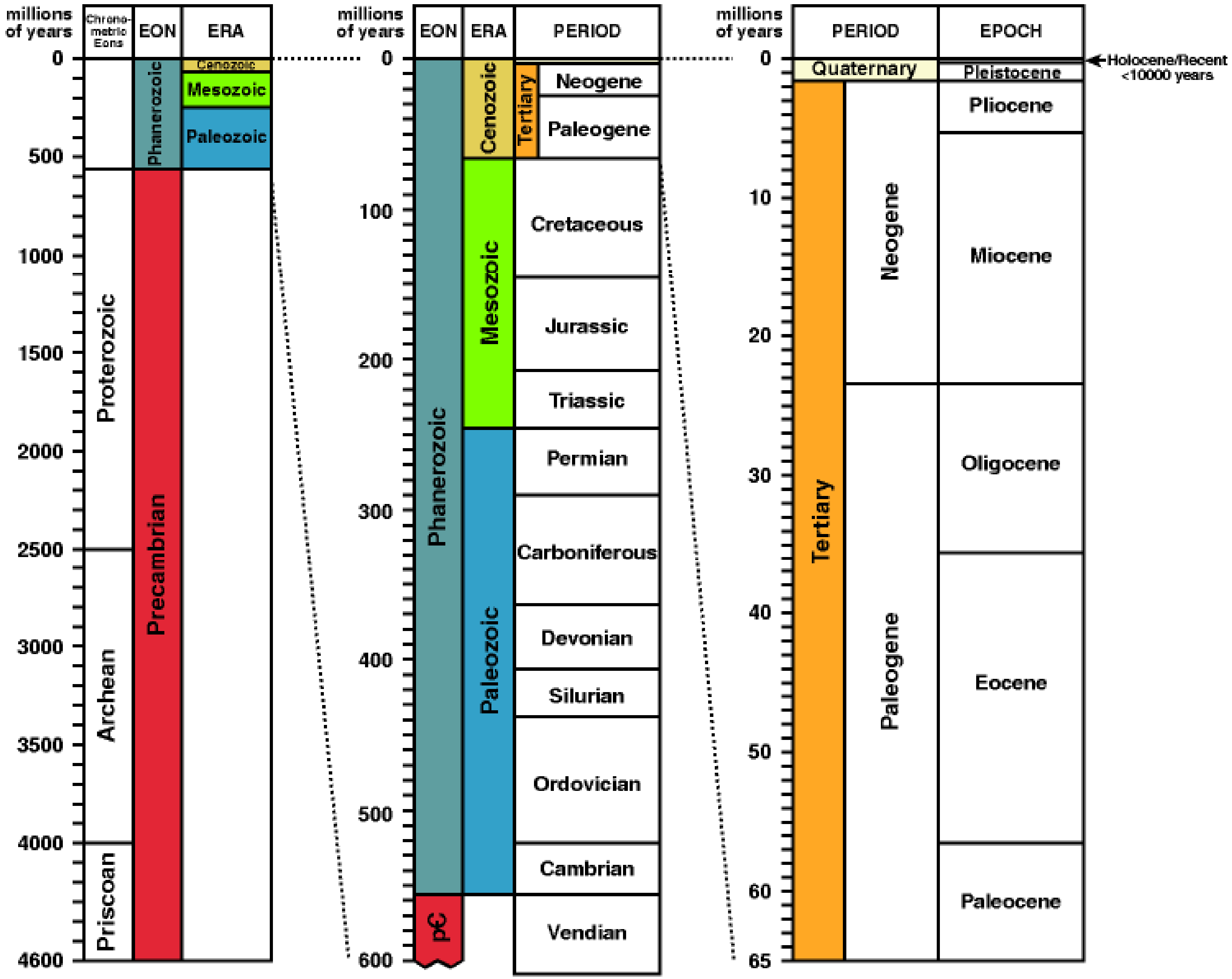
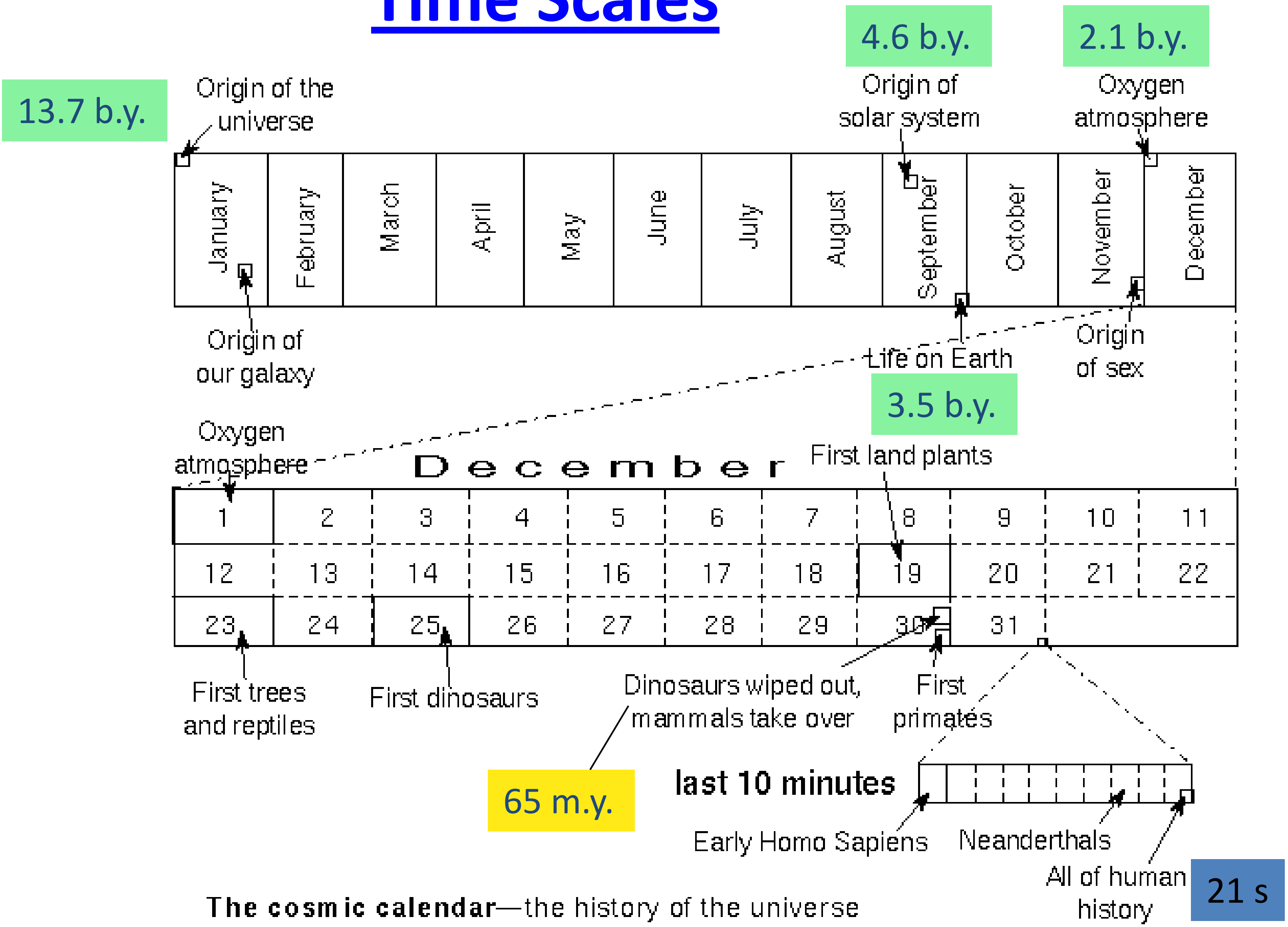
12.340
Global Warming Science

Paleoclimatology and the History of Earth's Climate


millions of years
Chrono-metric Eons
EON
ERA
0
500
1000
1500
2000
2500
3000
3500
4000
4600
Proterozoic
Archean
Priscoan
Phanerozoic
Precambrian
Cenozoic
Mesozoic
Paleozoic
millions of years
EON
ERA
PERIOD
0
100
200
300
400
500
600
Phanerozoic
pЄ
Cenozoic
Mesozoic
Paleozoic
Tertiary
Neogene
Paleogene
Cretaceous
Jurassic
Triassic
Permian
Carboniferous
Devonian
Silurian
Ordovician
Cambrian
Vendian
millions of years
PERIOD
EPOCH
0
10
20
30
40
50
60
65
Quaternary
Tertiary
Neogene
Paleogene
Pleistocene
Holocene/Recent <10000 years
Pliocene
Miocene
Oligocene
Eocene
Paleocene

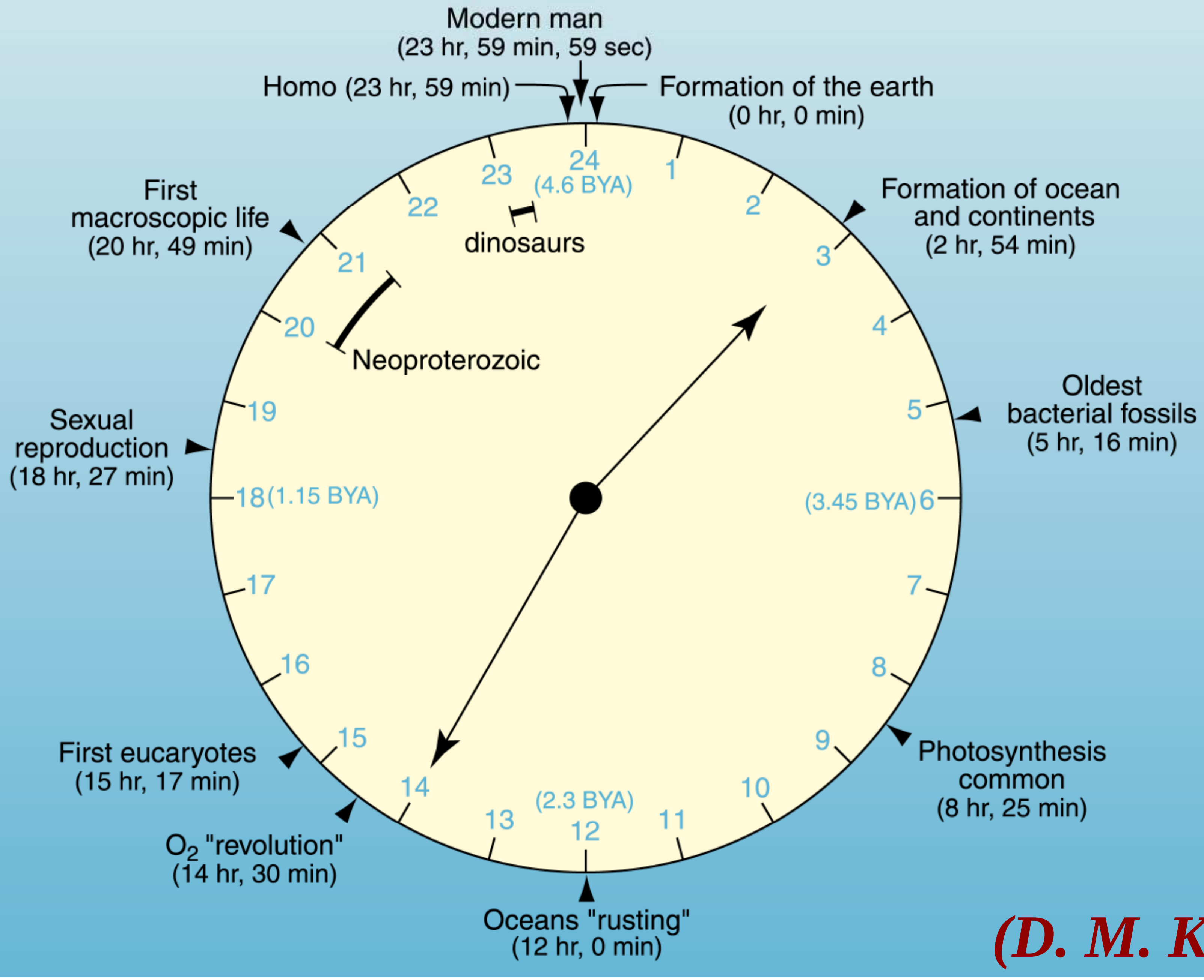
Time Scales



The cosmic calendar—the history of the universe compressed to one year. All of recorded history (human civilization) occurs in last 21 seconds!

Avg. human life span=0.15 s

4.6 Billion Years of Earth's History



Modern man
(23 hr, 59 min, 59 sec)

Homo (23 hr, 59 min)

Formation of the earth
(0 hr, 0 min)

First
macroscopic life
(20 hr, 49 min)

Formation of ocean
and continents
(2 hr, 54 min)

Oldest
bacterial fossils
(5 hr, 16 min)

Sexual
reproduction
(18 hr, 27 min)

Photosynthesis
common
(8 hr, 25 min)

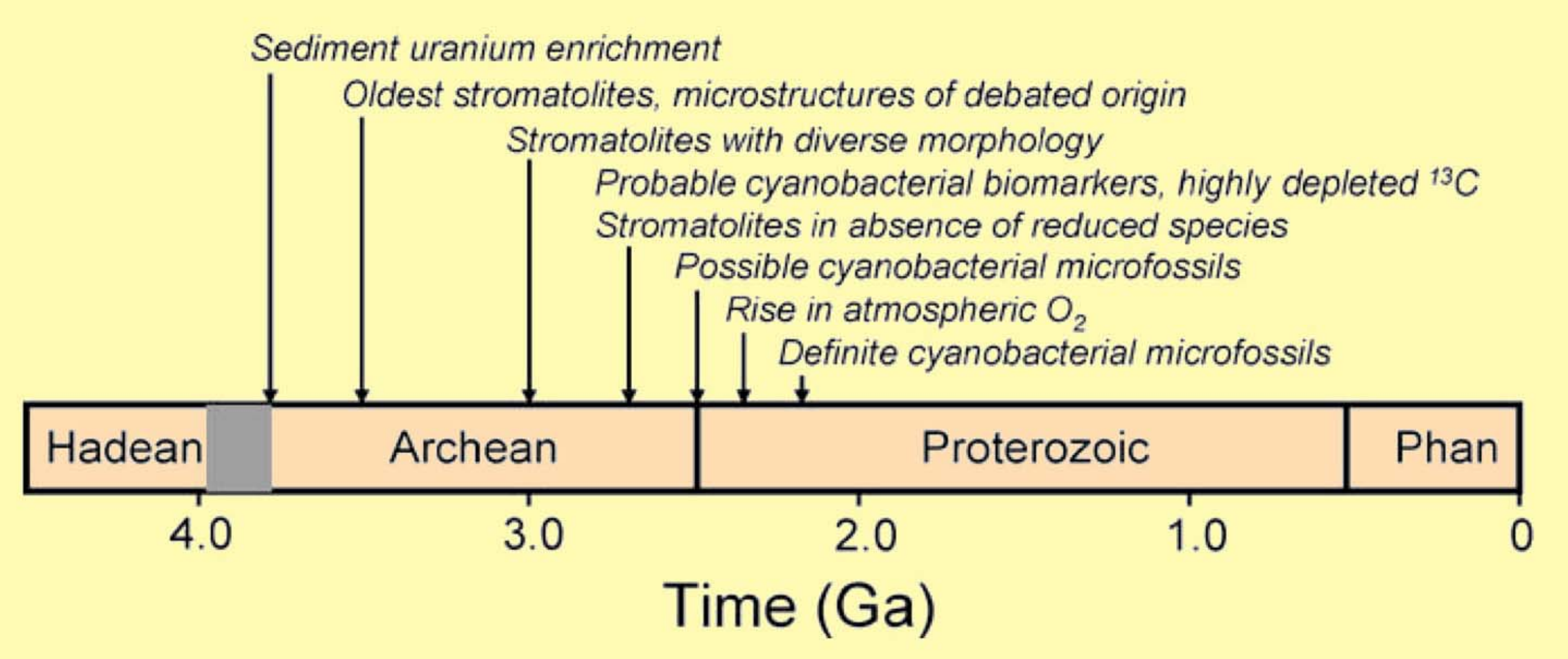
First eucaryotes
(15 hr, 17 min)

O_2 "revolution"
(14 hr, 30 min)

Oceans "rusting"
(12 hr, 0 min)

(D. M. Karl)

Evolution of early life on earth



A summary of the geologic evidence pointing to the early emergence of cyanobacteria. Concept modified after figure 2 in Knoll (2003).

