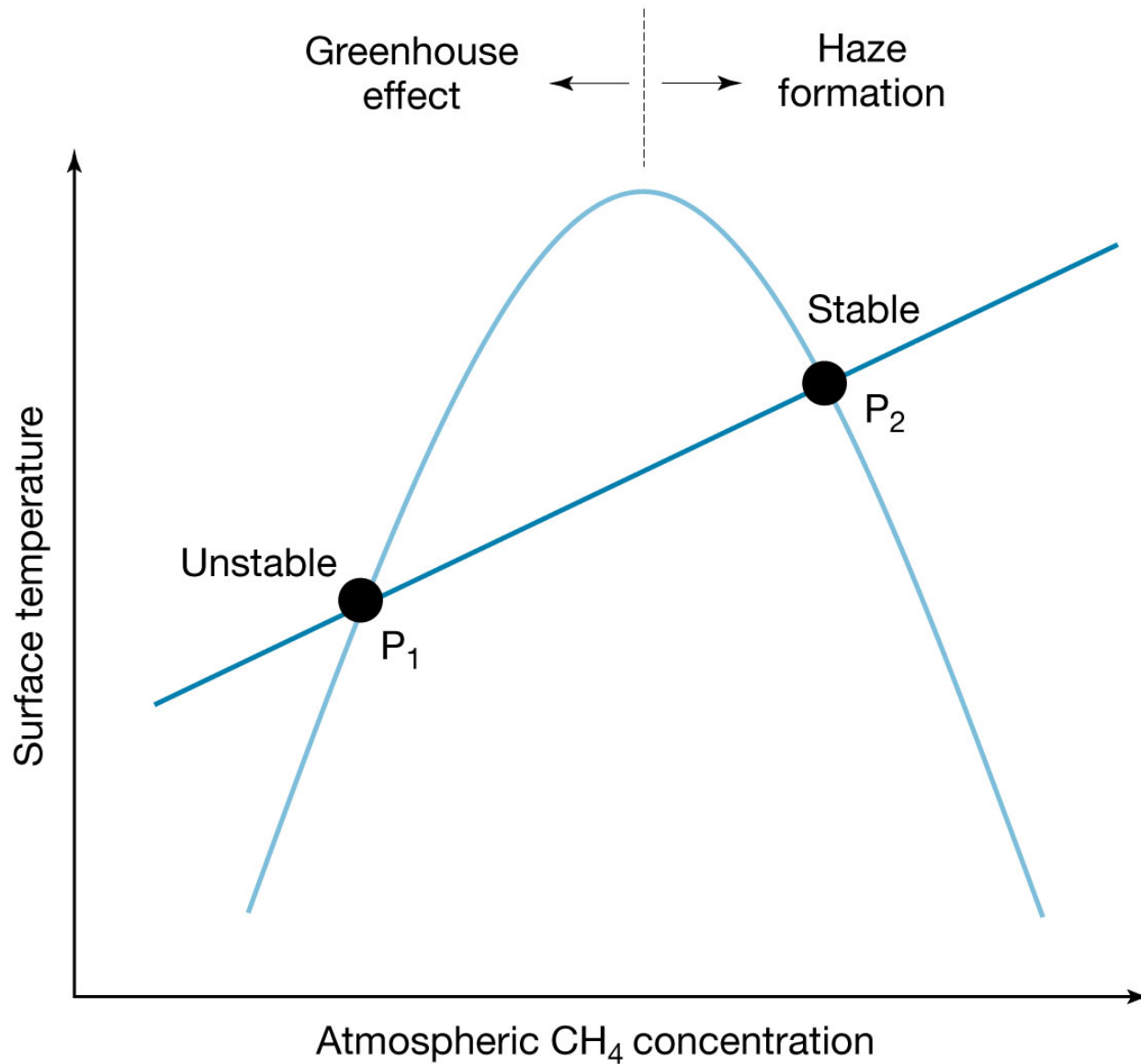
- Methanogens produce more methane on a warmer planet - increasing greenhouse effect
- CO<sub>2</sub>, CH<sub>4</sub> comparable in concentration

