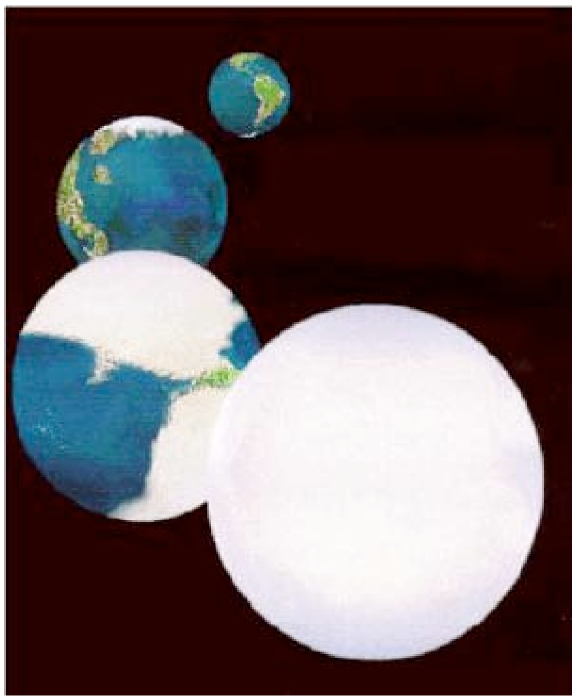
Lecture 23

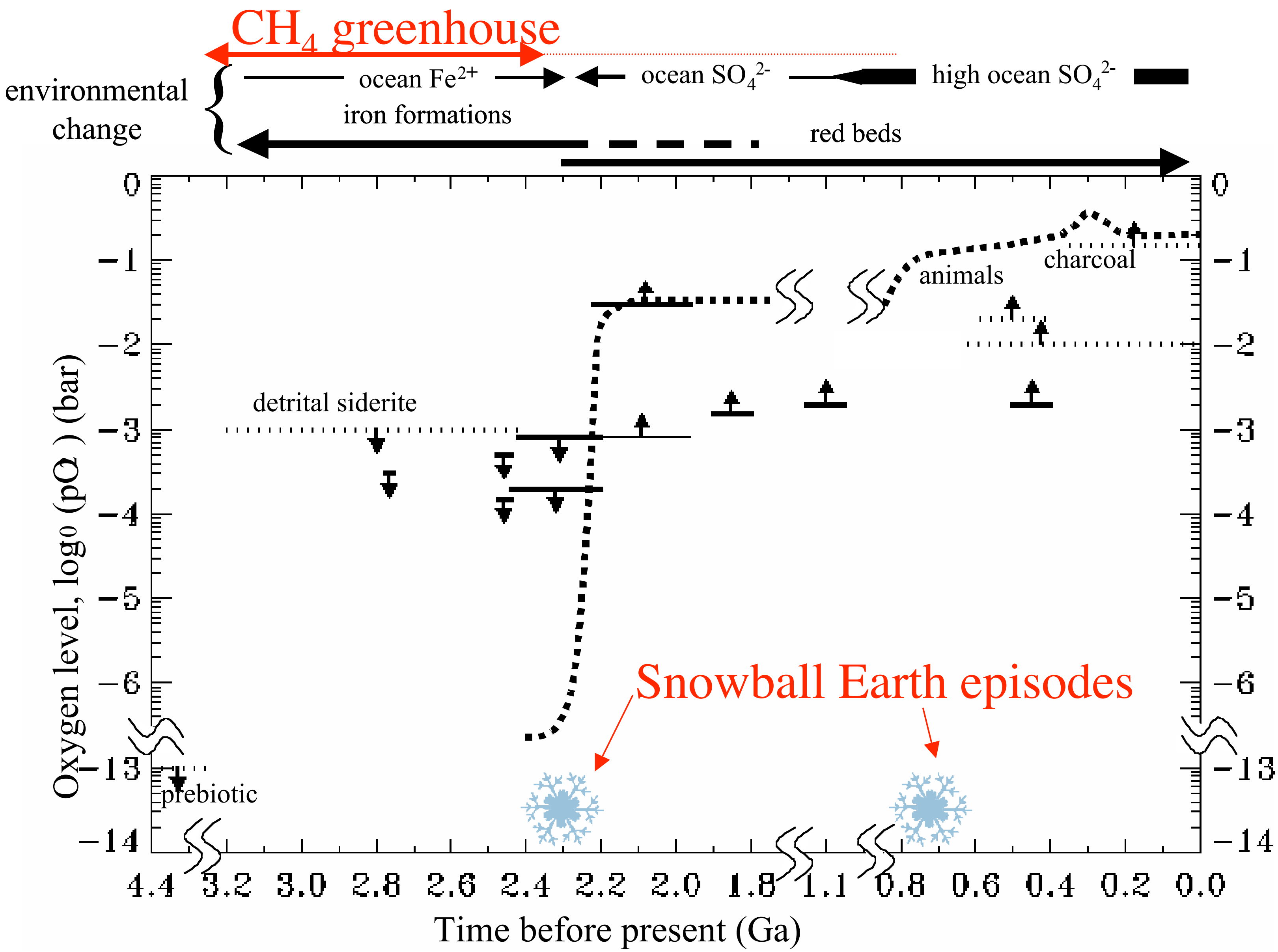
Recap on oxygen history of Earth's atmosphere