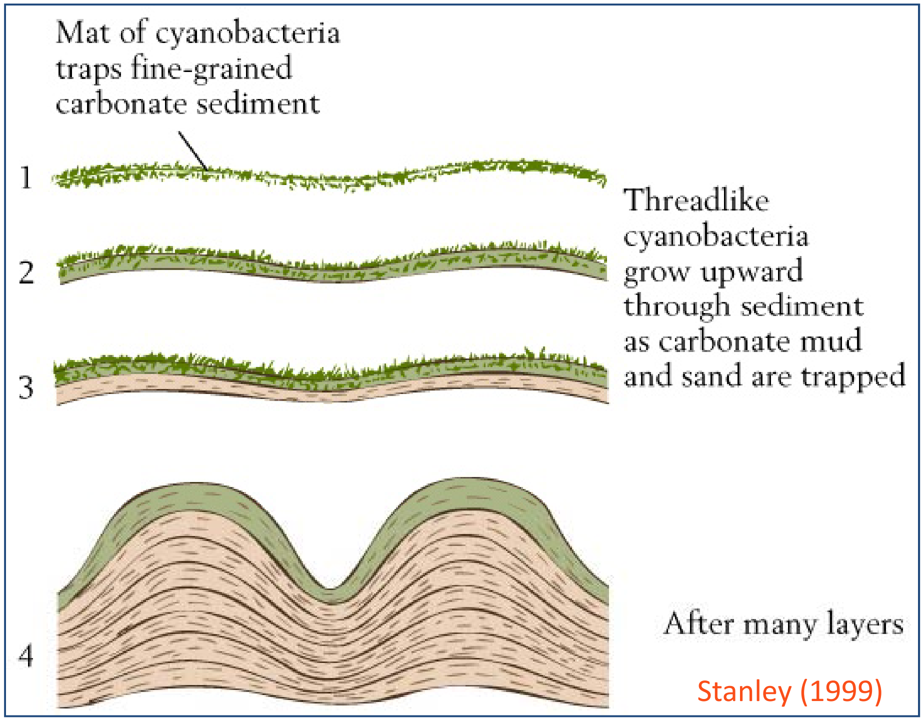
Canfield (2005) Ann.Rev.EarthPlanet.Sci 33:1-38

Modern Living Stromatolites: Shark Bay, Australia

http://www.sharkbay.org

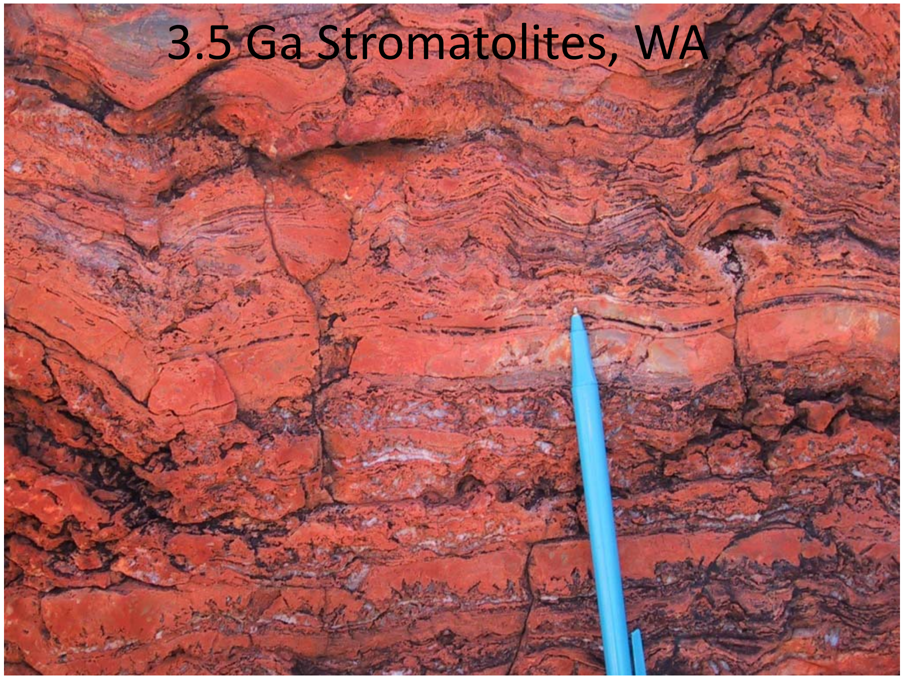
- Hamelin Pool's stromatolites result from the interaction between microbes, other biological influences and the physical and chemical environment.
- The cyanobacteria trap fine sediment with a sticky film of mucus that each cell secretes, then bind the sediment grains together with calcium carbonate which is separated from the water in which they grow. Because the cyanobacteria need sunlight to grow and they have the ability to move towards light, their growth keeps pace with the accumulating sediment.

What are Stromatolites & how do they form?



Stanley (1999)

~2 Ga Stromatolites, Slave Province, Canada



3.5 Ga Stromatolites, WA

Living Stromatolites, Shark Bay, Australia

An abiotic origin for stromatolites?

-->Grotzinger, J. and Rothman, D.H., “An abiotic model for stromatolite morphogenesis,” *Nature*, 382, 423-425, October 3, 1996.

- Statistically feasible that the morphology of stromatolites can occur through non-biological processes.

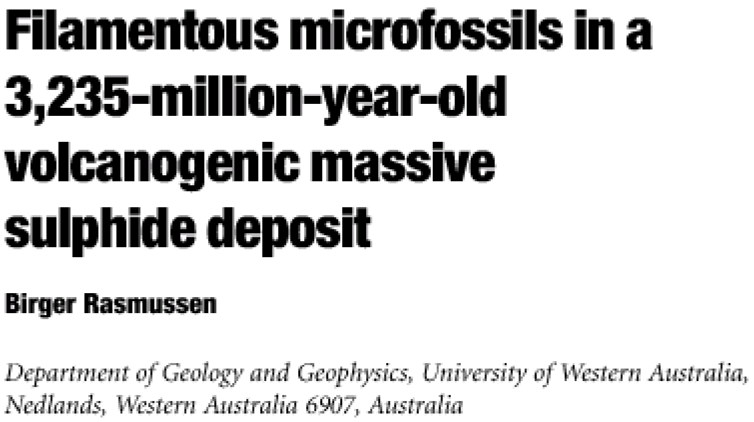
-->Grotzinger & Knoll, 1999

- Argue that Archean stromatolites could be simple inorganic precipitates.

The majority view seems to be that stromatolites are the first good evidence for life, placing its origin in the vicinity of 3.5 Ga.

By 3.47 Ga isotopically-depleted sulfur minerals have been cited as evidence for microbial life…

3.2 Ga Hyperthermophilic Microbes from W. Australia



Filamentous microfossils in a 3,235-million-year-old volcanogenic massive sulphide deposit

Birger Rasmussen

Department of Geology and Geophysics, University of Western Australia, Nedlands, Western Australia 6907, Australia

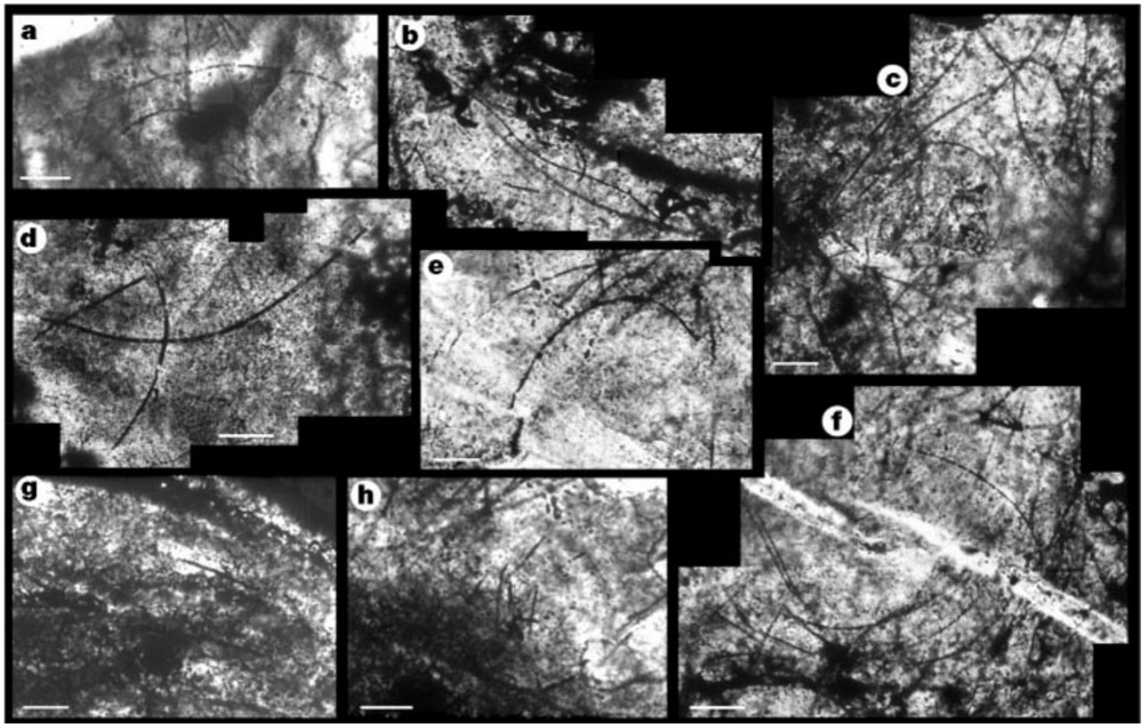


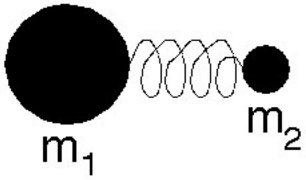
Figure 3 Photomicrographs of filaments from the Sulphur Springs VMS deposit. Scale bar, 10 μm. **a**–**f**, Straight, sinuous and curved morphologies, some densely intertwined. **g**, Filaments parallel to the concentric layering. **h**, Filaments oriented sub-perpendicular to banding.

Rasmussen (2000) *Nature*, Vol. 405:676-679

Two geochemical tools:

1. Stable isotope ratios:

$$\delta^{18}O = \left[\frac{(^{18}O/^{16}O)_{sample}}{(^{18}O/^{16}O)_{standard}} -1 \right] \times 1000$$