CH<sub>4</sub>-Climate Feedback Loop

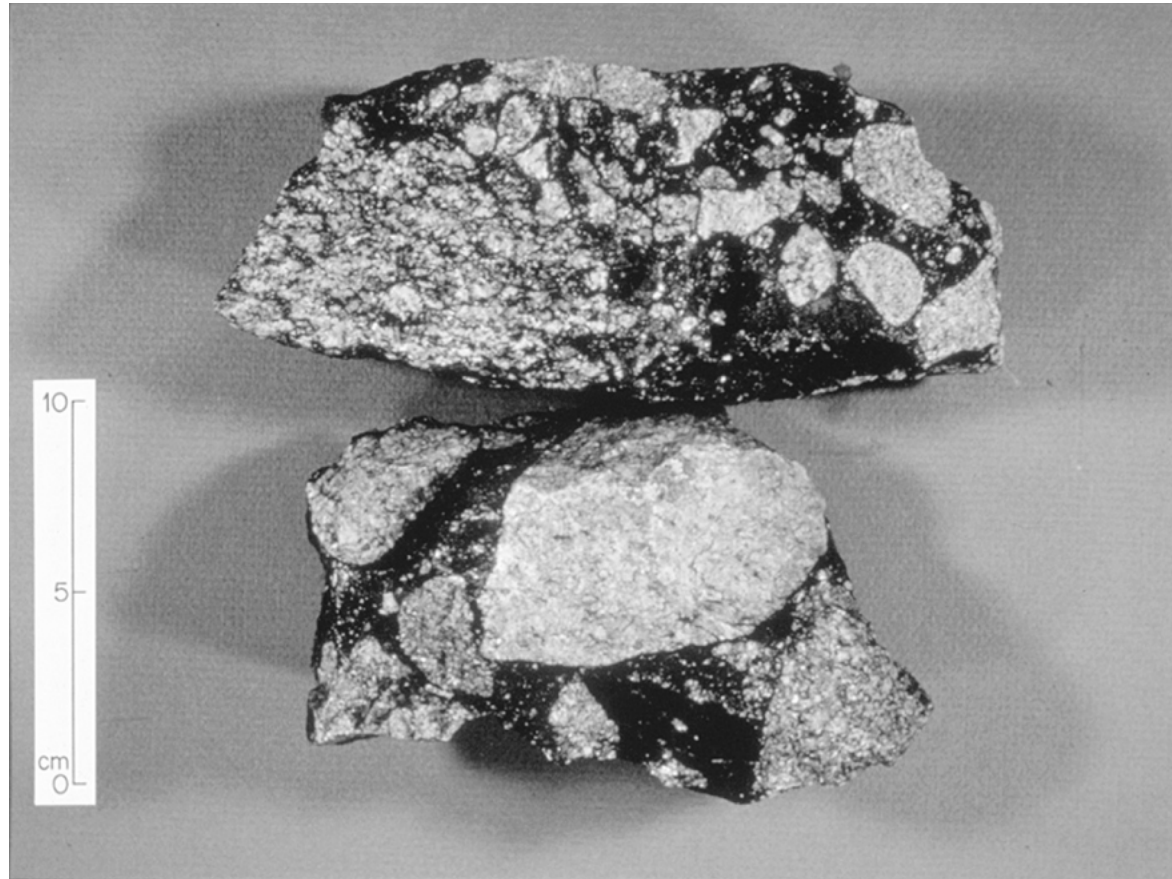


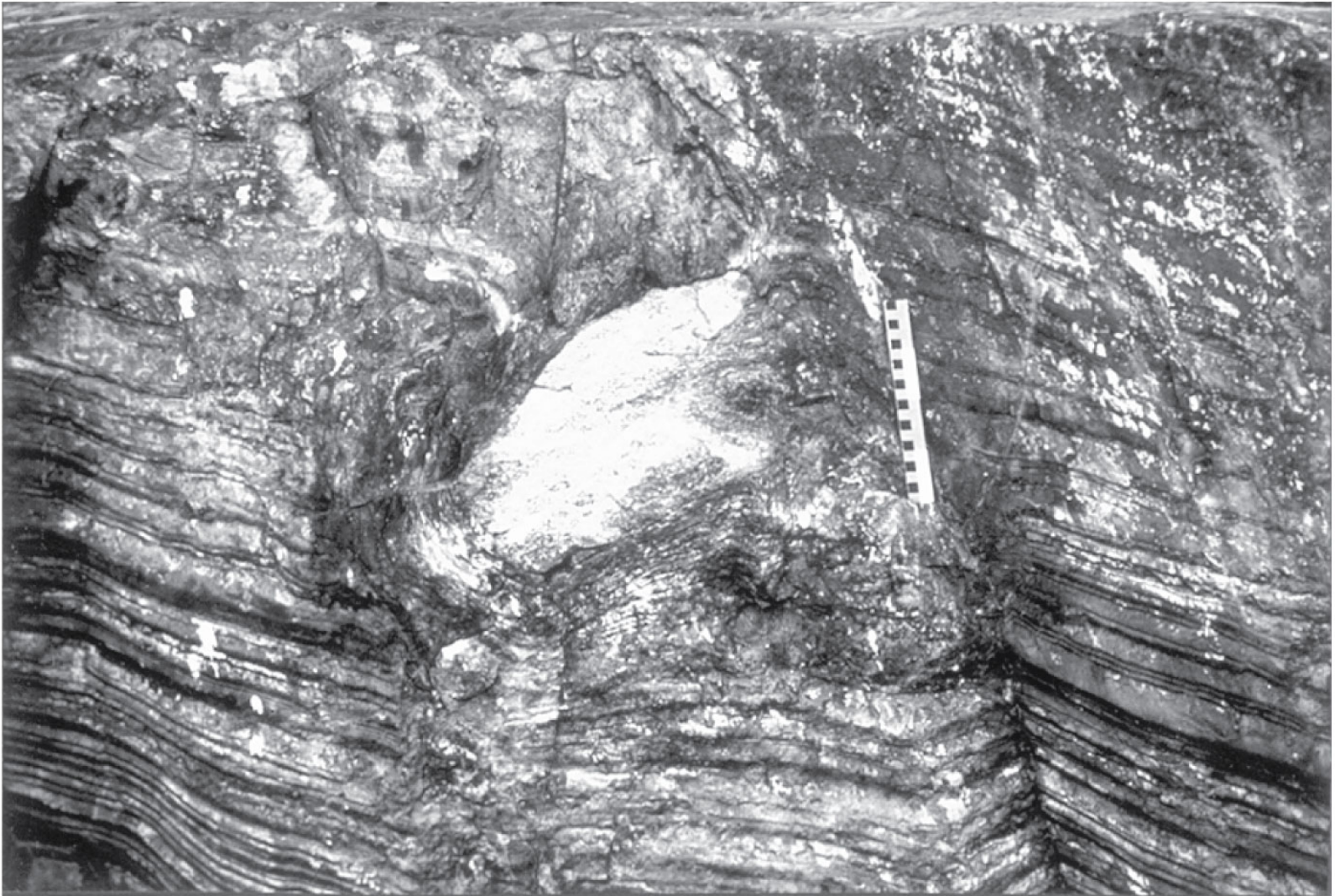


# A bit like daisyworld...



# Evidence of past glaciations





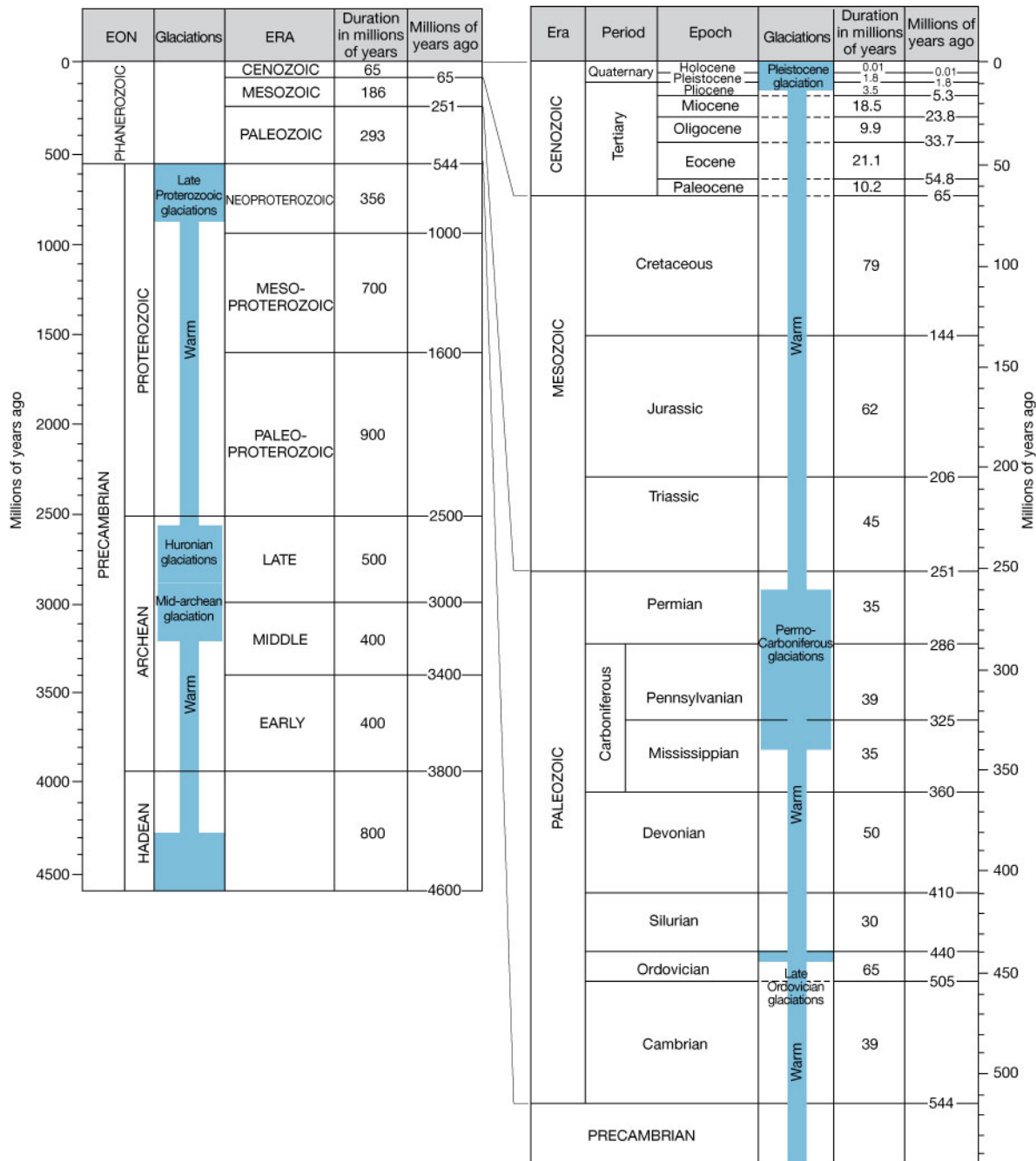
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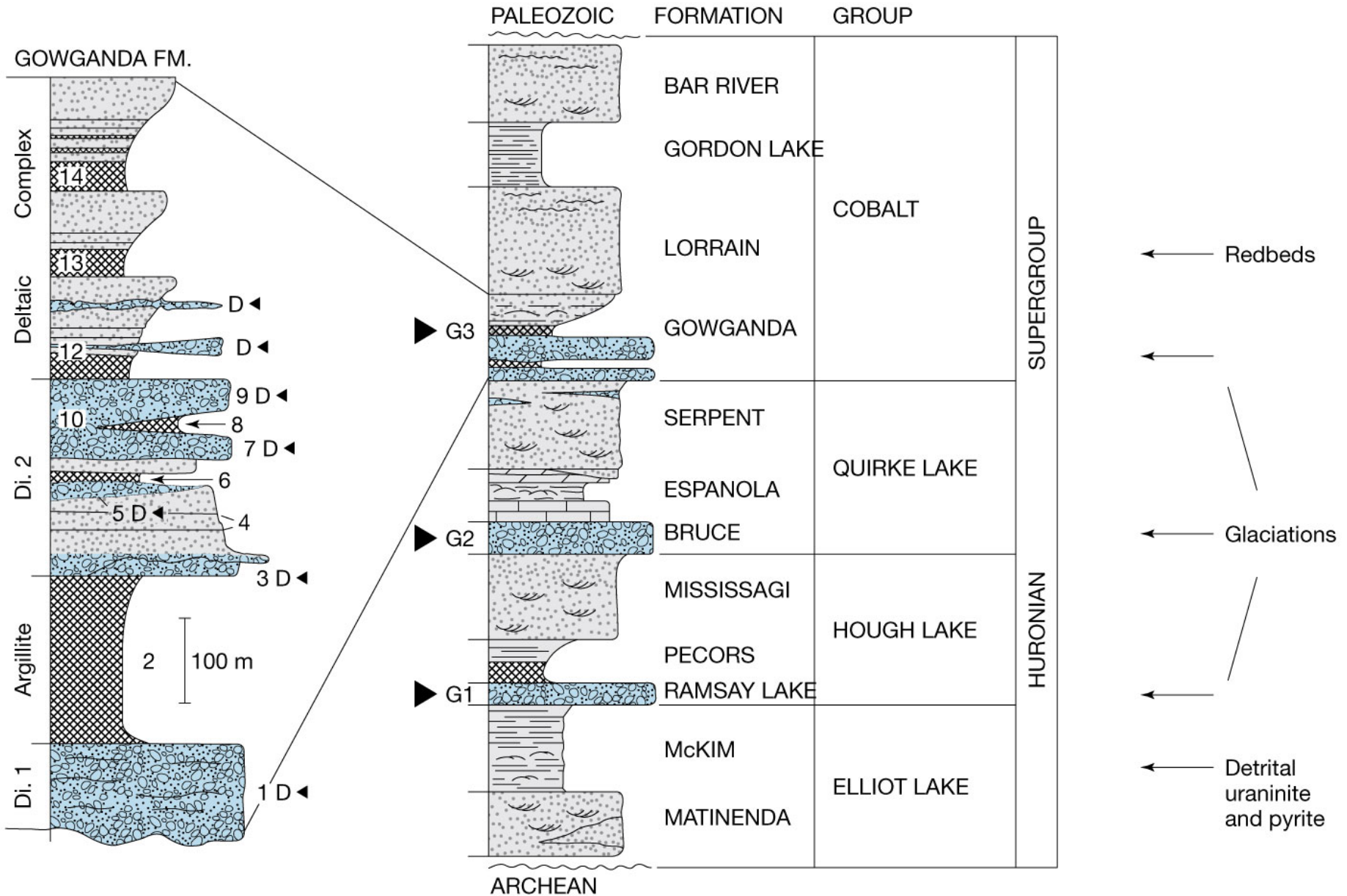
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Glacial dropstone from Gowganda Fm. (Huronian Glaciation)