Snowball Earth

(p. 237-240, textbook &
Scientific American article by
Paul Hoffman & Dan Schrag
about the Neoproterozoic "Snowball Earth")

History of Earth's O_2

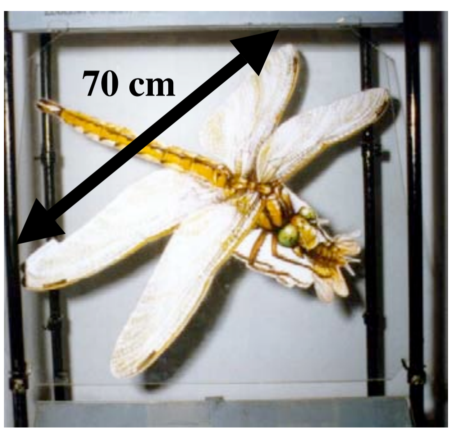


(Downward arrows indicate upper limits on O2; upward arrows, lower limits on O2, from geochemicals)

Later O_2 history

A SECOND RISE OF O_2 ~800-600 Ma also appears to have occurred, marked by increased sulfate (SO_4^{2-}) in the oceans. Sulfate derives from O_2 reacting with sulfur minerals on land; dissolved sulfate is transported by rivers to the ocean.

The earliest animal fossils (575-555 Ma) appear after the 2nd rise of O_2. Such fossils were first identified in the **Ediacaran** hills, southern Australia."**Ediacaran**" fossils appear on 6 continents.



In the Carboniferous (~300 Ma), O_2 may have been a higher concentration than today. Insects rely on diffusion of O_2 for respiration. O_2 was high enough then to support giant (70 cm wingspan) dragonflies that would be unable to function today.

Snowball Earth

Low-latitude glaciations occur in Earth history during two times:
2.4-2.2 Ga: there are 3 tropical glaciations during this time (part of the Paleoproterozoic era (2.5-1.6 Ga))
0.8-0.6 Ga: there are 2 to 4 tropical glaciations during this time (part of the Neoproterozoic era (0.9-0.544 Ga))

Theory: Once ice extends to within 30° of the equator, there is runaway ice-albedo feedback. (Colder => higher albedo => colder) Some argue for a totally ice-covered Earth on this basis. Other scientists disagree and argue for a "Slushball" Earth with areas of open water near the equator.

Evidence for glaciation:

1) tillites
2) glacial striations
3) dropstones

Glacial geology is one of many indicators of **paleoclimate**, i.e., past climate

1) Tillites

Mixtures of pebbles, sand and mud packed together to form rock. Formed from debris when glaciers grind up rocks. The debris is dragged along and deposited as rubble, or *moraines* along the flanks of the ice sheet