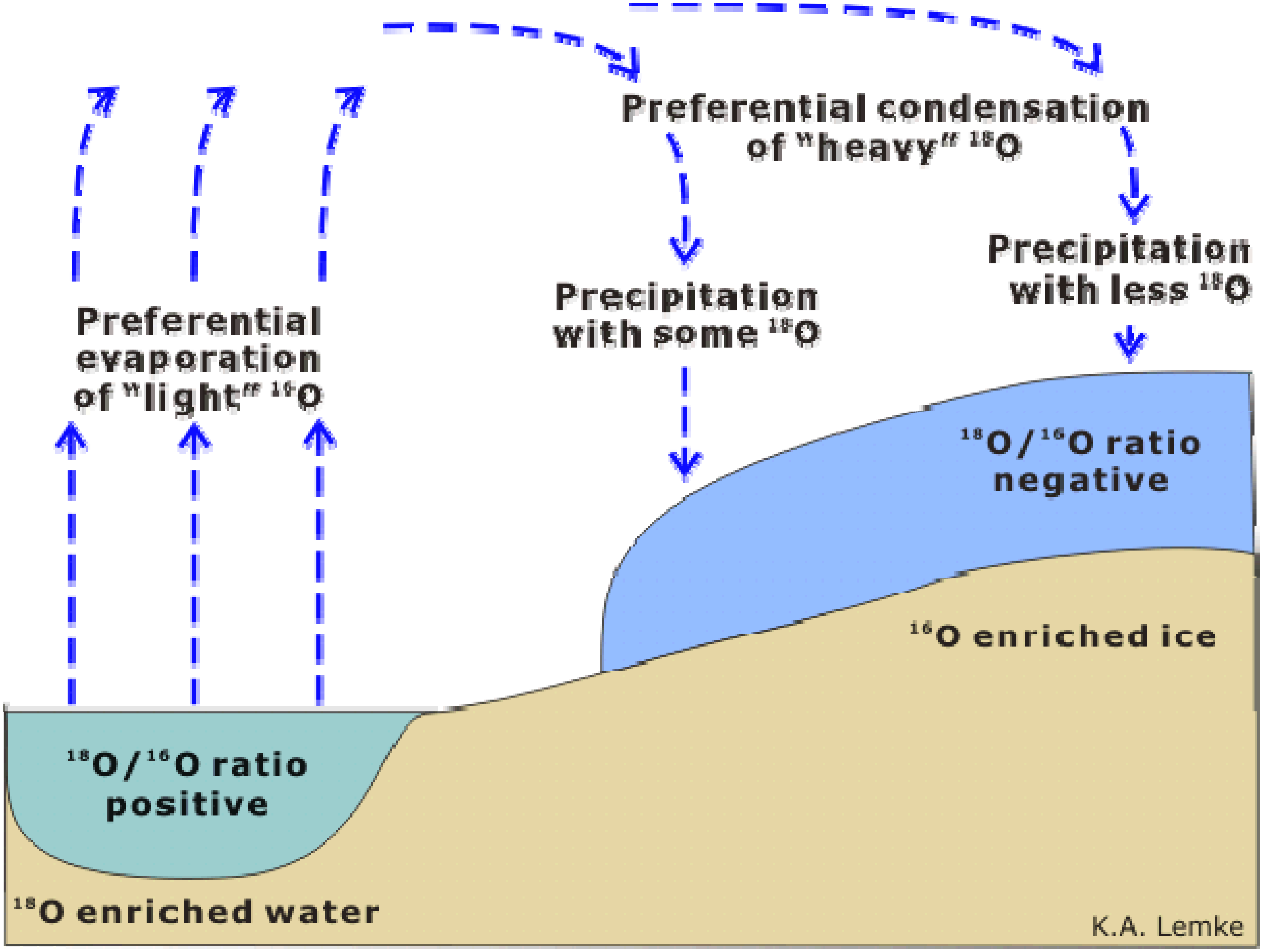


mass-dependent isotope fractionation

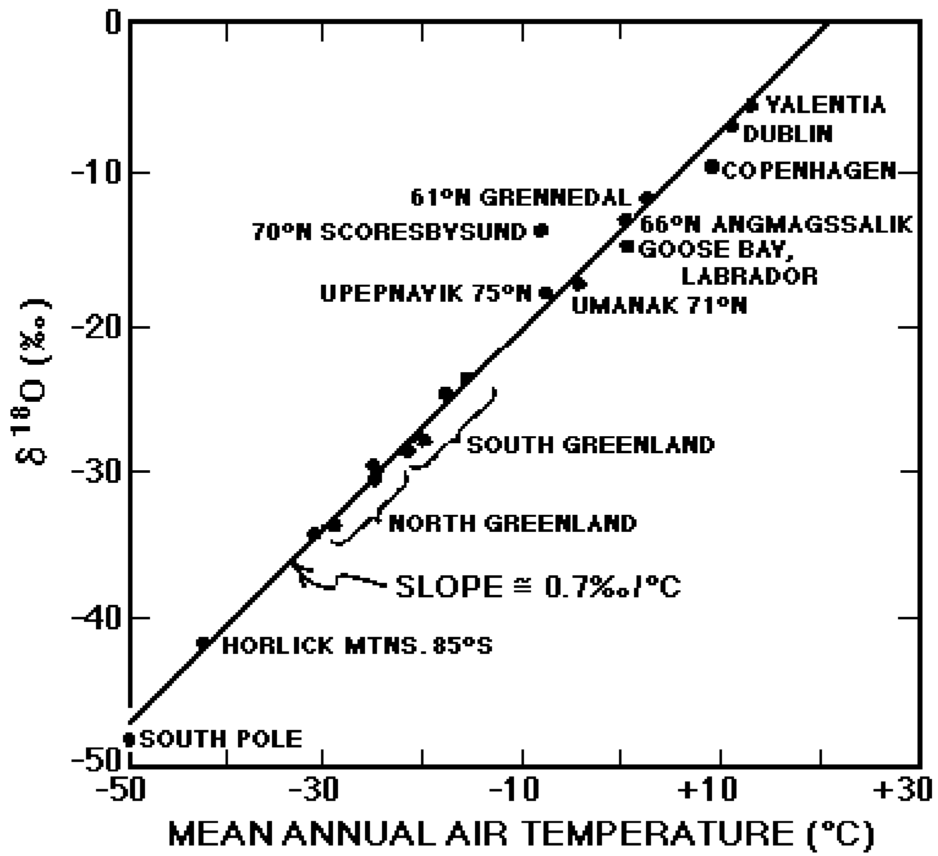
2. Triple stable isotope ratios:

$$\Delta^{33}S = \delta^{33}S - 0.515\ \delta^{34}S$$

mass-independent isotope fractionation


Preferential condensation of "heavy" ^{18}O
Preferential evaporation of "light" ^{16}O
Precipitation with some ^{18}O
Precipitation with less ^{18}O
^{18}O/^{16}O ratio negative
^{16}O enriched ice
^{18}O/^{16}O ratio positive
^{18}O enriched water
K.A. Lemke

Strong correlation between the isotopic composition of snow and mean annual air temperature in the present climate



Observed $\delta^{18}O$ in average annual precipitation as a function of mean annual air tamperature (Dansgaard, 1964). Note that all the points on this graph are for high latitudes (>45°). The $\delta^{18}O$ values are calculated as follows:

$$\delta^{18}O = \frac{^{18}O/^{16}O\ \text{sample} - {}^{18}O/^{16}O\ \text{std.}}{^{18}O/^{16}O\ \text{std.}} \times 1000$$

Broecker, WS. The Glacial World According to Wally,
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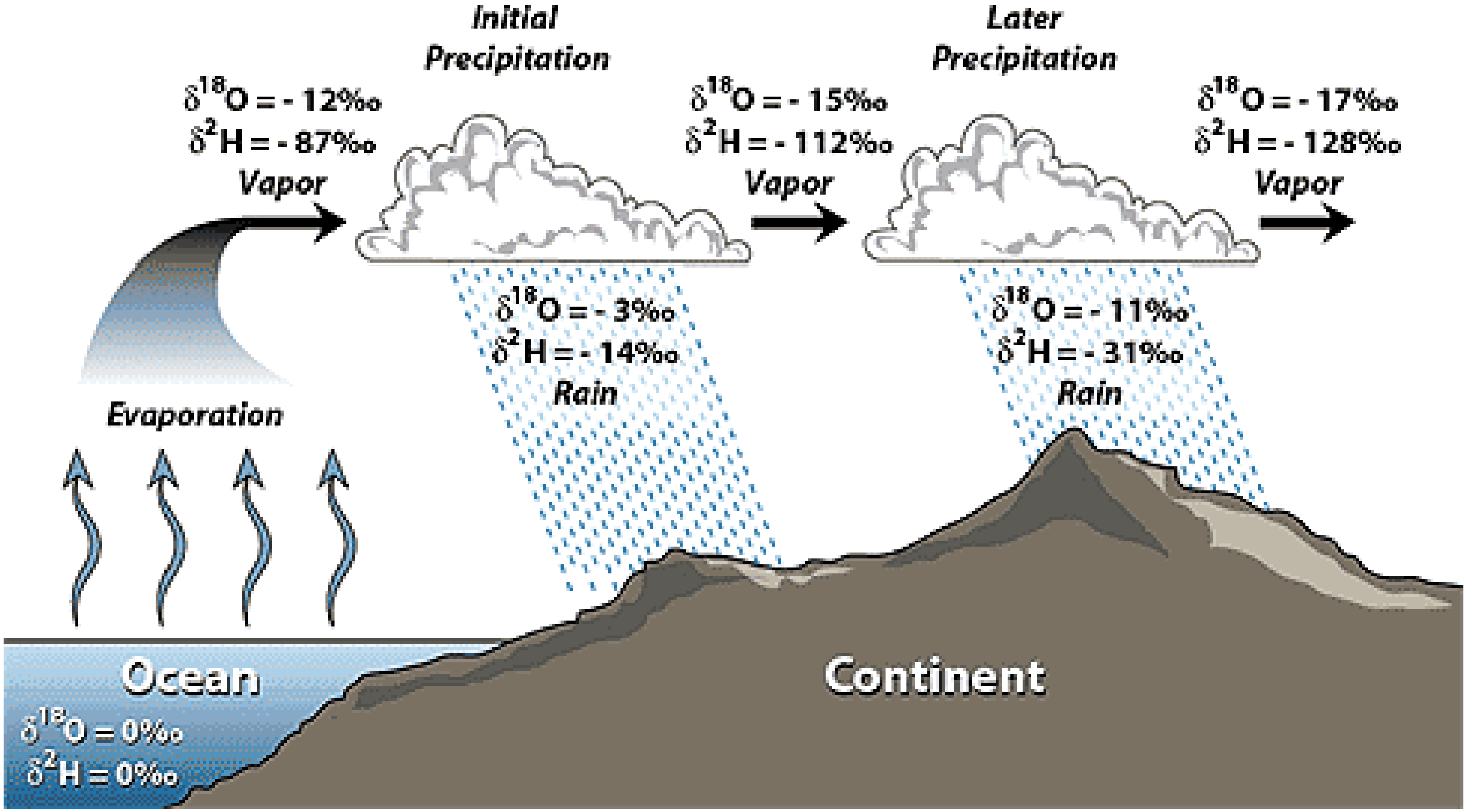
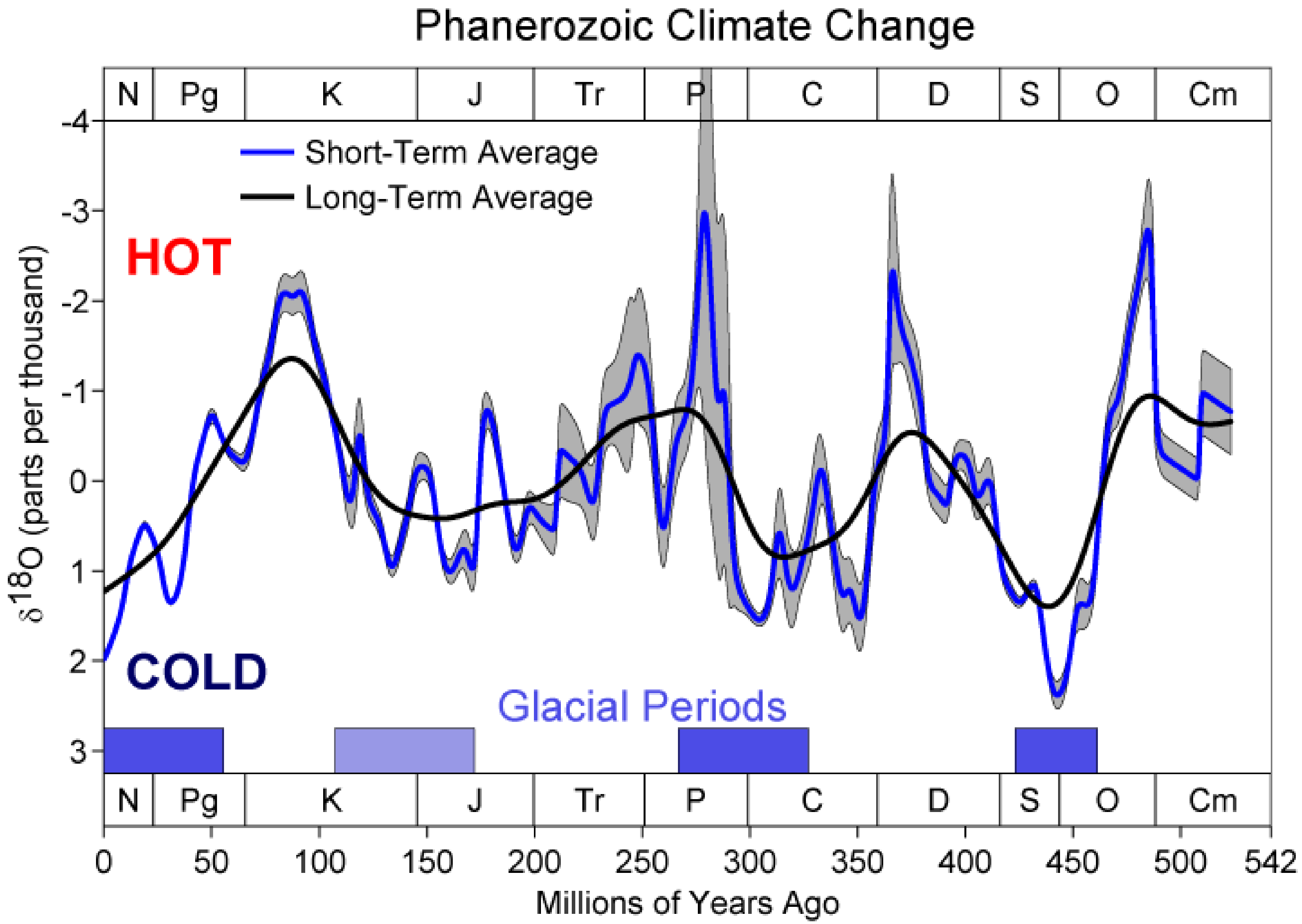
But Other Factors Influence Isotopic Composition as Well