# Glaciation Record...

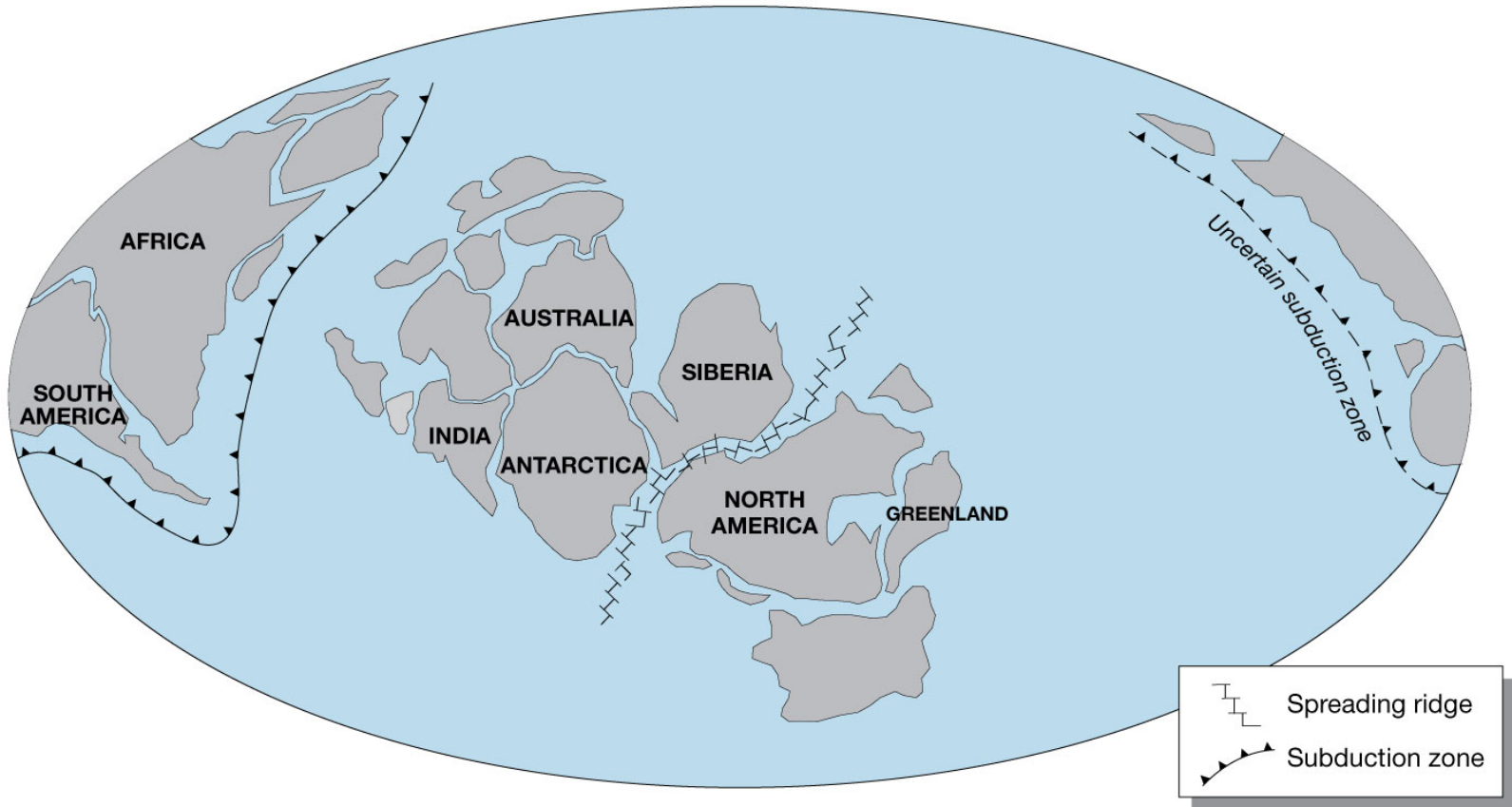
- Huronian...rise of oxygen, loss of methane?
- Neoproterozoic
- Late Ordovician?
- Carboniferous
- Pleistocene