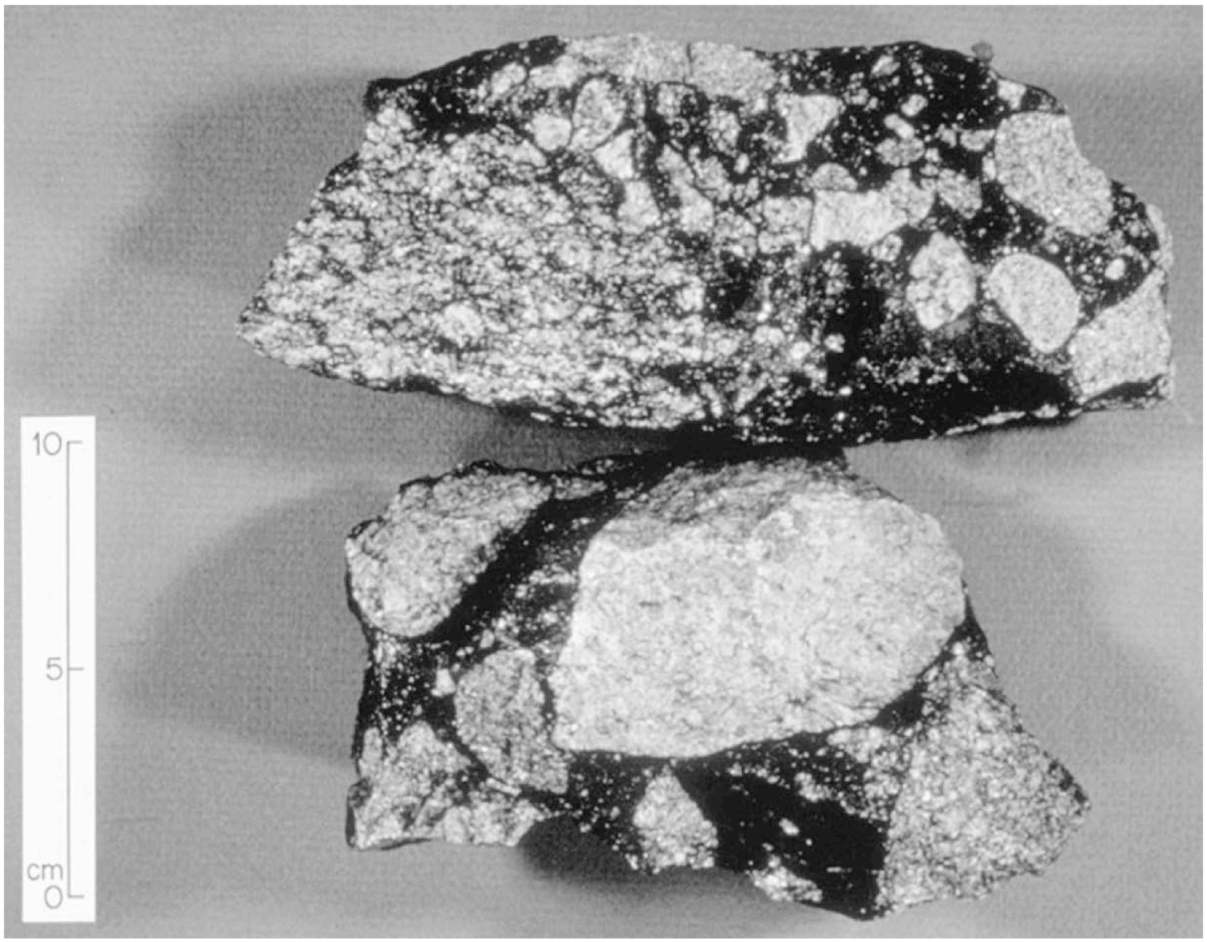


Fig.12-7

2) Glacial striations

Parallel scratches where the glacier has dragged rocks

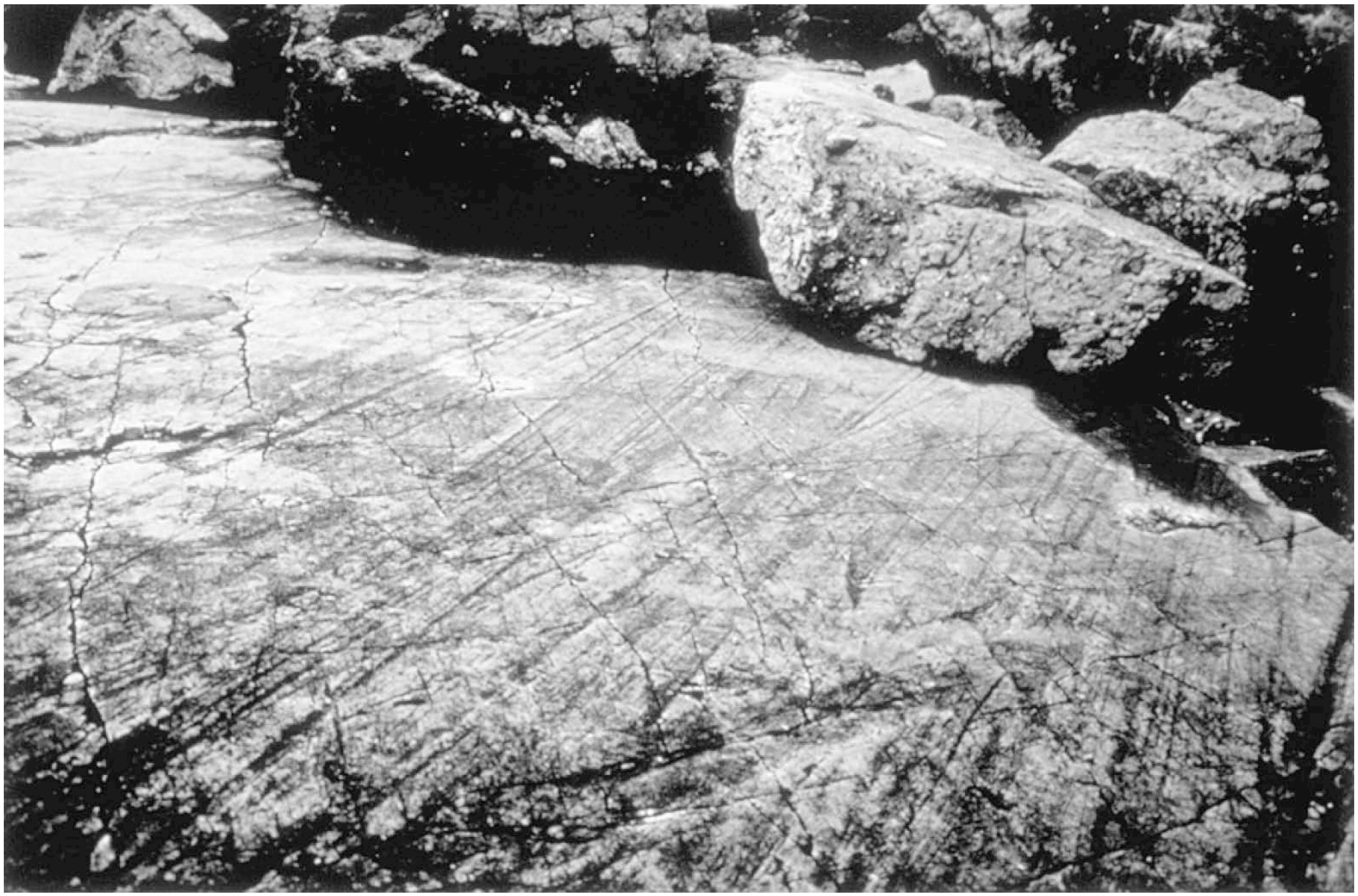
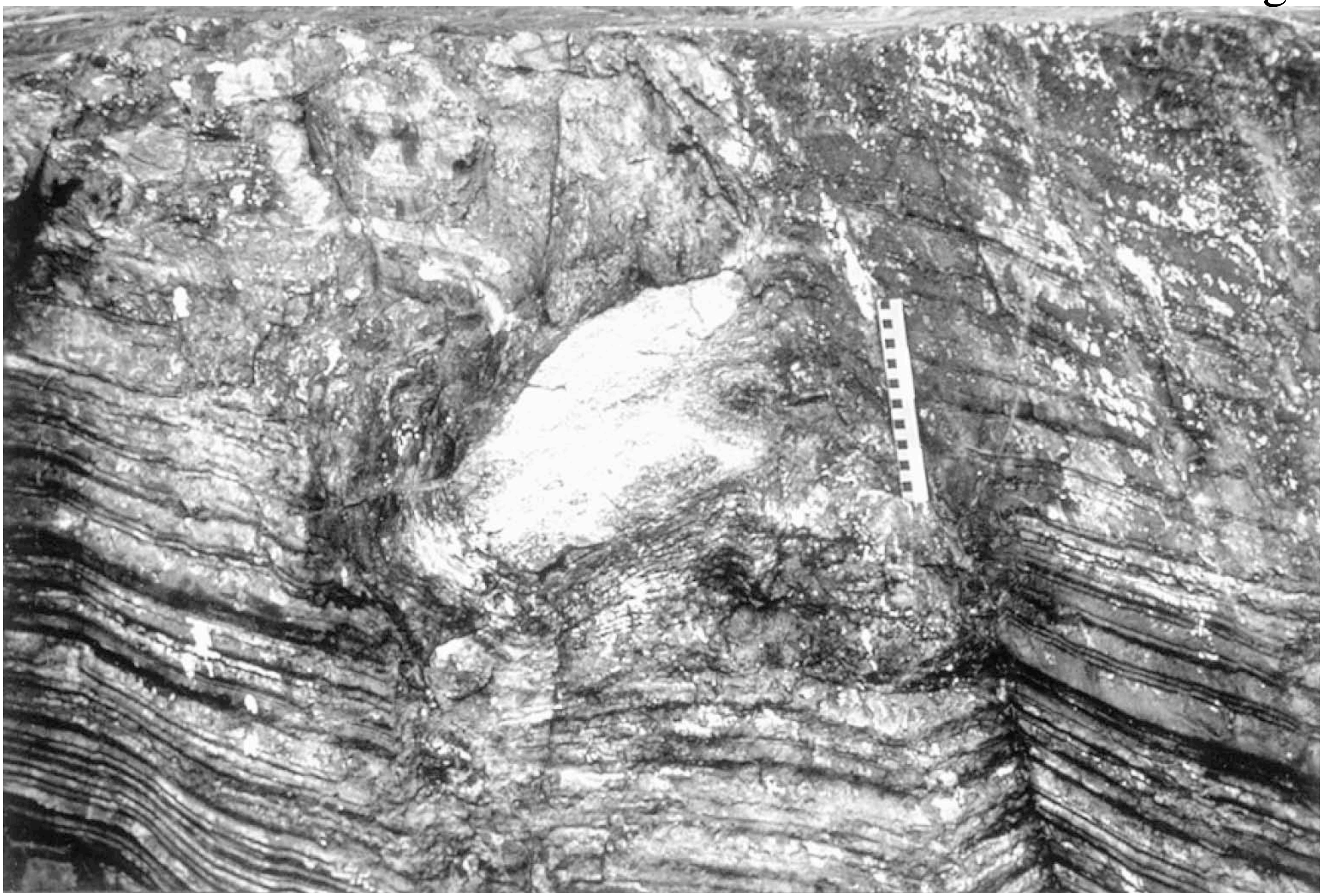


Fig.12-7

3) Dropstones

Chunks of rock dropped from melting icebergs that end up in otherwise finely laminated marine sediments

Fig.12-7



History of the Snowball idea…

(here and henceforth, we deal with the Neoproterozoic episodes)

1) **Geology**.