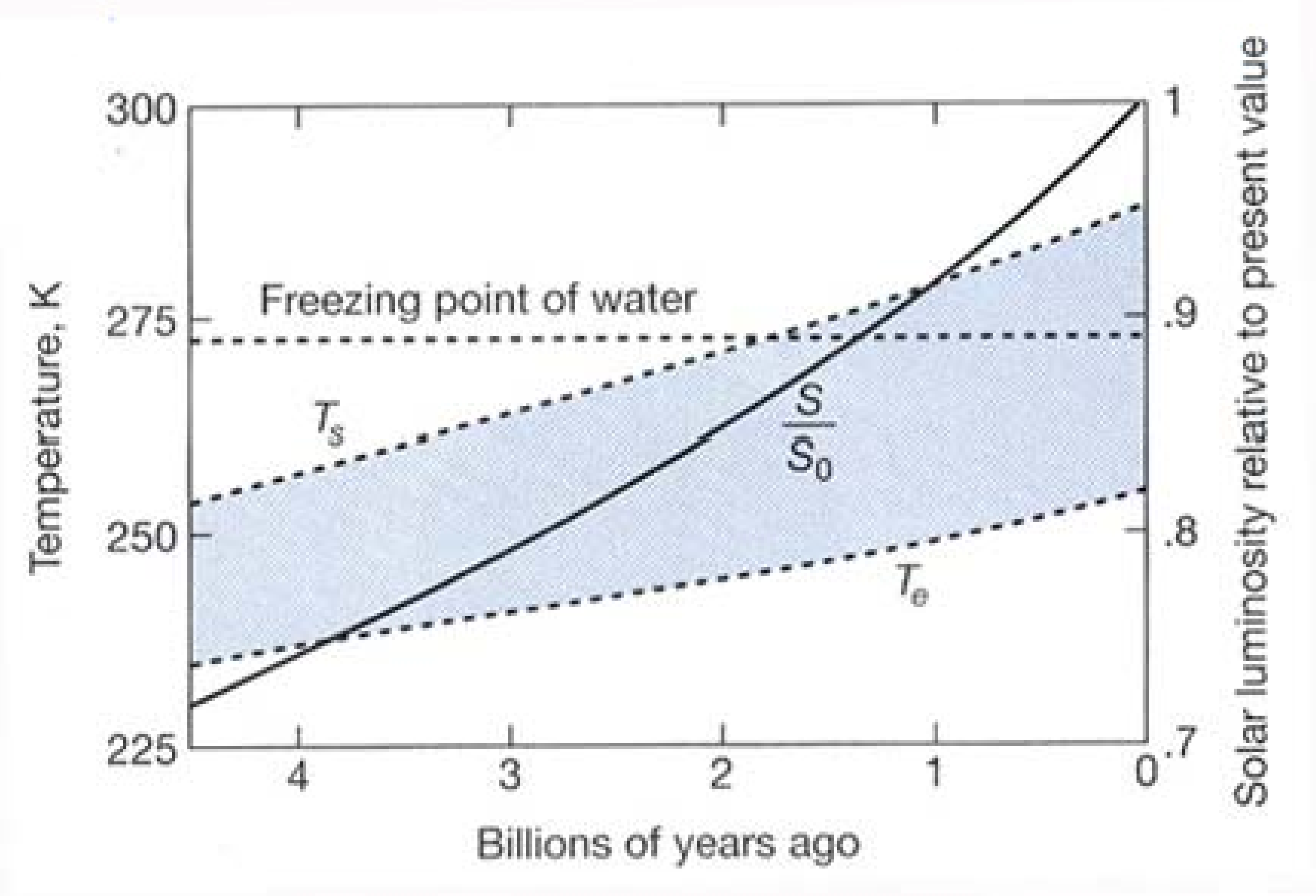




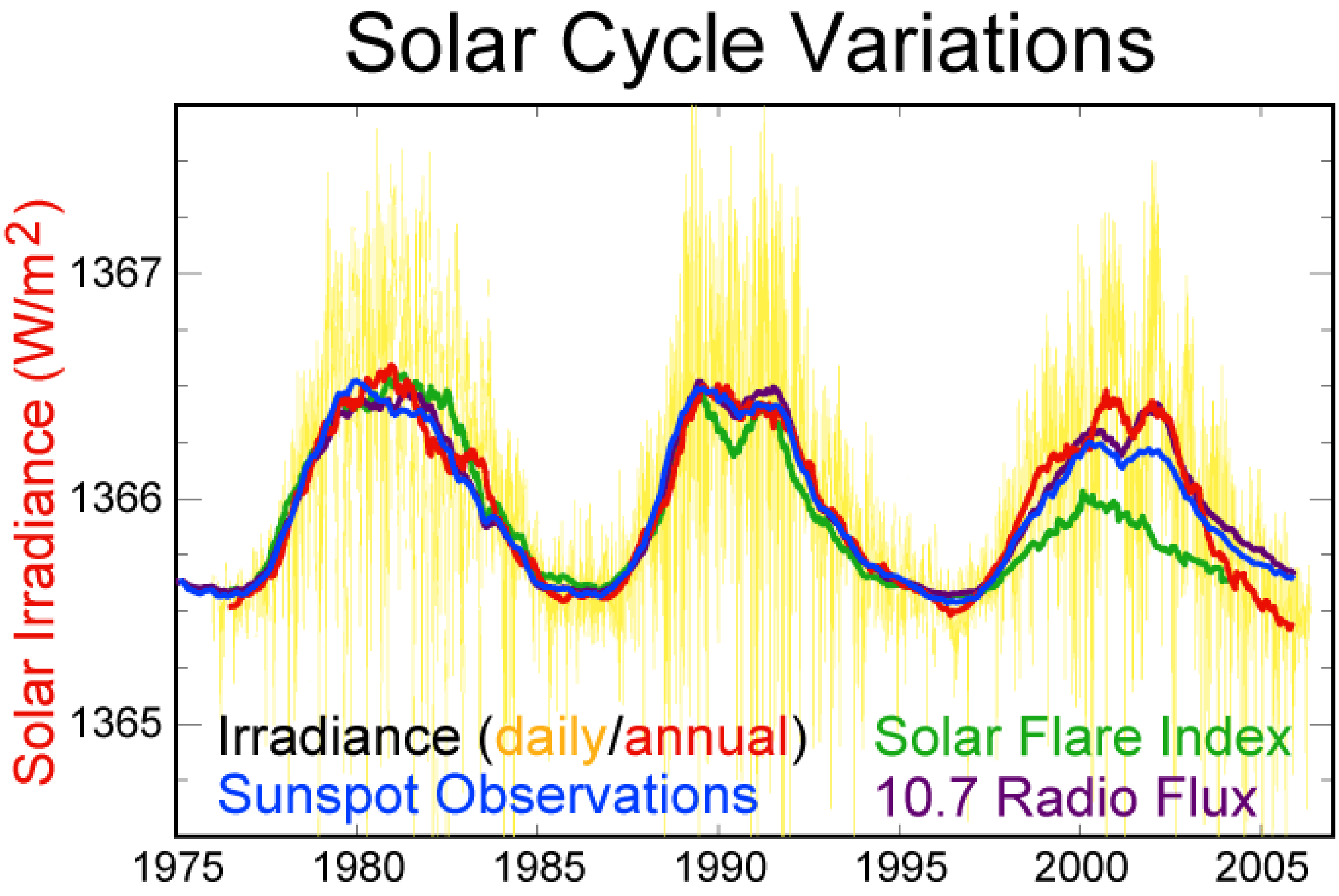
Oxygen isotopic composition of fossils, reflecting both local temperature and global amount of land ice

The ‘Faint Young Sun Paradox’

Why didn't the Earth Freeze?

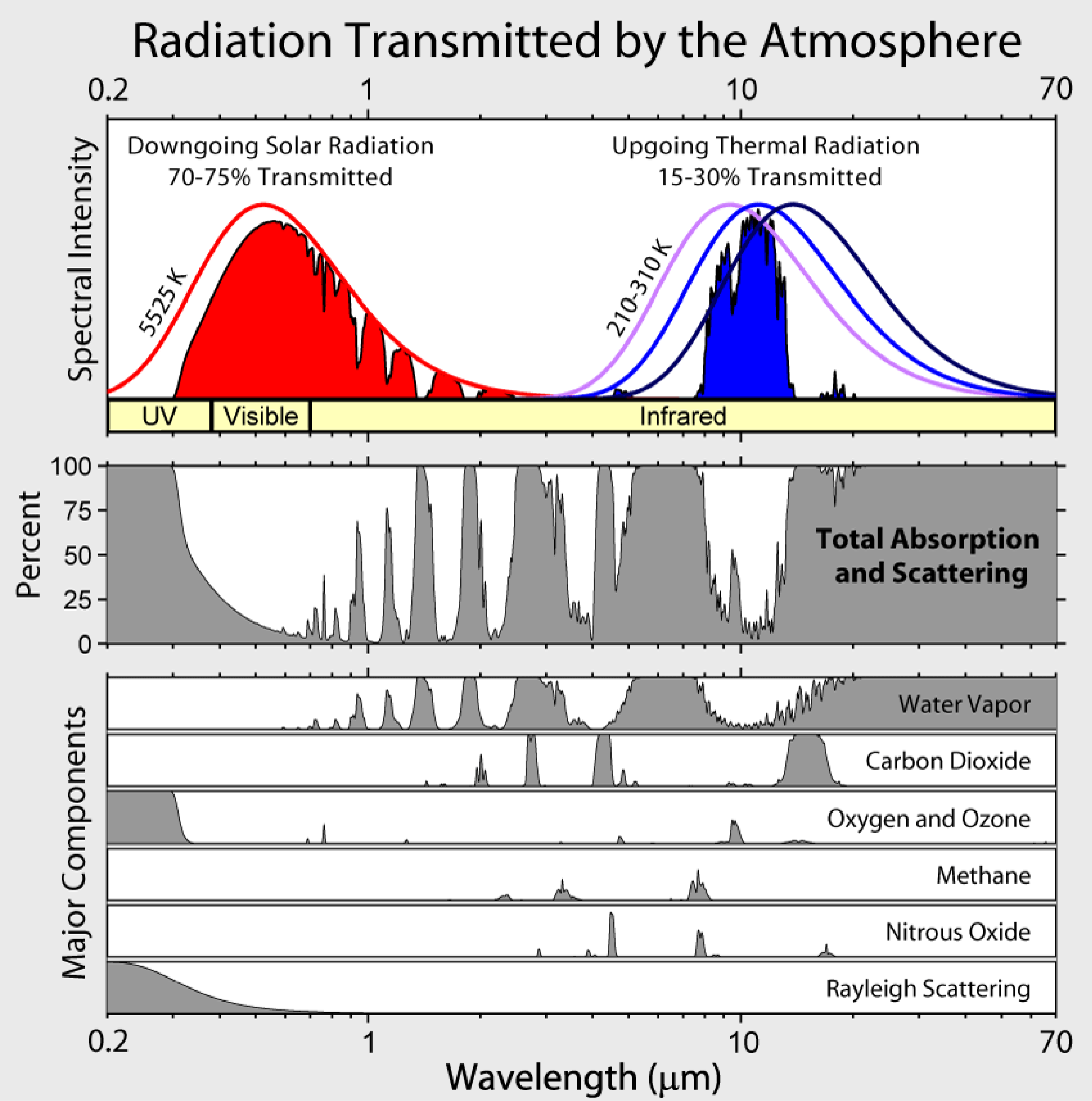


Contemporary Solar Variability



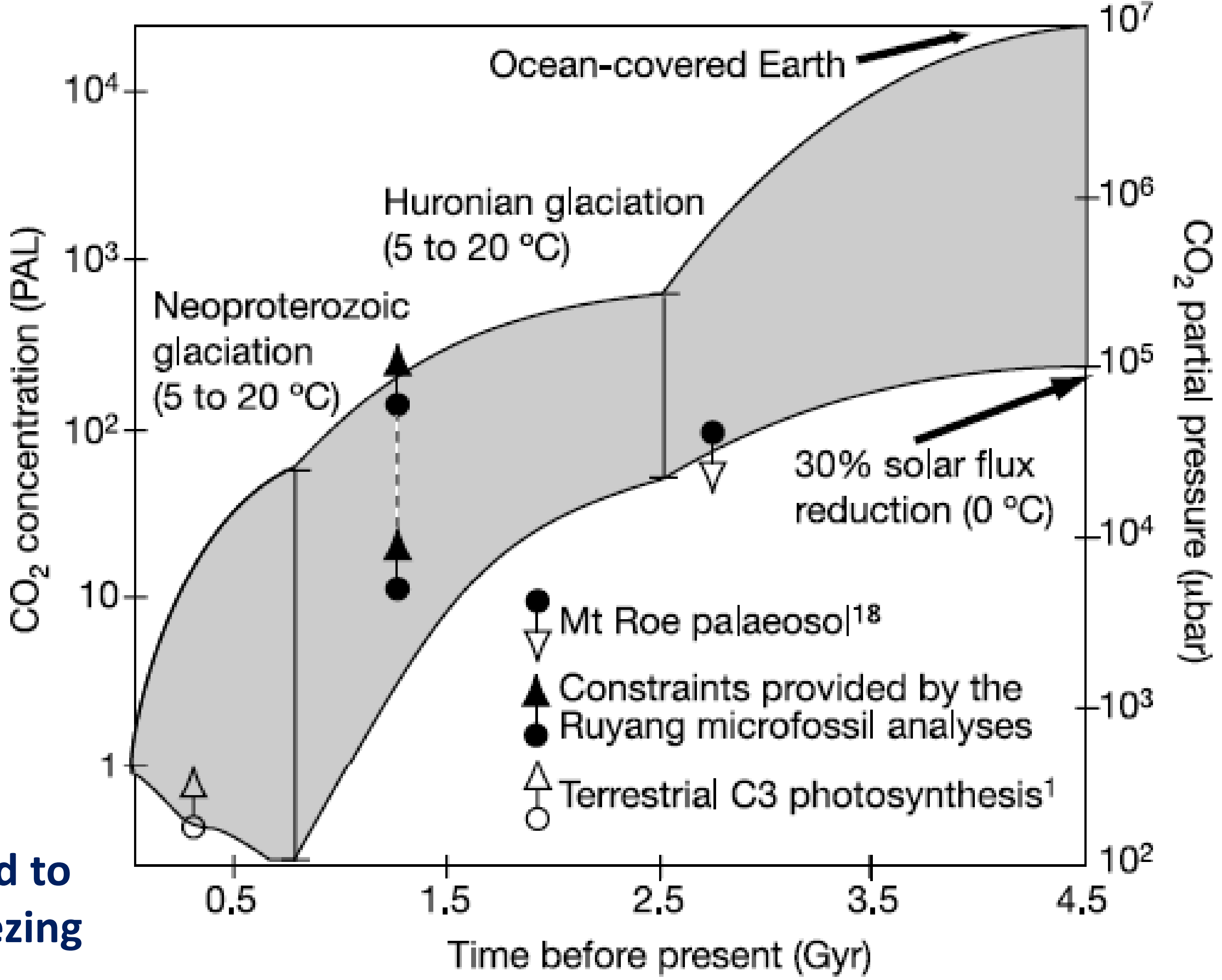
- Contemporary Solar Variability ~0.1%
- Associated with 11-year sunspot cycle

Candidate Explanation: High Levels of Greenhouse Gases CO_2 and/or Methane) in Early Atmosphere



Radiation Transmitted by the Atmosphere

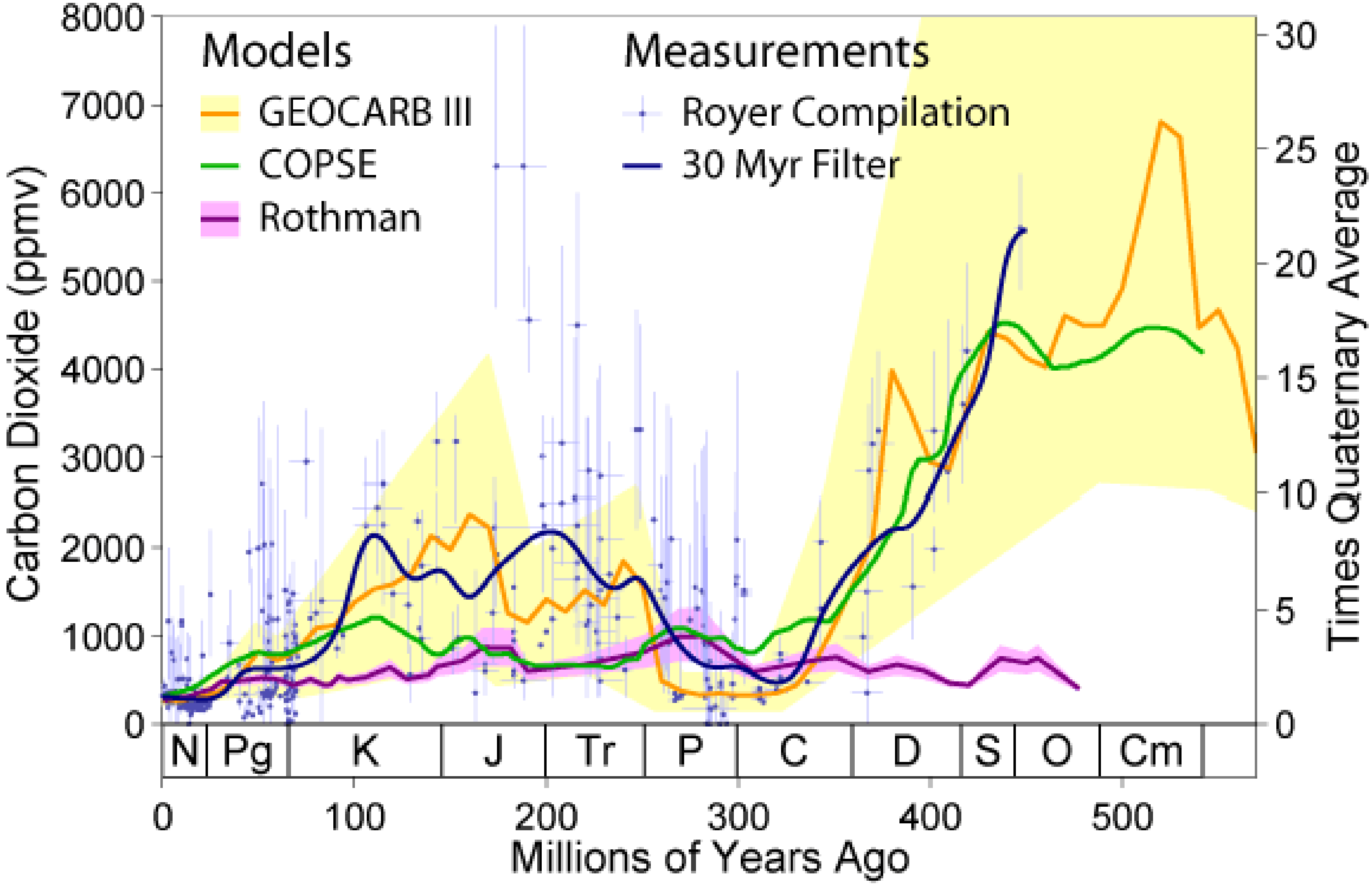
Precambrian pCO_2 Needed to Prevent Freezing