# Neoproterozoic Glaciation

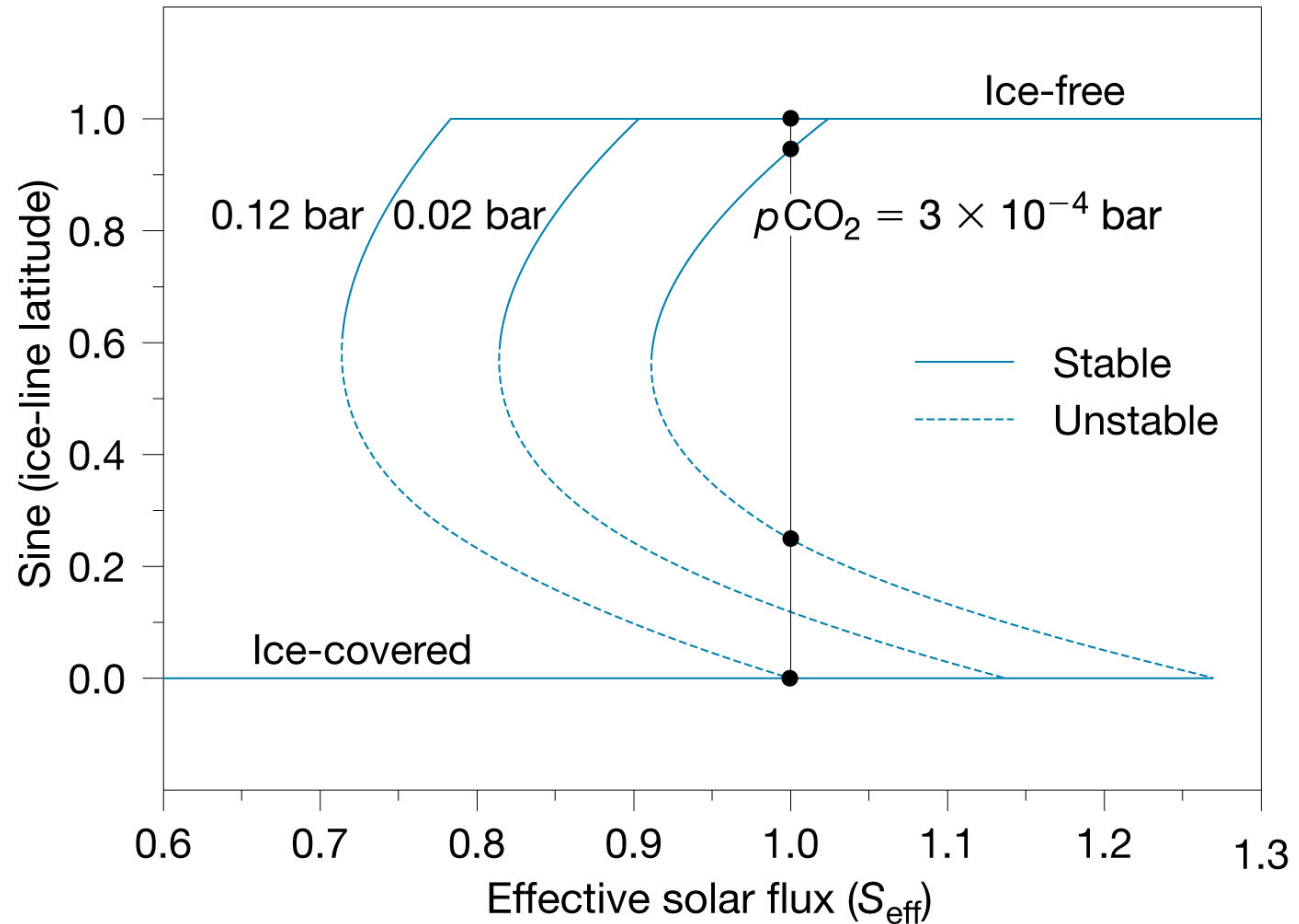


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Continents largely tropical - yet evidence for glaciation on all of them between 800 my and 600 my ago (except Antarctica, and that's just because it's so glaciated now we can't look).

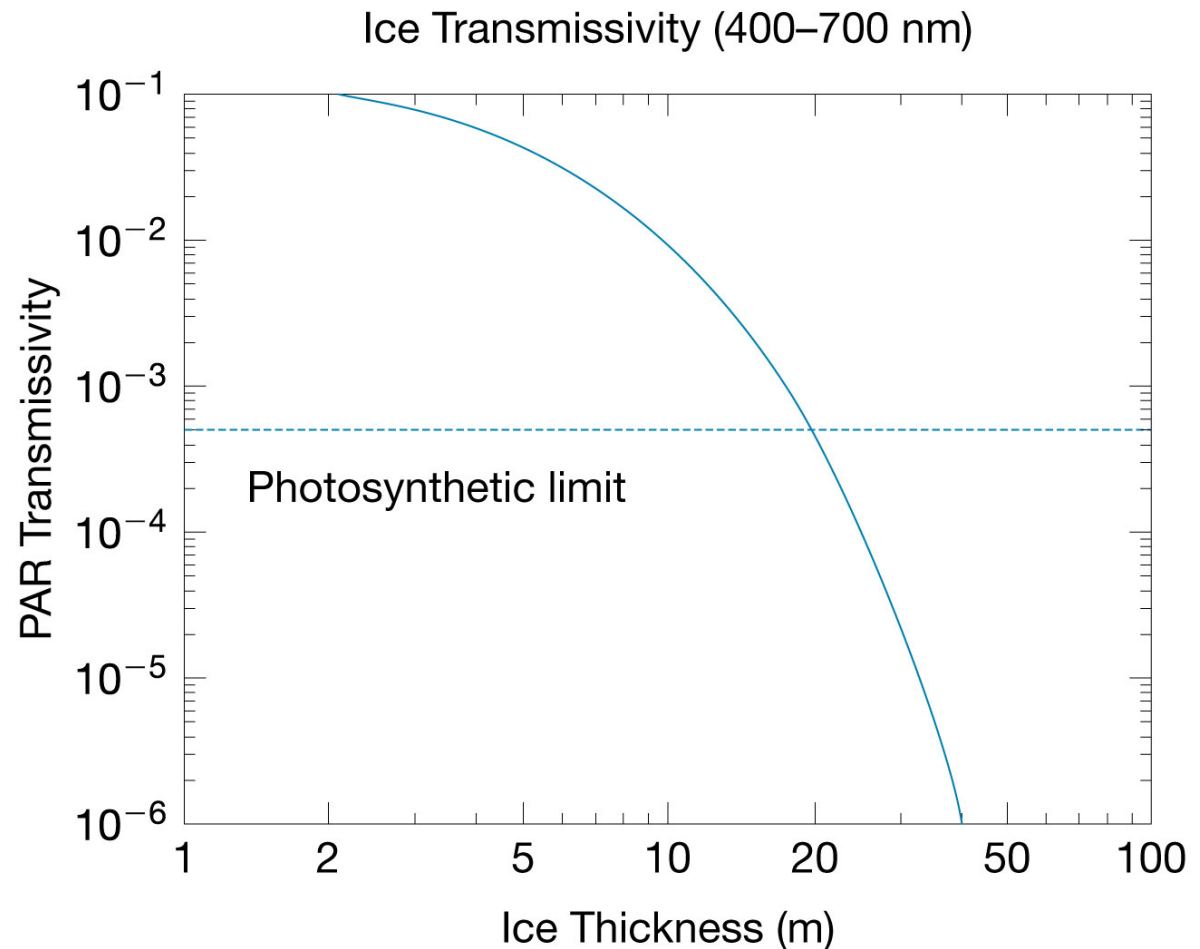
# How can Earth become completely ice-covered?

- This plot give “ice line” latitude for different CO<sub>2</sub> levels as a function of solar radiation input
- Unstable regions indicate “runaway icehouse” (unstable) conditions