Sir Douglas Mawson (U. of Adelaide) in the 1940s noted low latitude glaciation in Neoproterozoic rocks.
Found dropstones of limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$), that form primarily in tropical waters. Suggested glaciers had advanced over tropical carbonate platforms like today's Bahamas.

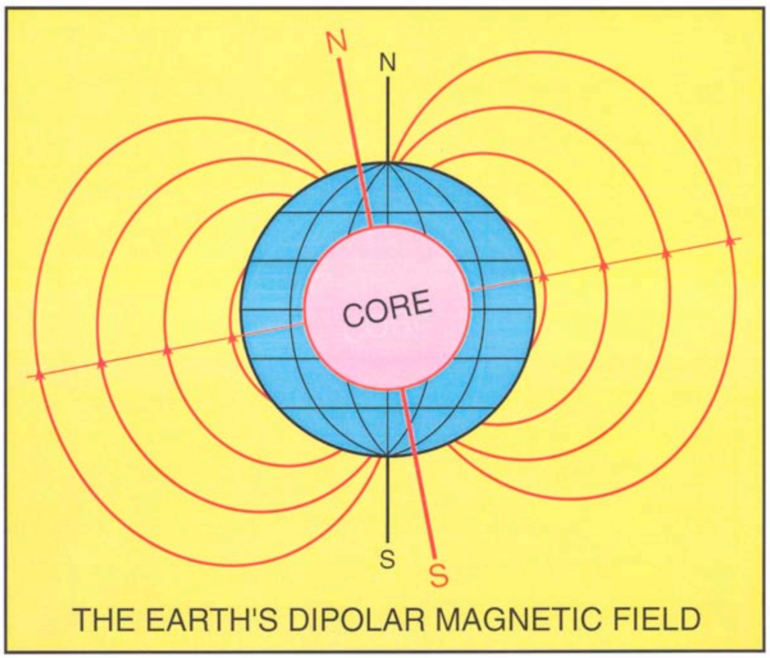
Brian Harland (U. of Cambridge) used paleomagnetism to infer a low latitude location. However, at the time (1960s), most considered his paleomagnetic measurements suspect since the technique was new.

2) **Climate science. Michail Budyko** (1969) showed that the Earth freezes over if edges of the polar ice caps wander equatorward farther than 30º latitude. Mean global temperatures of –35 to -50ºC were predicted with an equatorial ice thickness of 1.5 km, up to 3 km at the poles. There was no conceivable escape. Thus, it could not have ever happened. Right?

The Snowball idea largely melted away. Then…

Evidence for low-latitude glaciation becomes unequivocal

1987 – **Joe Kirschvink** (Caltech) shows S. Australia magnetization in glacial deposits indicate the deposits formed within a few degrees of the equator.



Field lines of Earth's magnetic field are perpendicular to the surface at the poles and parallel to the surface near the equator. Volcanic rocks containing iron minerals, such as **magnetite** (Fe_3O_4), become magnetized in the direction of the magnetic field before they harden into rock.

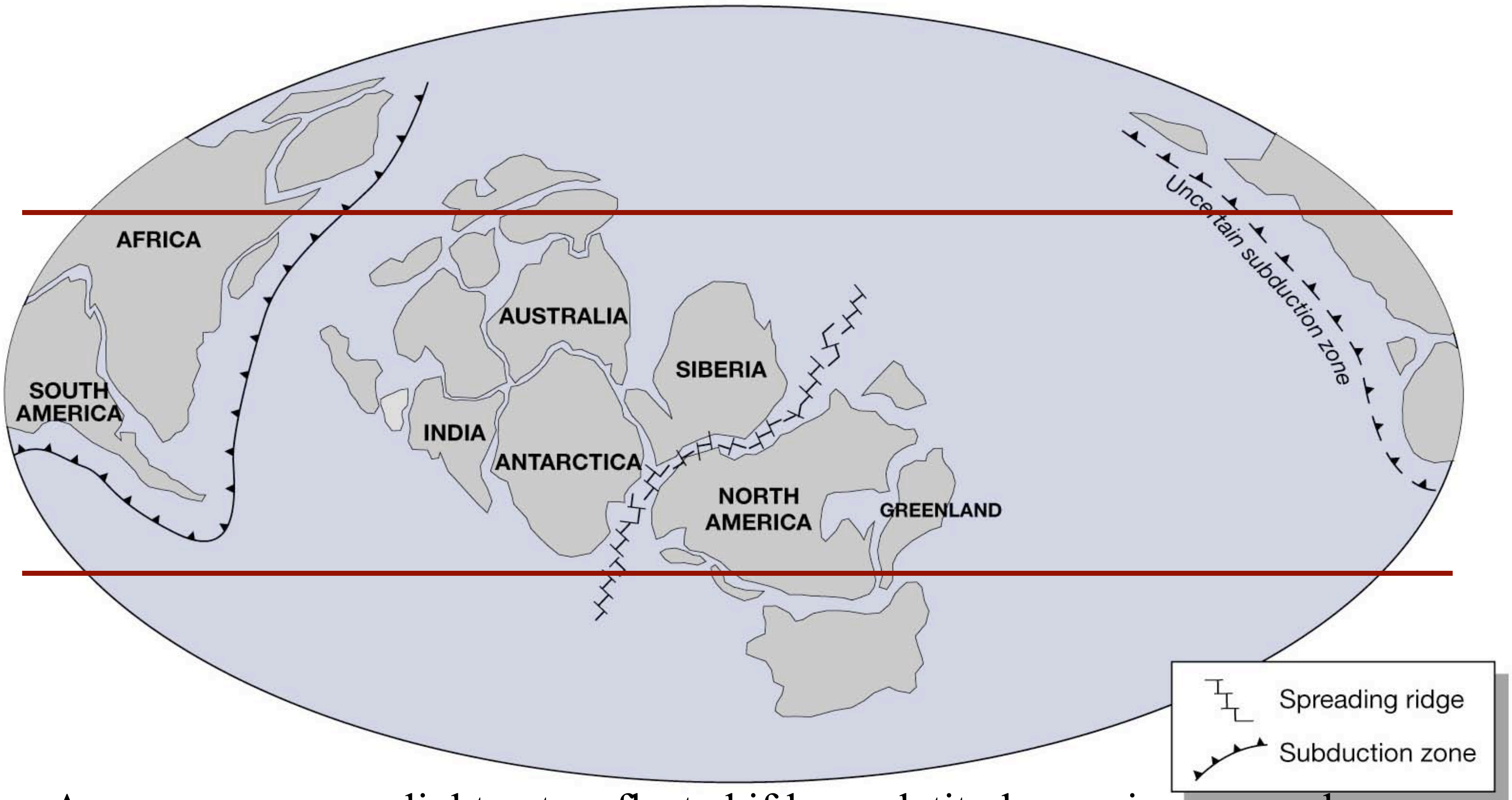
Thus, rocks in which the remnant magnetic field is parallel to the sediment beds would have formed in the tropics.