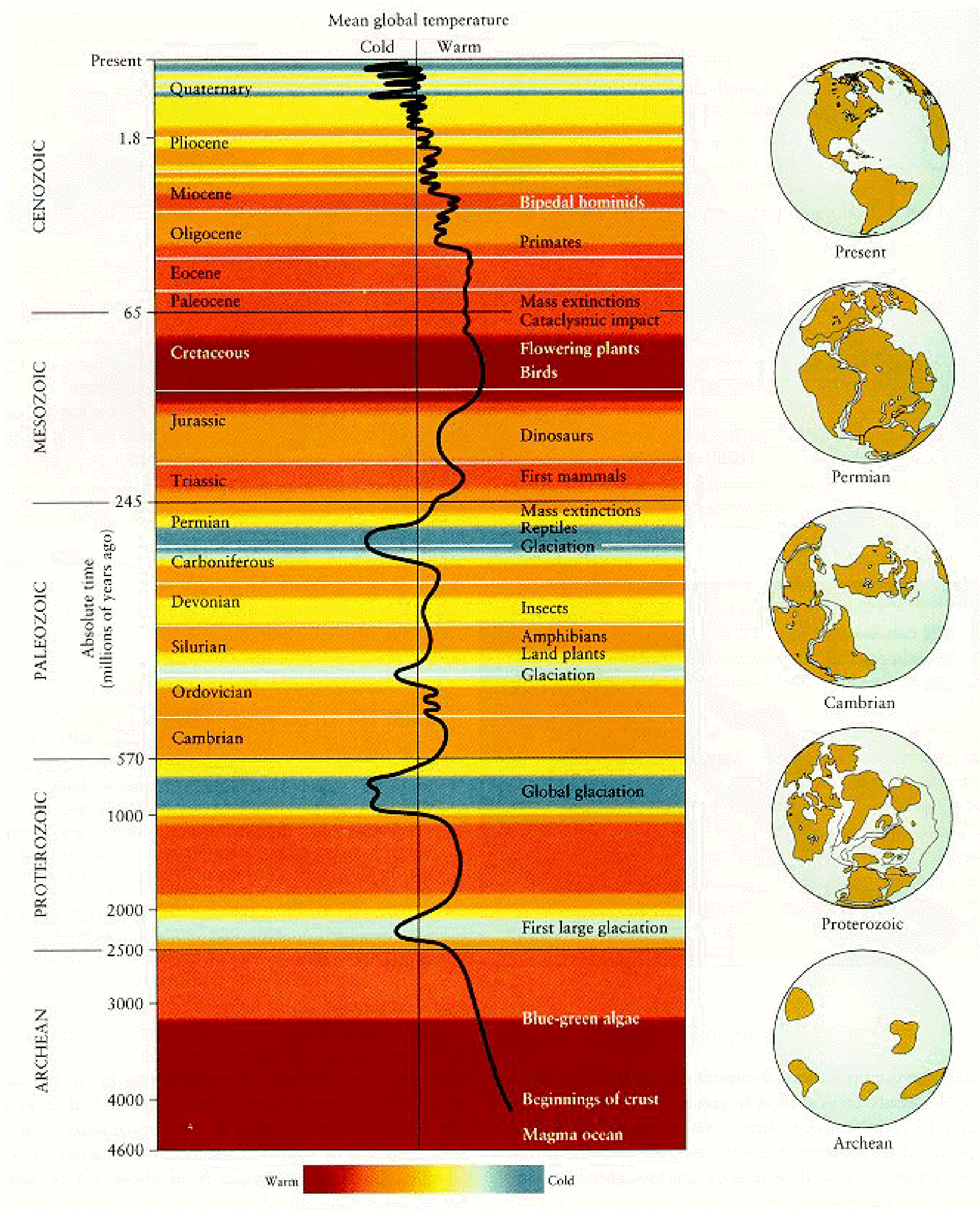
pCO_2 needed to prevent freezing

Kaufman & Xiao (2003), *Nature* Vol. 425: 279-282

Phanerozoic Carbon Dioxide



History of Earth's Climate



Glaciations

Evidence for Glaciers on All Continents

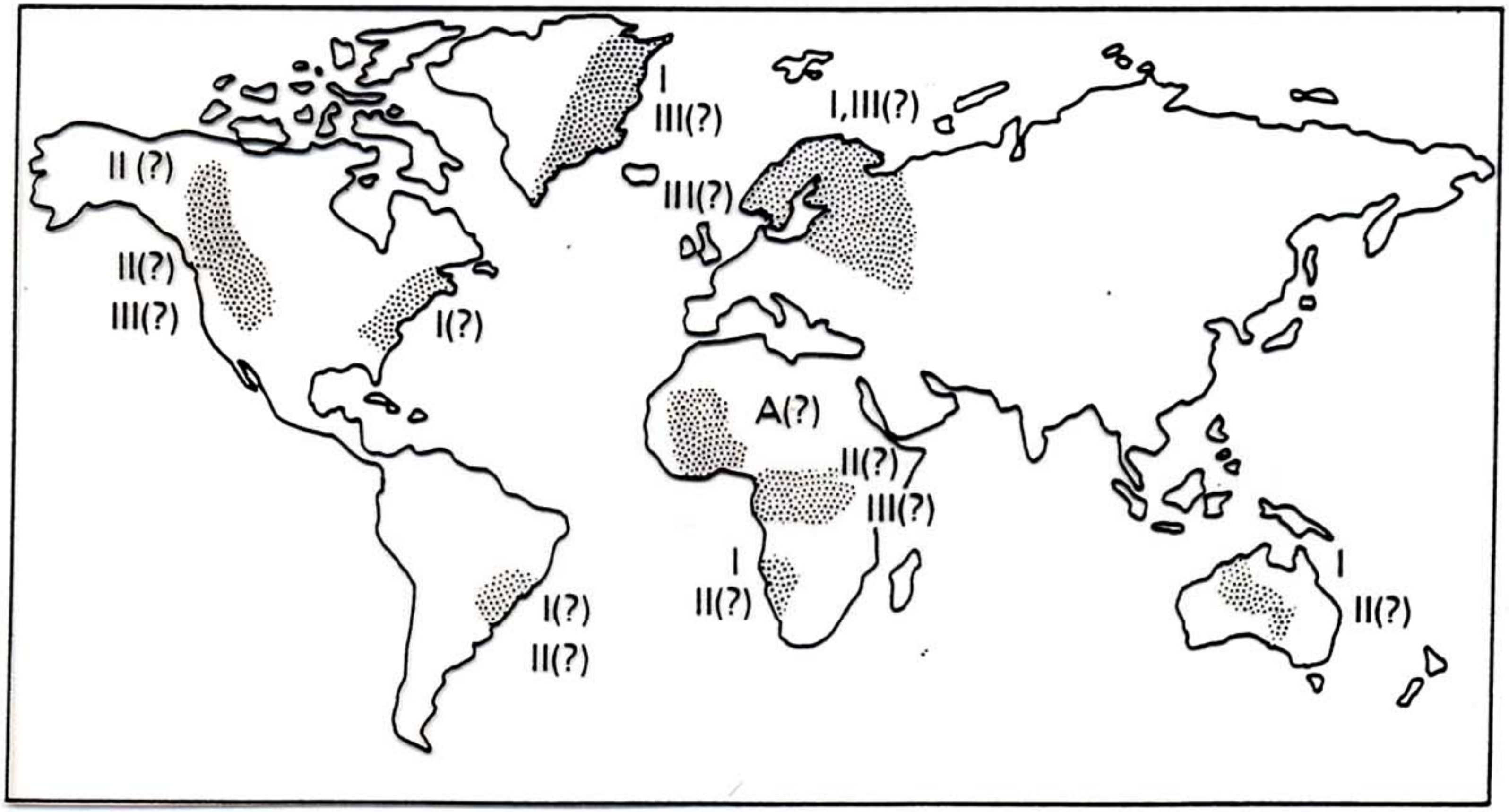


Fig. 12.3. Global distribution of major late Precambrian glacial centers on a map showing the present dispersal of continents. I, II, III refer to glaciations identified by Williams (1975) as centered on ~610 Ma, 750 Ma, and 950 Ma, respectively. A subsequent summary of late Precambrian glaciations (Hambrey and Harland, 1981a) suggests that these glaciations may not be as episodic as inferred by Williams. The letter A signifies that all three time intervals may be represented. [Modified from Frakes, 1979] *Reprinted by permission from L. Frakes, "Climates Throughout Geologic Time," copyright, 1979, Elsevier Scientific Publishers.*

Glaciations 610 – 950 Ma

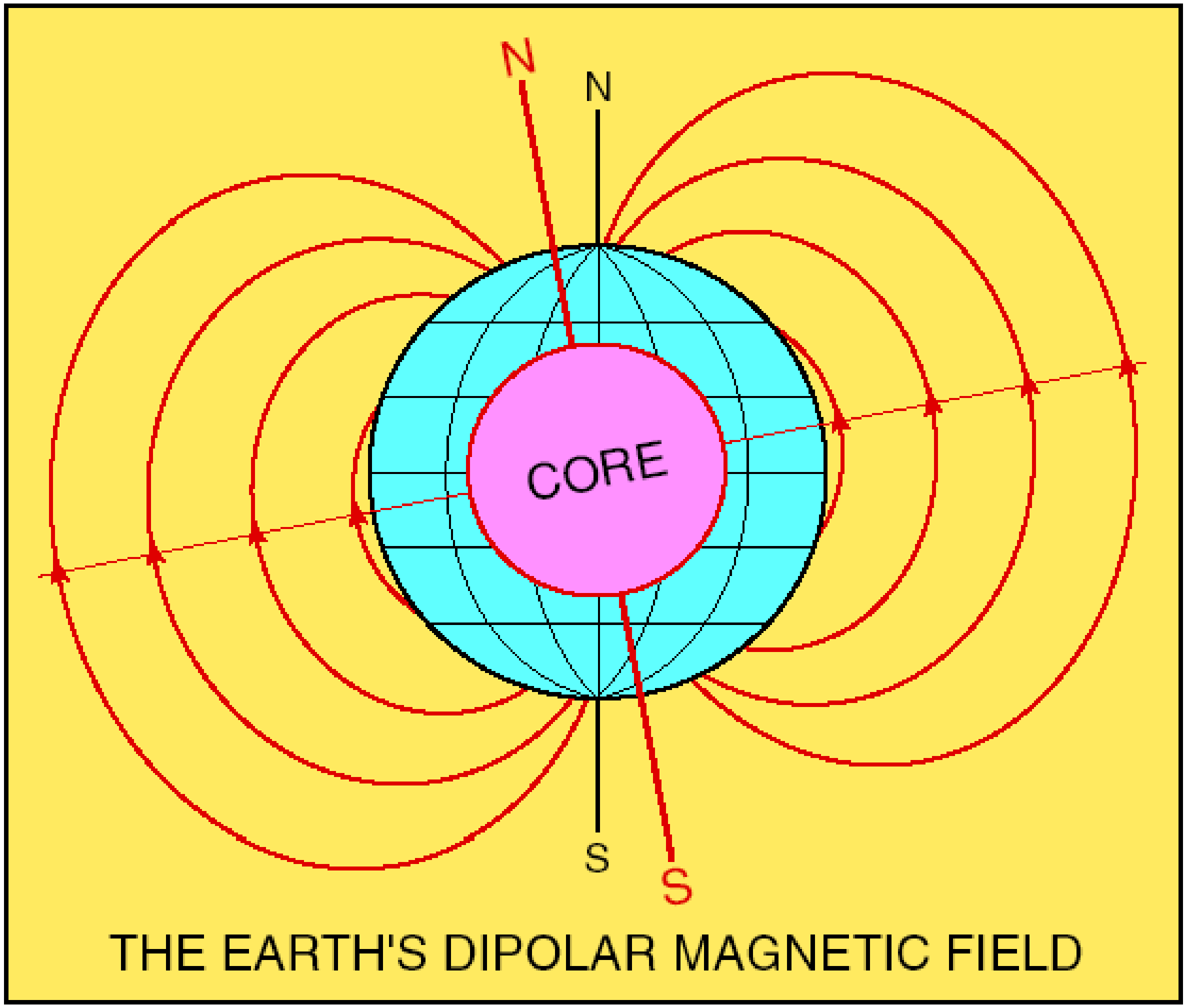
Equatorial Continents?

Hoffman, PF
& DP Schrag
Scientific American, 2000

EARTH'S LANDMASSES were most likely clustered near the equator during the global glaciations that took place around 600 million years ago. Although the continents have since shifted position, relics of the debris left behind when the ice melted are exposed at dozens of points on the present land surface, including what is now Namibia (*red dot).*

- Harland & Rudwick (1964) identified glacial sediments at what looked like equatorial latitudes by paleomagnetism.
- George Williams (1975) identified low latitude glacial sequence in S. Australia & attributed to episode of extreme obliquity (tilt).