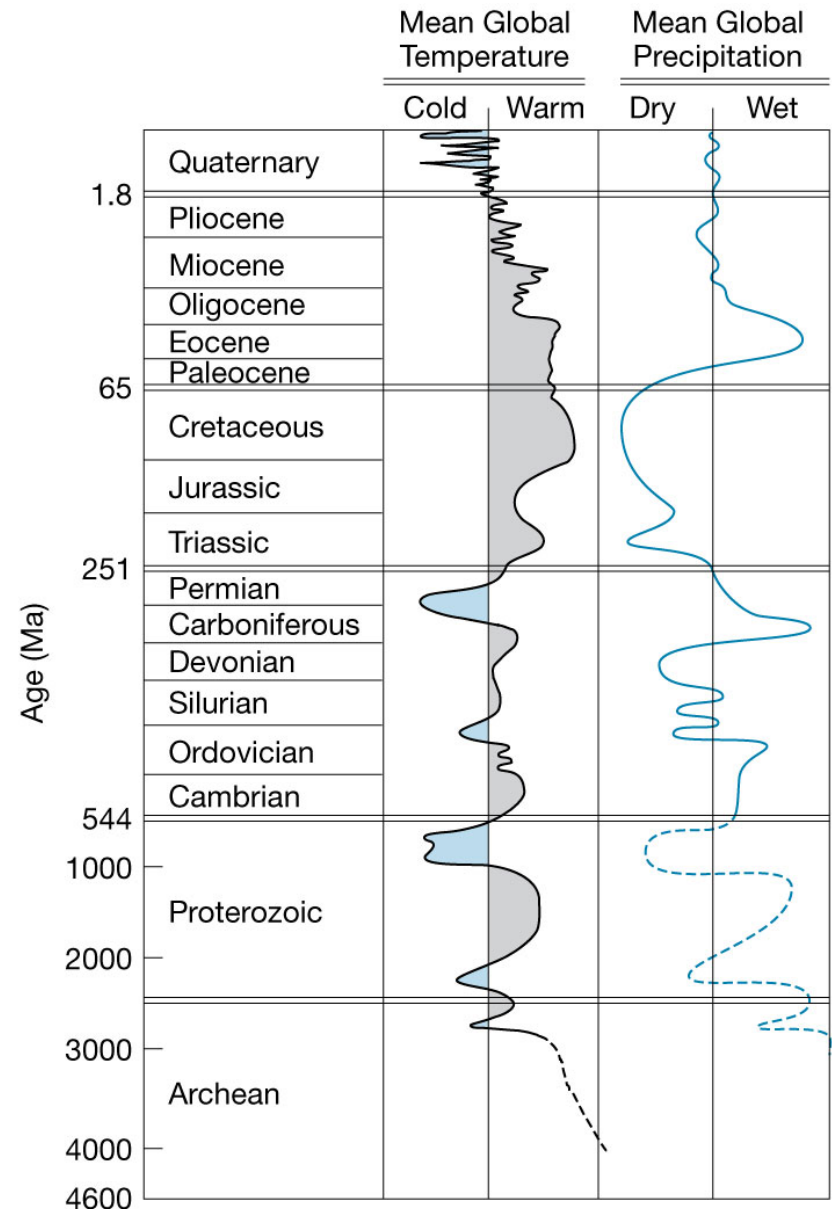
# How did photosynthetic life survive the icehouse?