1992 – Kirschvink postulates that the Earth had frozen over and escaped through build-up of volcanic CO_2. He calls the concept "**Snowball Earth**".

Possible continental positions during Late Proterozoic Glaciations: Fig 12-10

Critical latitude for "runaway" ice-albedo (~30 degrees):

Why would ice-albedo feedback get stronger as the ice-line got to lower and lower latitudes???



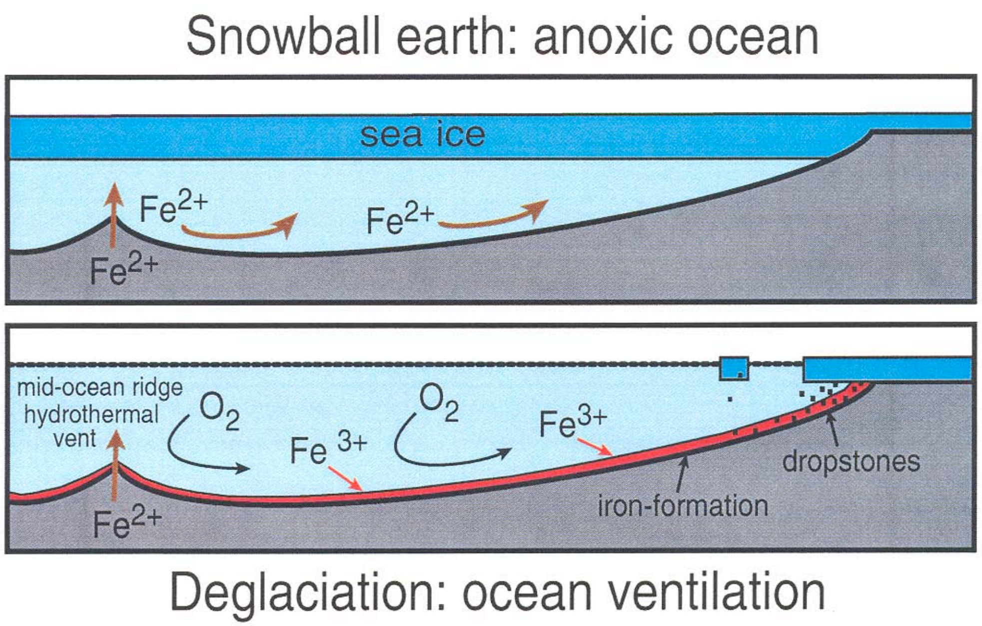
Answer: - more sunlight gets reflected if lower latitudes are ice-covered