Determining Paleolatitude from Remnant Magnetism



THE EARTH'S DIPOLAR MAGNETIC FIELD

- •Paleomagnetism: latitude of formation of rock
- •Natural Remnant Magnetism (NRM): inclination varies with “magnetic” latitude
  - -vertical @ magn poles
  - -horz. @ magn equator (many Neoprot glac deposits)
- •Magnetic polar drift averages out on T~10 ky

Image from P. Hoffman

Paleolatitude from Paleomagnetism

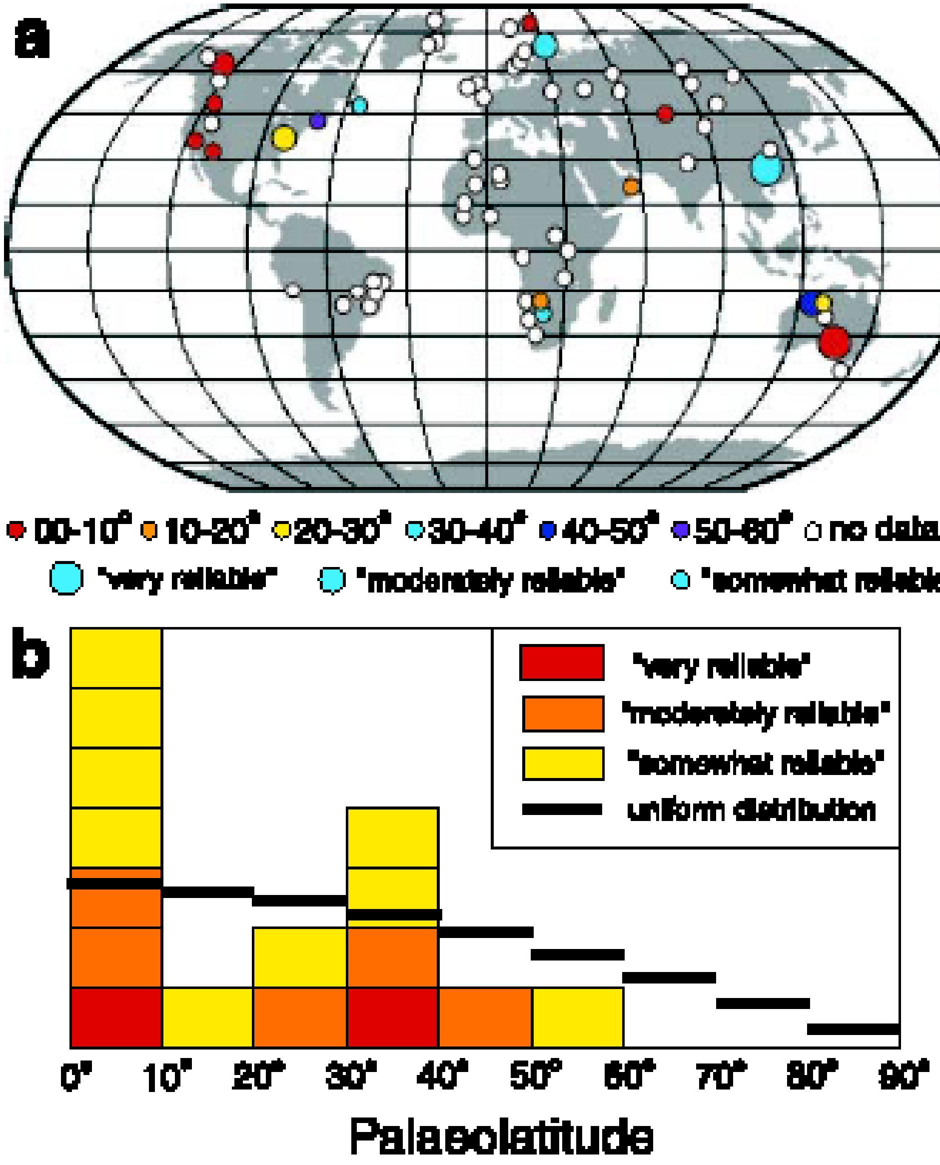
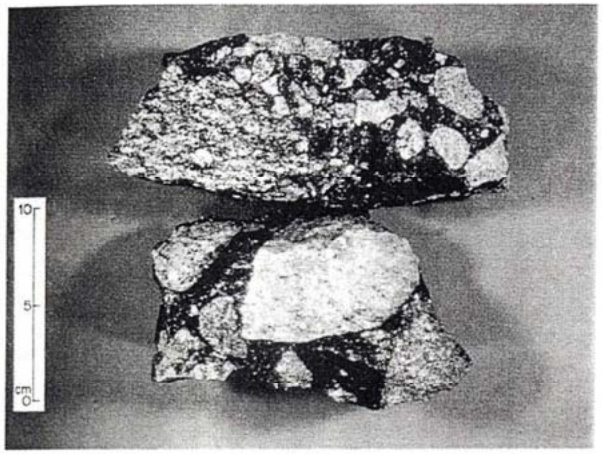


Fig. 1 Global distribution (a) of Neoproterozoic glaciogenic deposits with estimated palaeolatitudes based on palaeomagnetic data (modified from Evans, 2000). 'Reliability' takes into account not only palaeomagnetic reliability but also the confidence that the deposits represent regionally significant, low-elevation ice sheets (Evans, 2000). Histogram (b) of the same glaciogenic deposits according to palaeolatitude. The discontinuous steps show the expected density function of a uniform distribution over the sphere. Note the preponderance of low-latitude deposits and absence of high-latitude deposits. This finding would not be invalidated by plausible non-diplole components of the field, which would effectively raise the palaeolatitudes of only the mid-latitude results (Evans, 2000). The minimum in the distribution in the subtropics may reflect the meridional variation in precipitation minus evaporation due to the Hadley cells.

Hoffman & Schrag (2002) *Terra Nova*, Vol. 14(3):129-155.

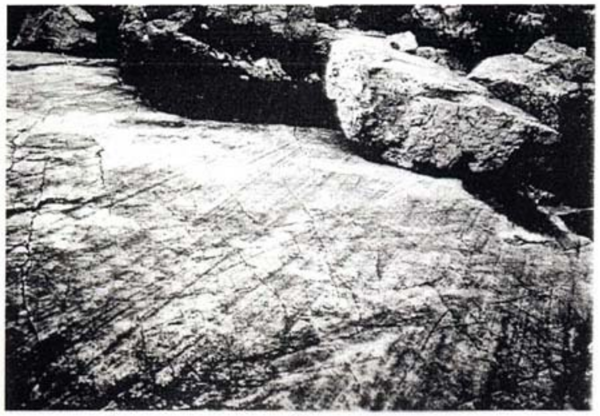
Geologic Evidence for Glaciers

Geologic Evidence For Glaciation



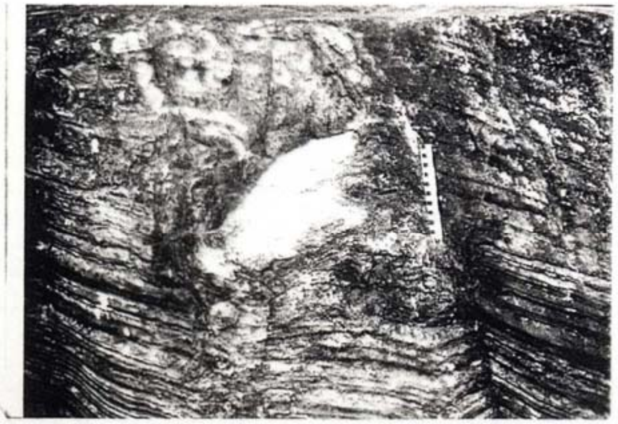
(a)

Tillites



(b)

Glacial Striations

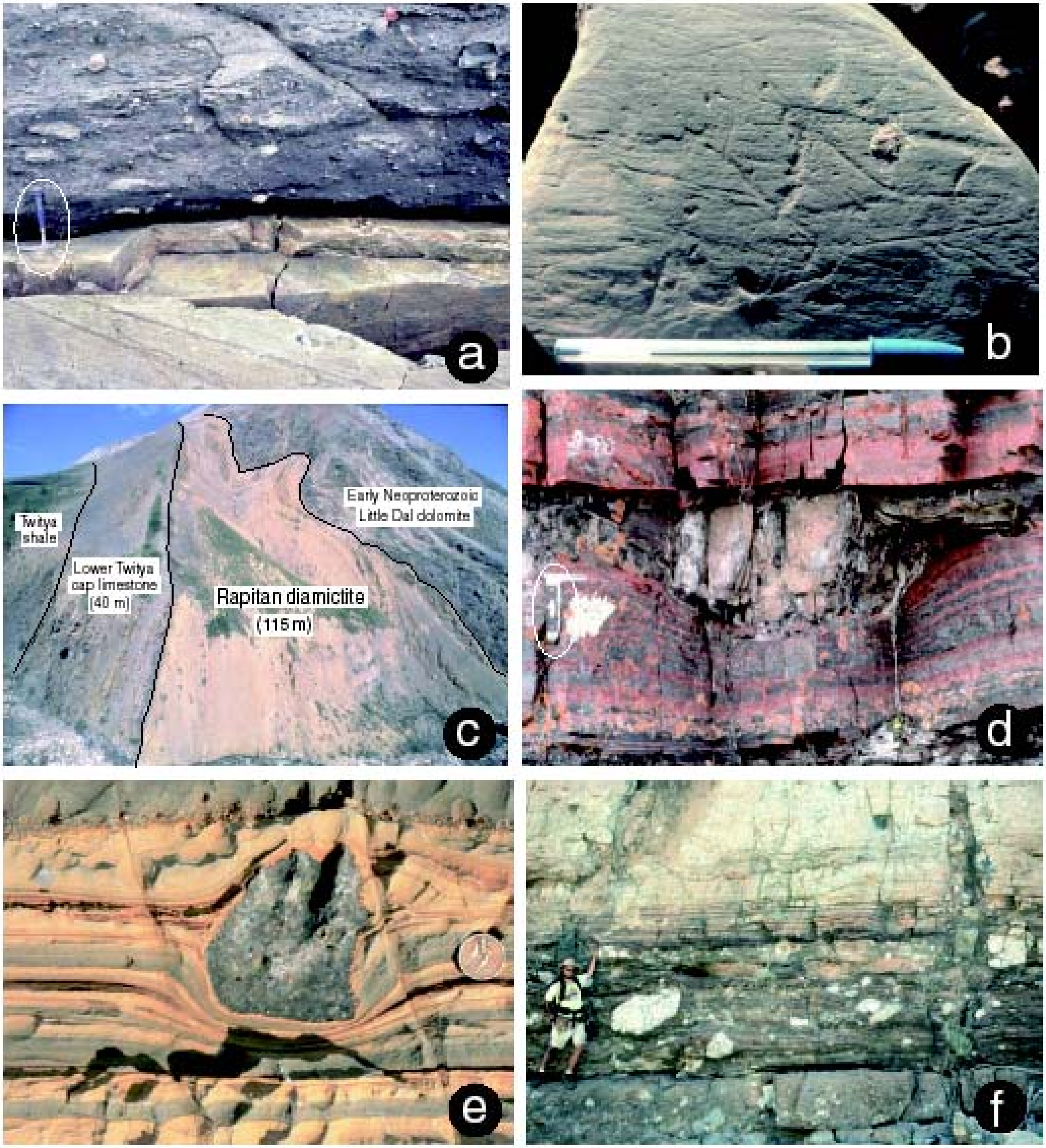


Dropstones

- *Tillites*: Packed pebbles, sand & clay. Remnants of moraines
- *Glacial Striations*: Scratches from rocks dragged by moving ice
- *Dropstones*: Rocks transported by icebergs and dropped into finely laminated sediment (IRD).

Kump et al. (1999)

Neoproterozoic Glacial Deposits



From Norway, Mauritania, NW Canada, Namibia.

- Glacial striations
- Dropstones

Hoffman & Schrag (2002)
Terra Nova, Vol.
14(3):129-155.

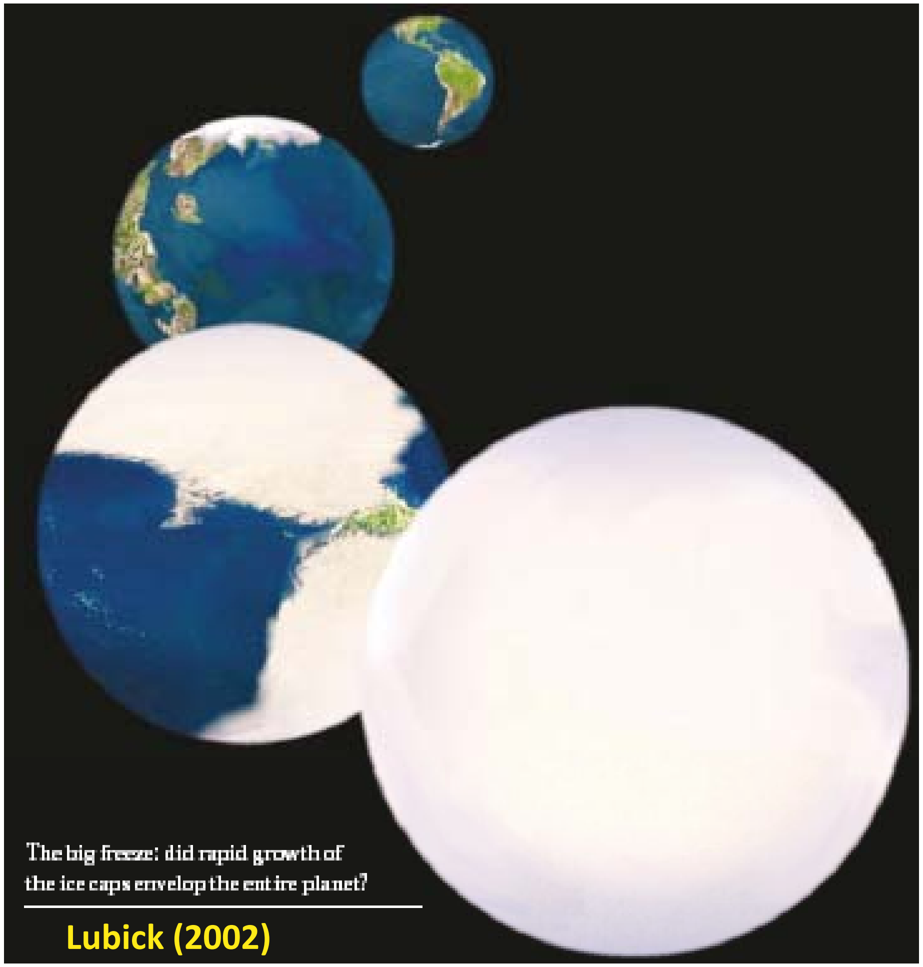
How to explain glaciers on all continents when those continents appear to have been close to the equator?

Snowball Earth Hypothesis

~4 global glaciations followed by extreme greenhouses 750-580 Ma

•Harland (1964); Kirschvink (1992)

•Hoffman et al. (1998) *Science*, v. 281: 1342-6; Hoffman & Schrag (2000) *Sci. Am.*, Jan: 68-75.



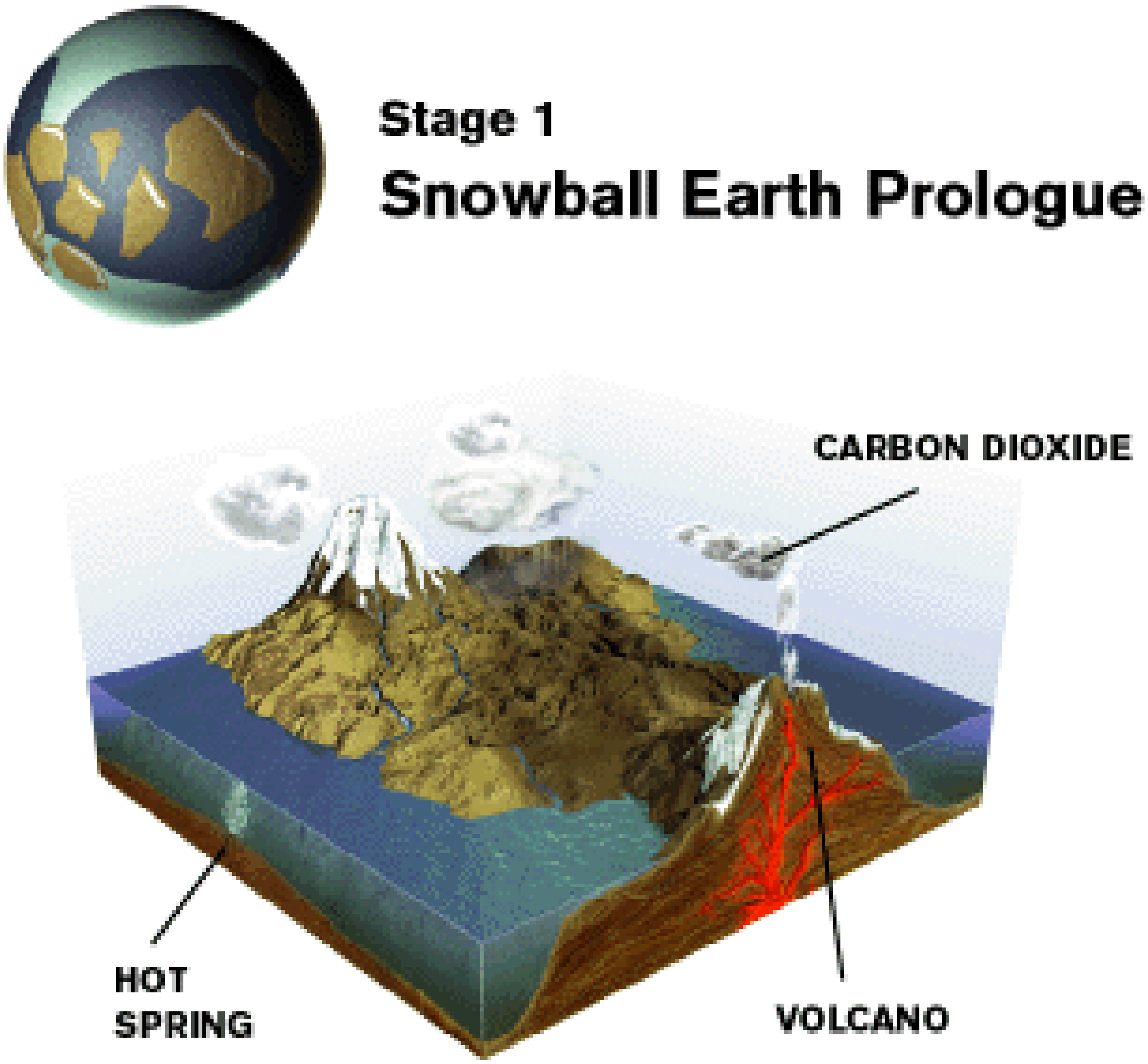
The big freeze: did rapid growth of the ice caps envelop the entire planet?