- Ice is transparent to some degree

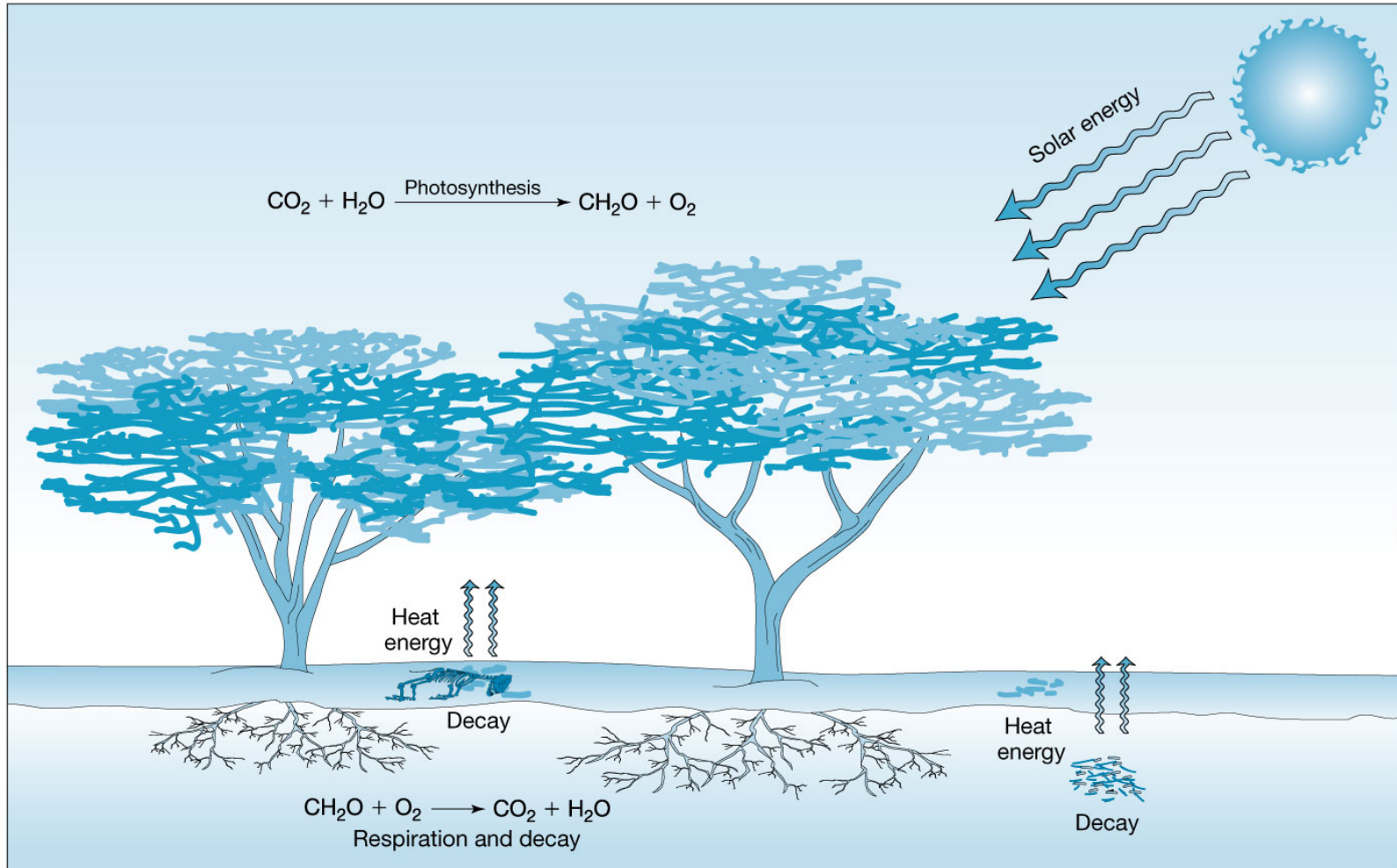


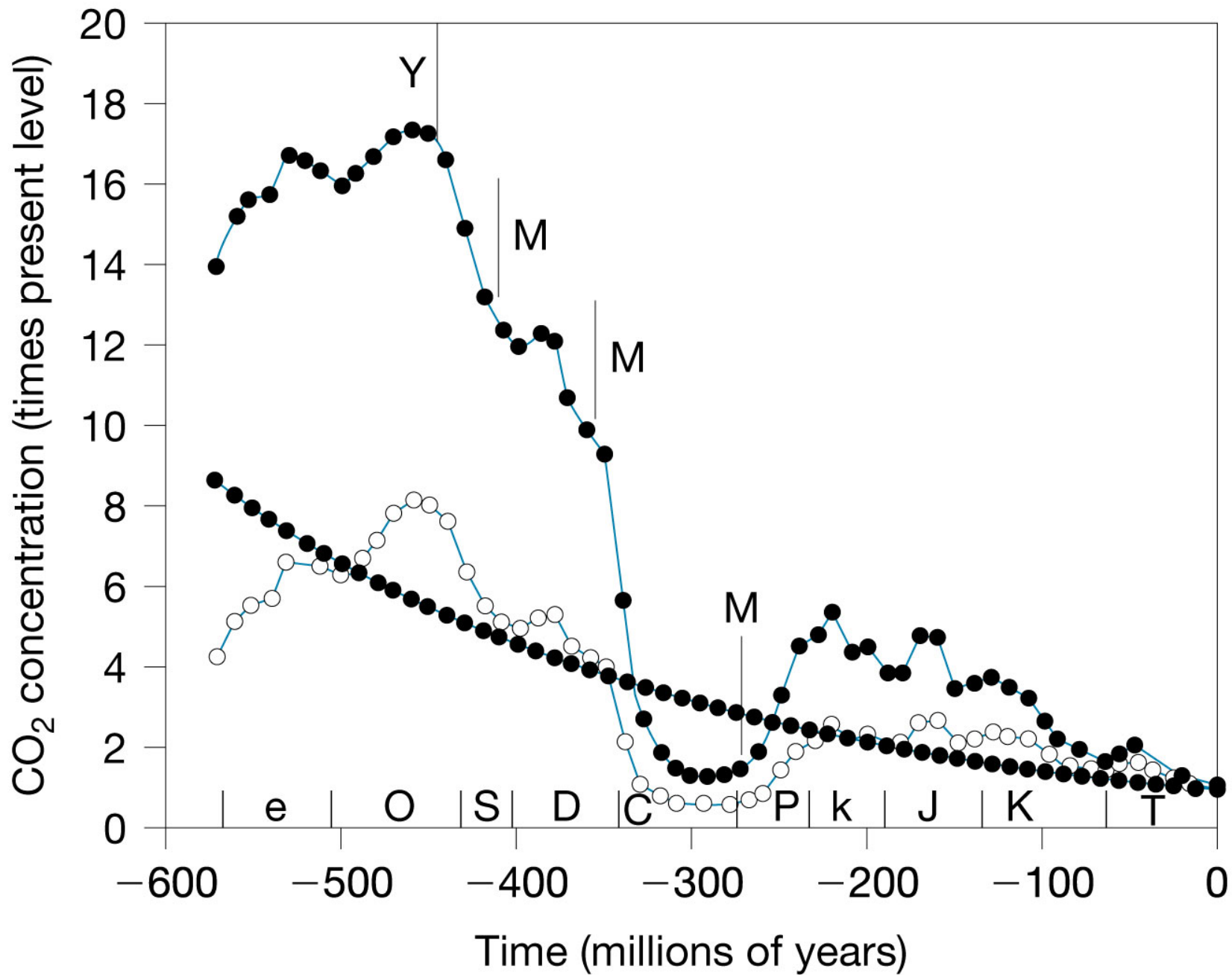
# Temperature, Humidity

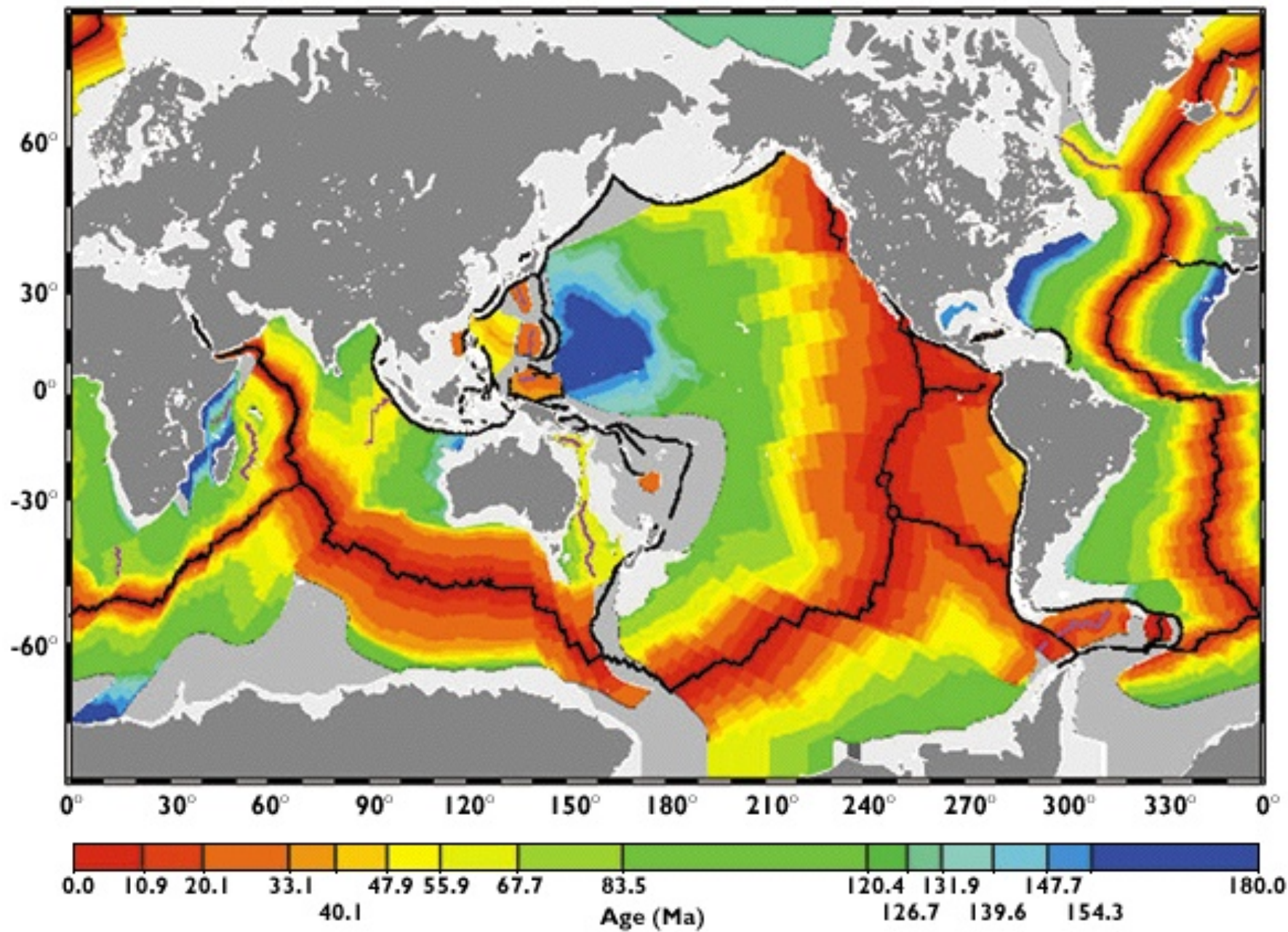
- The geologic record gives us indications of mean global temperature and mean global precipitation - not exact, but relative (high, low).
- How?
- Why this different glaciations?