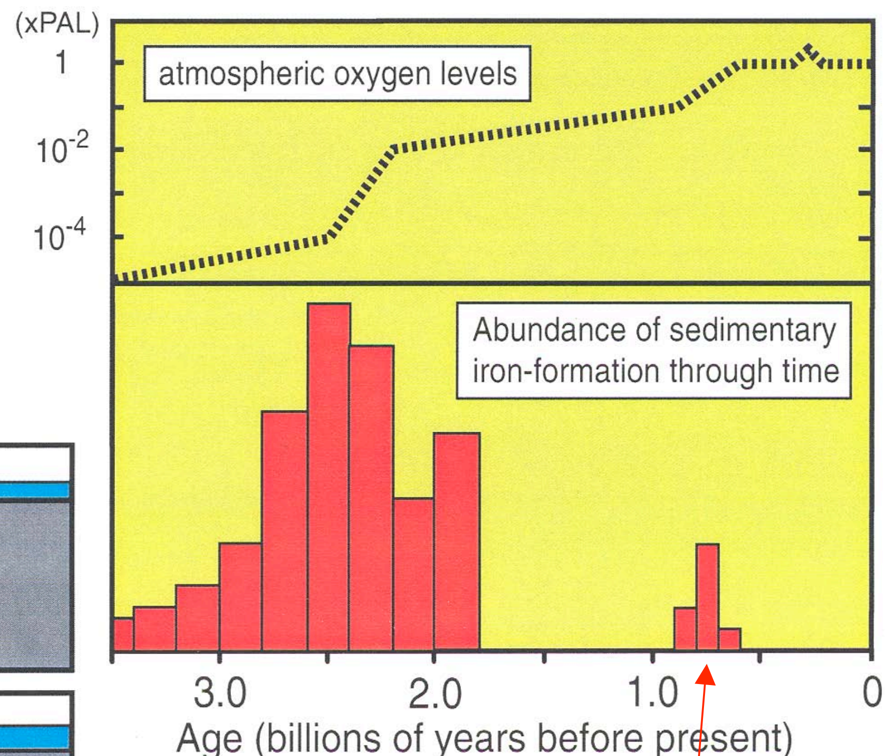
- the amount of area per degree latitude gets much larger (major factor)

Iron Solubility and Deposition in Relation to a Snowball Event

If O_2 is absent, iron is soluble as ferrous (Fe^{2+}) ion.

If O_2 is present, iron is insoluble as ferric (Fe^{3+}) ion.