Lubick (2002)

Snowball Events:

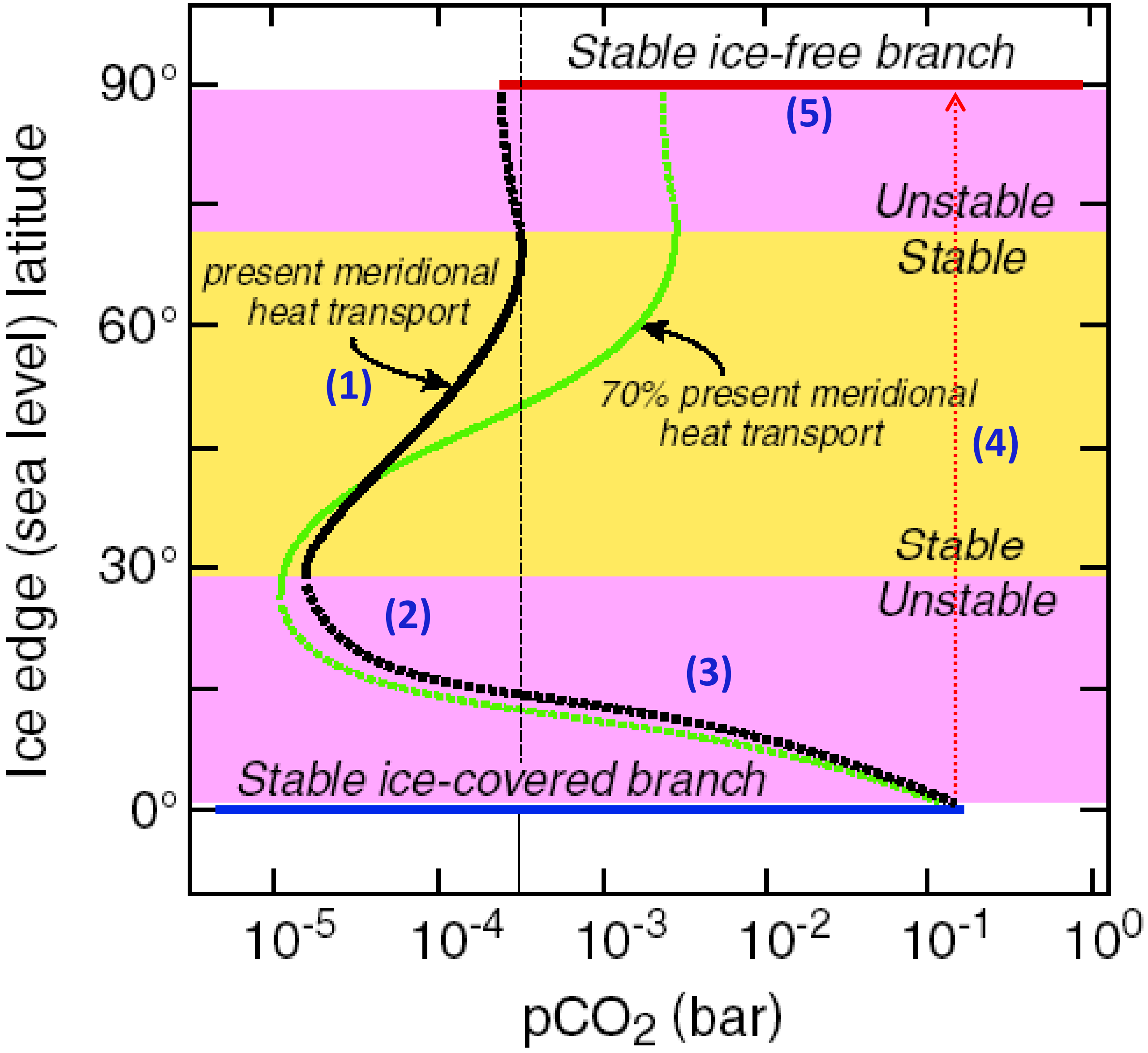
- Breakup of equatorial supercontinent 770 Ma
- Enhanced weathering from increased rainfall (more land close to sea)
- Drawdown atmospheric CO_2 → Global cooling
- Runaway albedo effect when sea ice < 30° latitude
- Global glaciation for ~10 Myr (avg T ~ -50°C)
- Sea ice ~1000 m thick, geothermal heat flux (0.07 W/m^2) keeps ocean liquid

Prologue to Snowball



- Breakup of equatorial supercontinent
- Enhanced weathering from increased rainfall (more land close to sea)
- Drawdown atmospheric CO_2 → Global cooling

Hoffman & Schrag (2000)



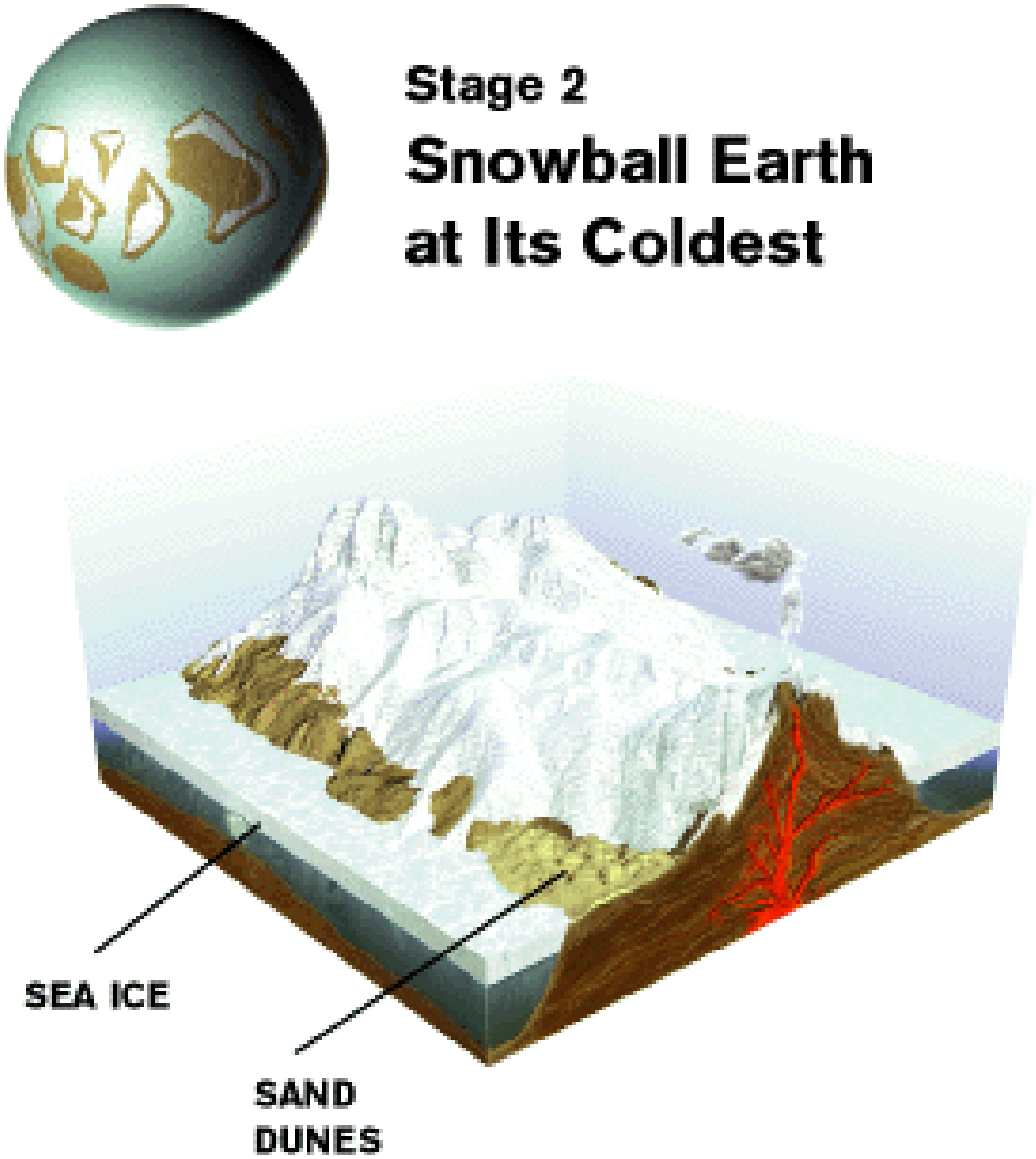
Steady-state ice lines as a function of atmospheric pCO_2, *see* Caldeira and Kasting (*Nature* **359**: 226, 1992), and Ikeda and Tajika (*Geophys. Res. Lett.* **26**: 349, 1999).

•Runaway Albedo Feedback

1. Eq. continents, incr. weathering, lowers CO_2, slow cooling, equatorward movement of ice.
2. Runaway albedo
3. Weathering shuts down
4. Slow buildup of CO_2 from volcanoes
5. Rapid decay of ice in 10^2 yr. High T_s from enhanced H_2O-T feedback.
6. Slow CO_2 drawdown from weathering

Image from P. Hoffman

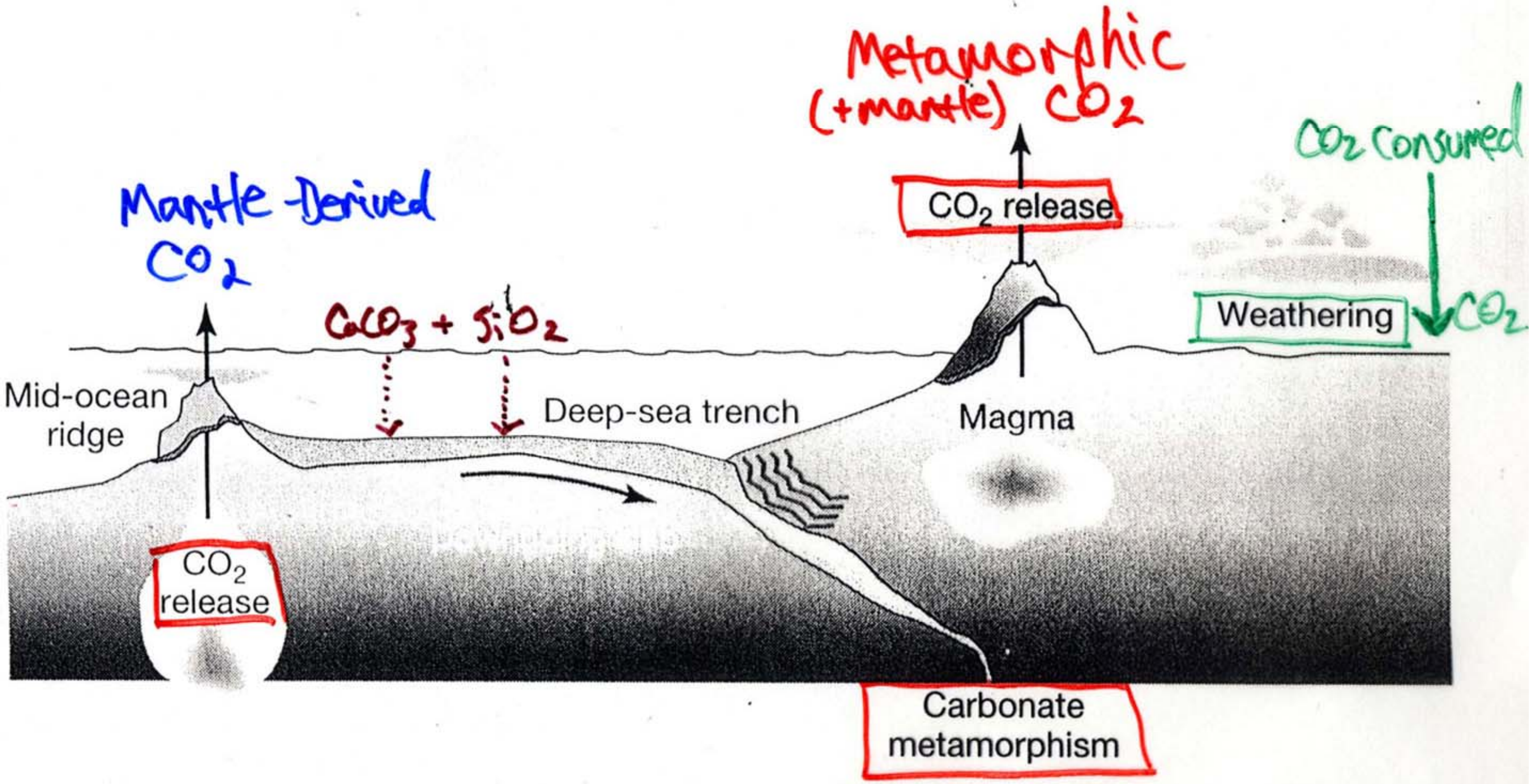
Deep Freeze



Hoffman & Schrag (2000)

- Global cooling causes sea ice margin to move equatorward
- Runaway albedo effect when sea ice <30° latitude
- Entire ocean possibly covered with ice