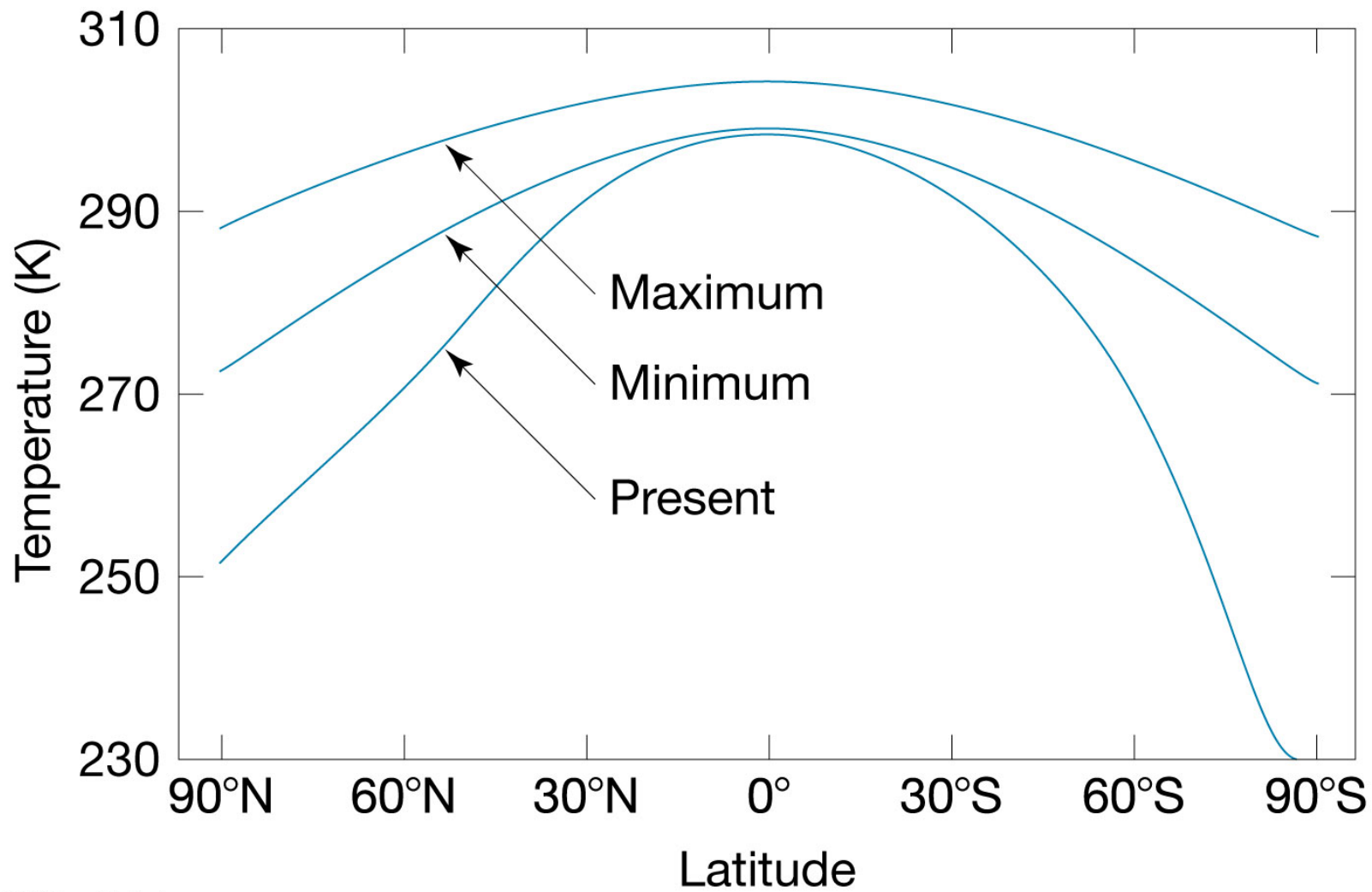


# Vascular land plants



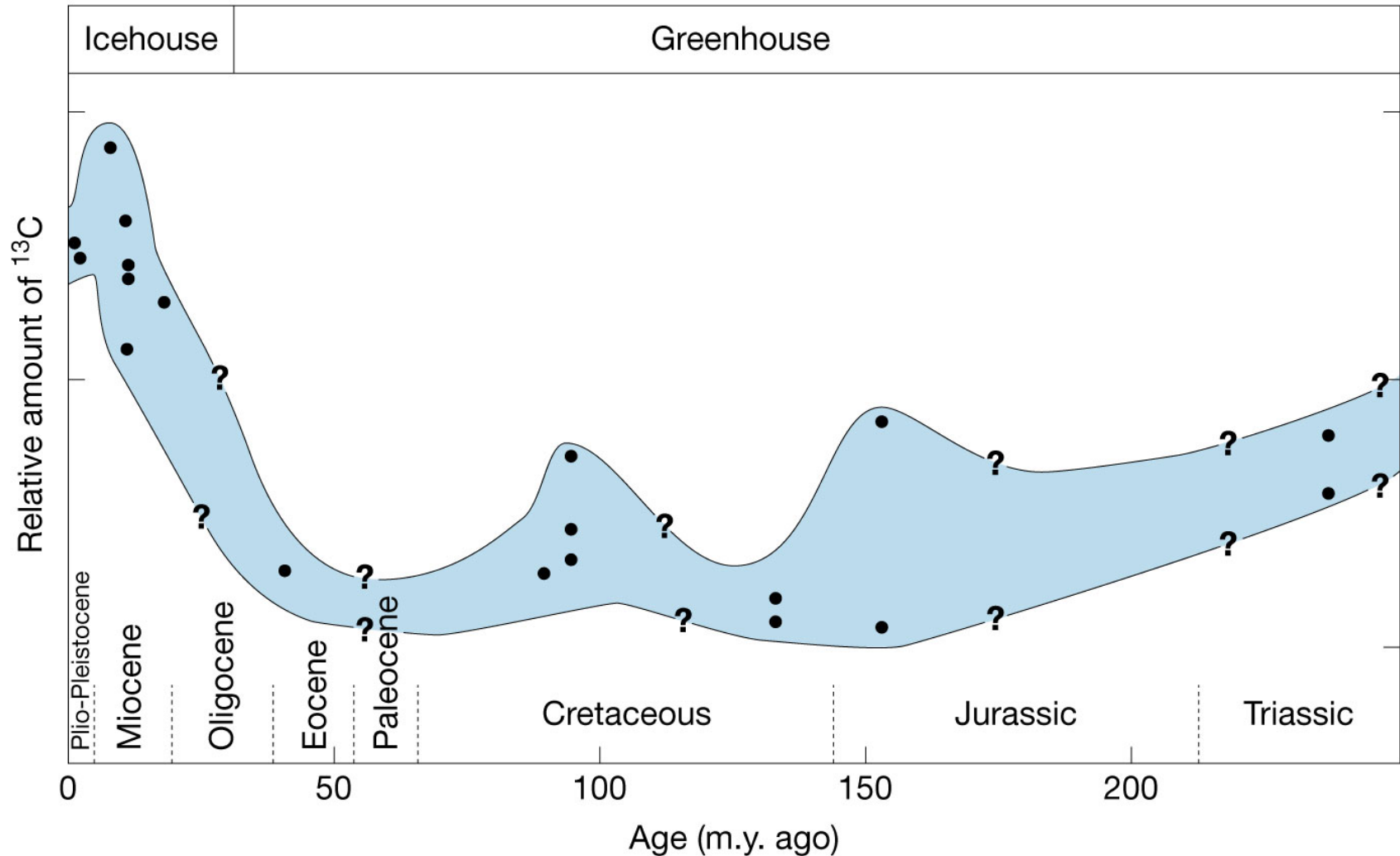




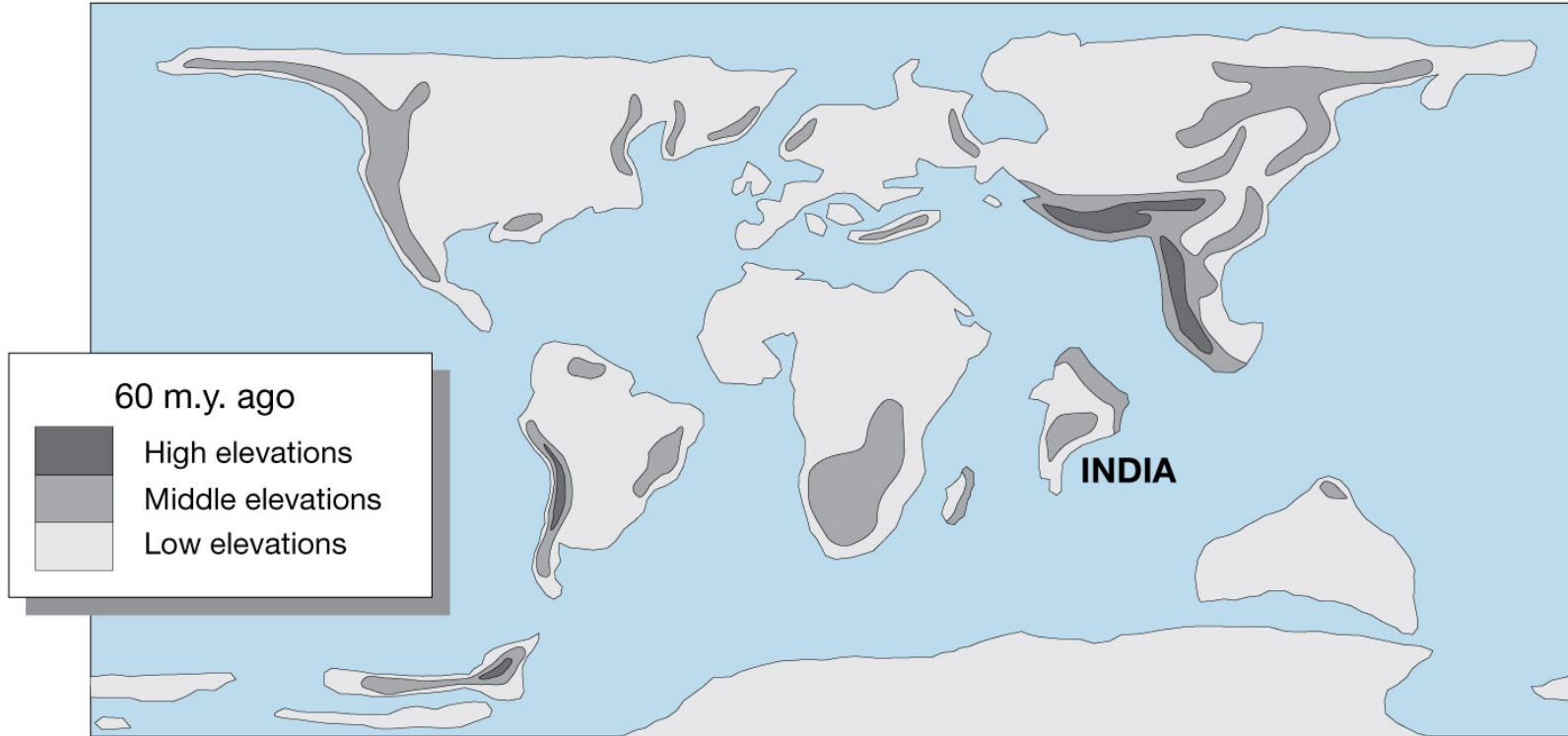


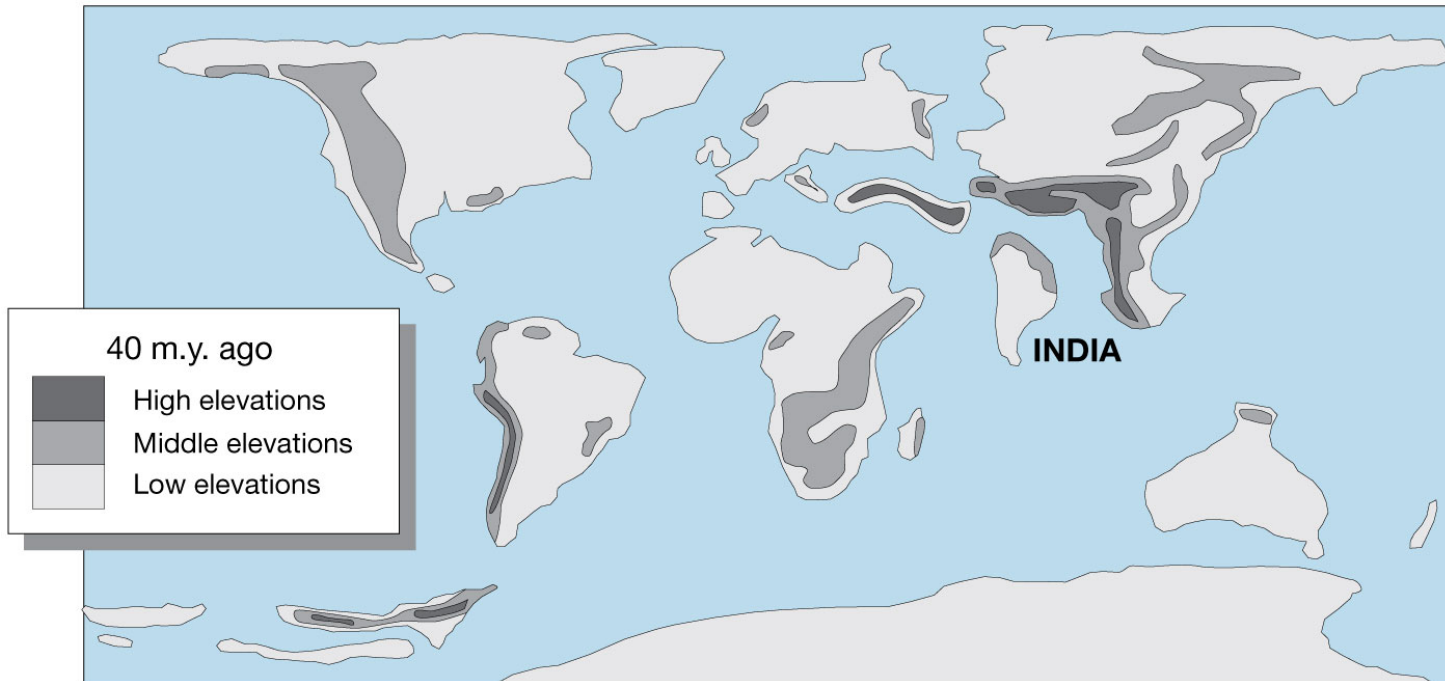


# Greater $^{13}\text{C}/^{12}\text{C}$ ratio in last 20 my

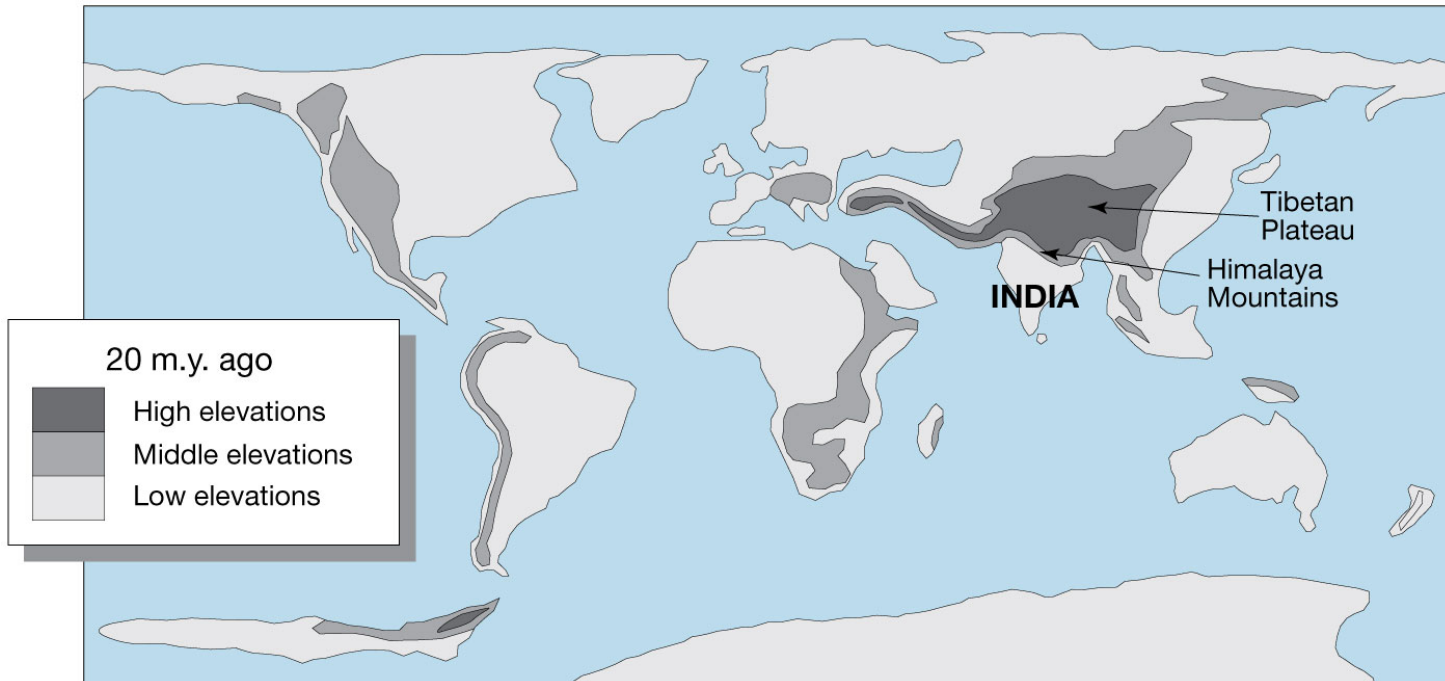


# Effect of collision of India with Asia?





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