Carbonate - Silicate Geochemical Cycle



$$CaCO_3 + SiO_2 \rightleftarrows CaSiO_3 + CO_2$$

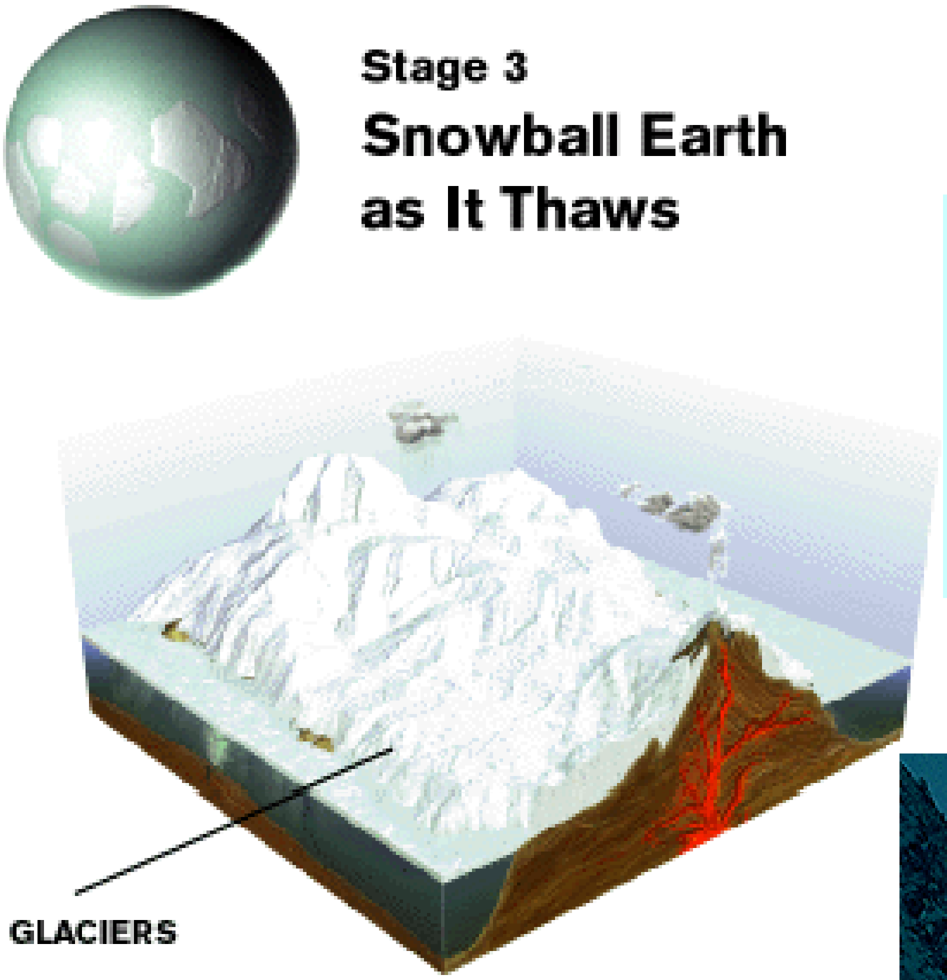
Weathering

Kump et al. (1999)

Snowball?

- Global glaciation for ~10 Myr (avg T ~ -50°C)

- Sea ice ~1000 m thick, geothermal heat flux (0.07 W/m^2) keeps ocean liquid



Hoffman & Schrag (2000)

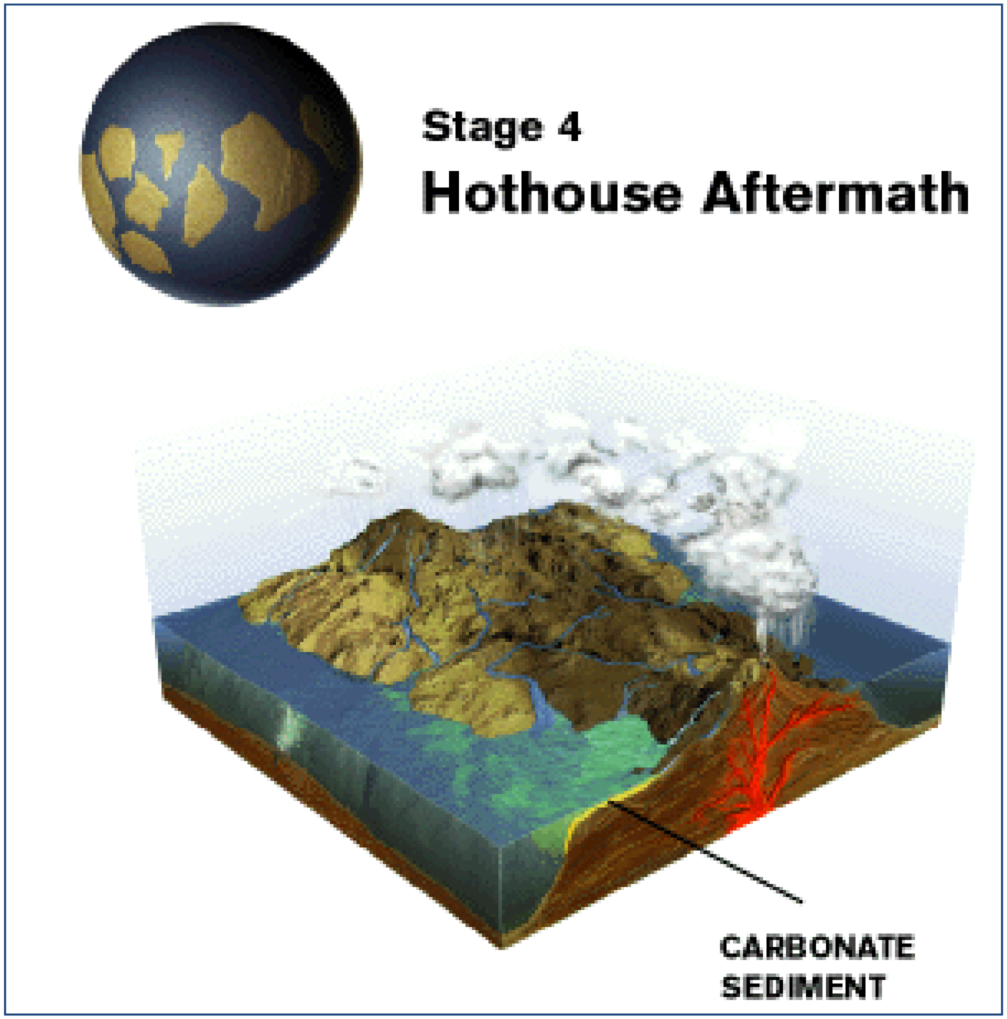
The Vallee Blanche, Mont Blanc, French Alps

Breaking out of the Snowball

- Volcanic outgassing of CO_2 over ~10^6 yr may have increased greenhouse effect sufficiently to melt back the ice

Lubick (2002) *Nature*, Vol. 417: 12-13.

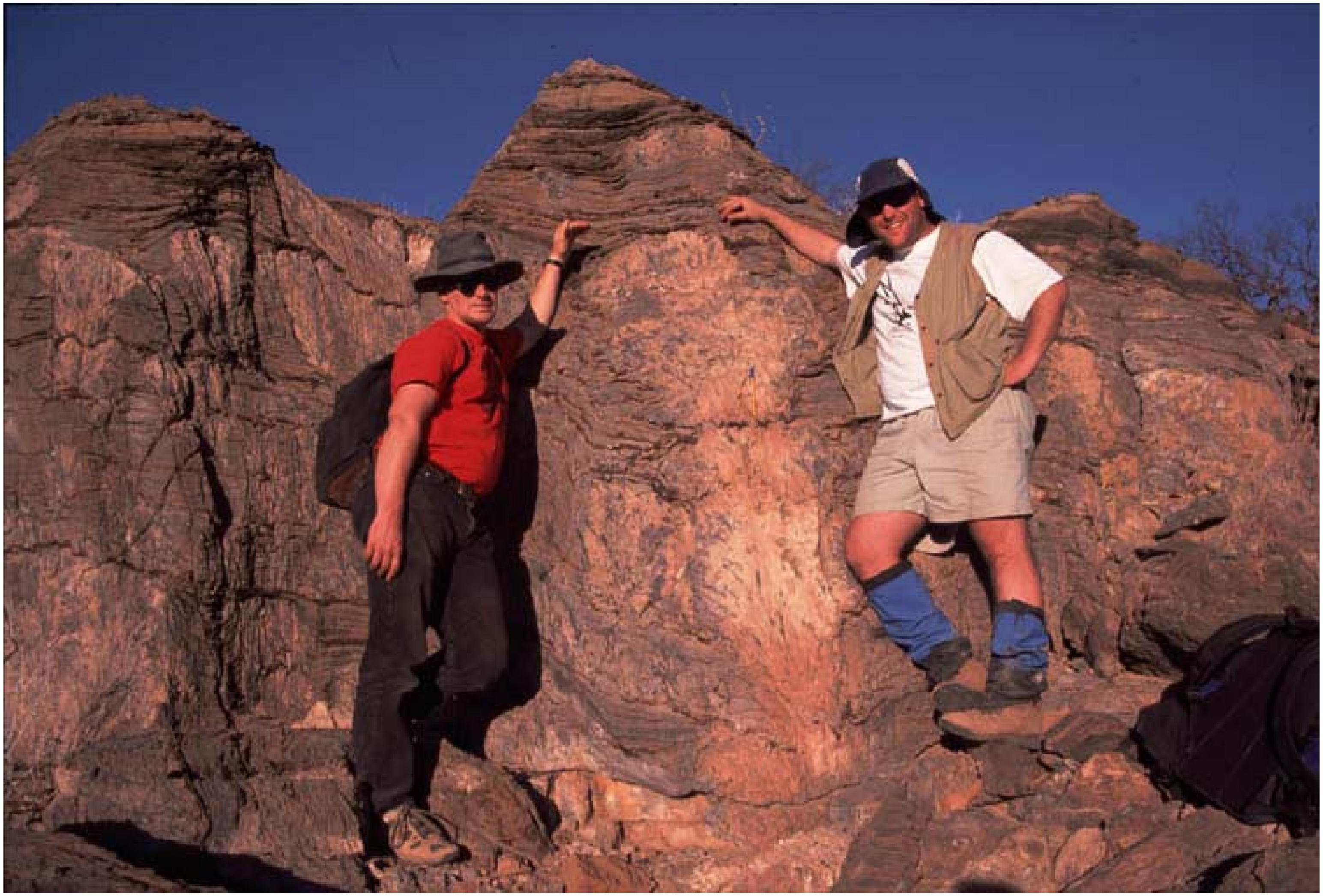
Bring on the Heat: Hothouse follows Snowball?



Hothouse Events

- Slow CO_2 buildup to ~350 PAL from volcanoes
- Tropical ice melts: albedo feedback decreases, water vapor feedback increases
- Global T reaches ~ +50°C in 10^2 yr
- High T & rainfall enhance weathering
- Weathering products + CO_2 = carbonate precipitation in warm water

Aragonite Fan in Namibia



- Carbonate fans form when $CaCO_3$ is rapidly precipitated from water.

Image from P. Hoffman

What kept this from happening after ~580 Ma?

- Higher solar luminosity (~5% increase)

- Less landmass near equator = lower weathering rates (?)

  → John Edmond: weathering rates limited by abundance of fresh rock, not temperature.

- Increased bioturbation (eukaryote diversity following re-oxygenation of ocean): Less C accumulation in sediments sequesters less atmospheric CO_2, offsetting lower weathering rates (from higher-latitude continents).

- lower iron and phosphorus concentrations in better-oxygenated Phanerozoic ocean [Fe(II) is soluble; Fe(III) is less so]: Decreased primary production = Decreased CO_2 drawdown.

→ What we would like to know:
CO_2 concentrations through snowball/hothouse cycle.

Potential Problems with the 'Snowball Earth hypothesis'

news feature

Snowball fights

Did the world freeze over some half a billion years ago? Two Harvard scientists think so, but convincing other climatologists is proving difficult. Naomi Lubick tracks the latest twists and turns in the snowball Earth debate.

The big freeze: did rapid growth of the ice caps envelop the entire planet?

P. E. SMITH/UNIV. TORONTO

Paul Hoffman and Daniel Schrag have had a busy few years. In 1998, the two Harvard University geologists rekindled a radical idea: that on at least one occasion between 580 million and 750 million years ago, the Earth lay entirely encrusted in ice for tens of millions of years. This 'snowball Earth' hypothesis seemed to explain some puzzling geological data. But it was controversial then, and the debate shows no sign of letting up.

Sceptics first asked how the Earth could freeze and thaw in such a short geological time. Climate modellers have since questioned whether ice sheets could have reached the Equator. And last year came an assault on Hoffman and Schrag's central line of geological evidence. The proponents of snowball Earth, it seems, are on the defensive once more.

The idea of a global glaciation was first proposed in the 1960s by Mikhail Budyko of the Main Geophysical Observatory in St Petersburg, Russia. Budyko looked at what would happen if the Earth's climate were to cool slightly, prompting an increase in the size of the polar ice-caps. Ice reflects heat from the Sun, so this growth would cause further cooling. Runaway growth of the ice-caps could result, Budyko argued, eventually leaving the Earth entirely sheathed in ice[1].

Budyko's ideas explained puzzling evidence, including signs of scouring of rocks by ice, that seemed to imply that glaciers reached the Equator on at least two occasions between 580 million and 750 million years ago, towards the end of the Neoproterozoic period. This was baffling, because ice sheets reached only as far as northern Europe during more recent ice ages. But Budyko's theory had some holes in it. What, for example, eventually caused the ice to thaw?

Iron out

In 1992, Joseph Kirschvink, a geologist at the California Institute of Technology in Pasadena, provided an explanation of how the ice could have receded[2]. Kirschvink, who coined the term 'snowball Earth', realized that normal cycles of rain and erosion, which play an important role in removing carbon dioxide from the atmosphere, would have shut down if ice had covered the oceans. Carbon dioxide released by volcanoes would then build up in the atmosphere, eventually creating enough greenhouse warming to melt the ice sheets.

Volcanic CO_2 may have caused a greenhouse effect that freed snowball Earth from its ice age.

MORGUNBLADET/AP

Kirschvink also pointed out that a snowball Earth could explain another strange geological deposit — iron-rich rocks that formed near the end of the Neoproterozoic. Iron is added to the ocean at geothermal vents in the sea floor and precipitates out of sea water when it comes into contact with oxygen. But if the oceans had been capped with ice, oxygen levels in water would have fallen and dissolved iron would have built up. Oxygen levels would have increased when the ice melted, causing large amounts of iron to precipitate out and fall to the sea floor.

Six years later, Hoffman and Schrag, together with colleagues at Harvard, published the paper that thrust the hypothesis back into the limelight[3]. They had studied ratios of carbon isotopes in rocks formed when carbon-containing compounds precipitated out of sea water. Photosynthetic marine microorganisms take up carbon, preferring the lighter carbon-12 isotope to the heavier carbon-13 — so photosynthesis causes carbon-12 levels in water to fall, leaving less of that isotope to precipitate out.

But when Hoffman and Schrag looked at 'cap carbonates' — sediments that were deposited towards the end of the Neoproterozoic glaciations — they found surprisingly high levels of carbon-12. In fact, the ratio of carbon isotopes suggested that almost no photosynthesis had occurred in the waters from which the rocks precipitated. This, they reasoned, was exactly what would occur if ice had covered the ocean and starved it of light.

Journals' correspondence columns were

- Ocean/atmosphere climate models cannot seem to keep entire ocean covered with ice.
- No evidence for lower sea level.
- Weathering reactions are slow….. Maybe too slow to be the source of cap carbonates.

Lubick (2002) *Nature*, Vol. 417: 12-13.