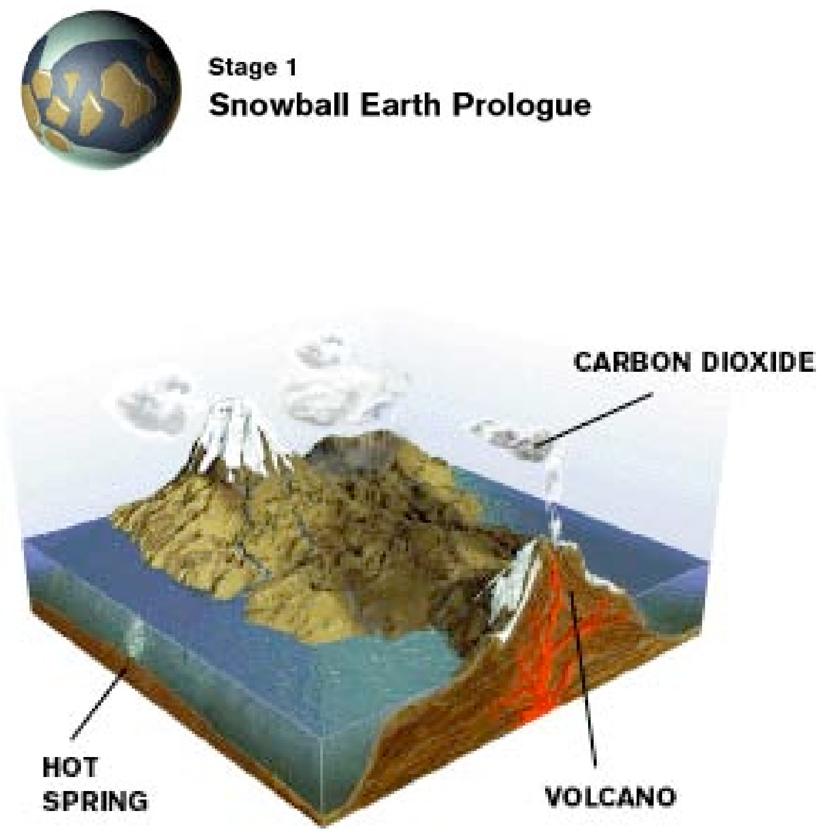


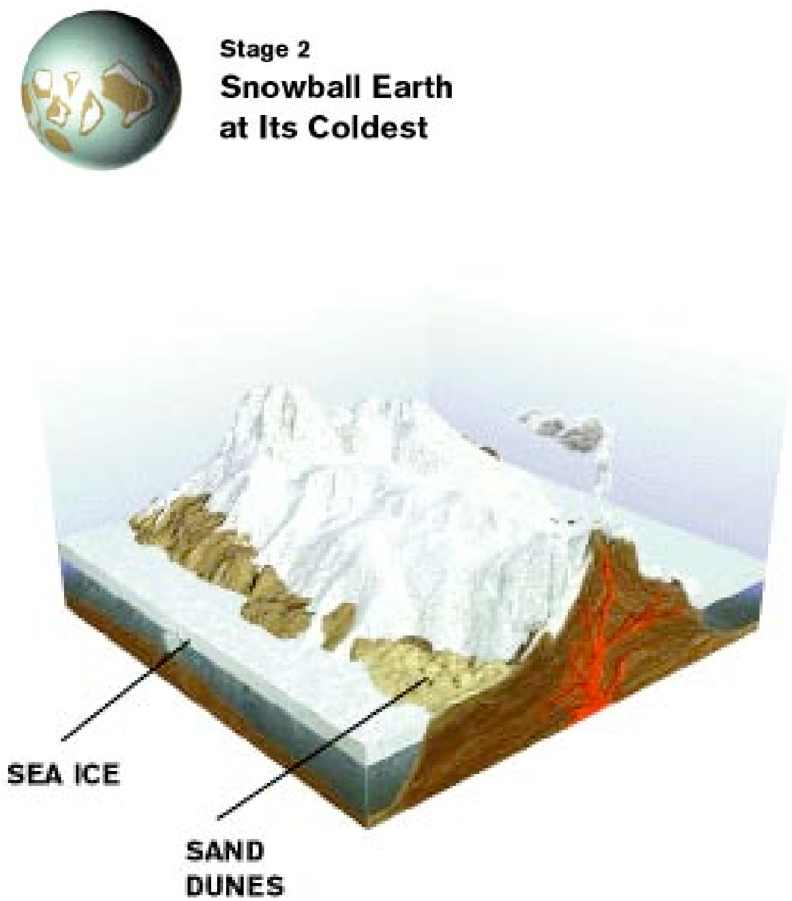


Banded Iron Formations (BIFs) re-occur during Snowball

http://www-eps.harvard.edu/people/faculty/hoffman/snowball_paper.html

Snowball initiation



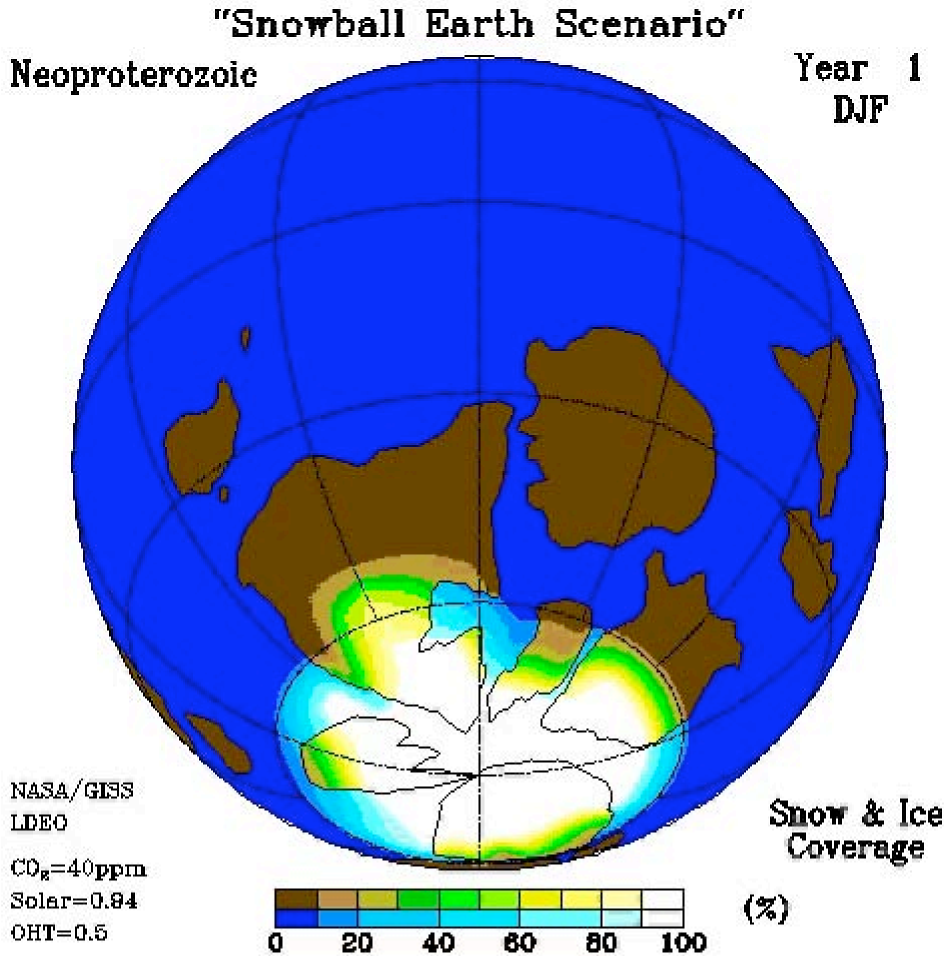


Loss of CO_2 with continental weathering? Or loss of CH_4 with a rise of O_2?

Runaway ice-albedo

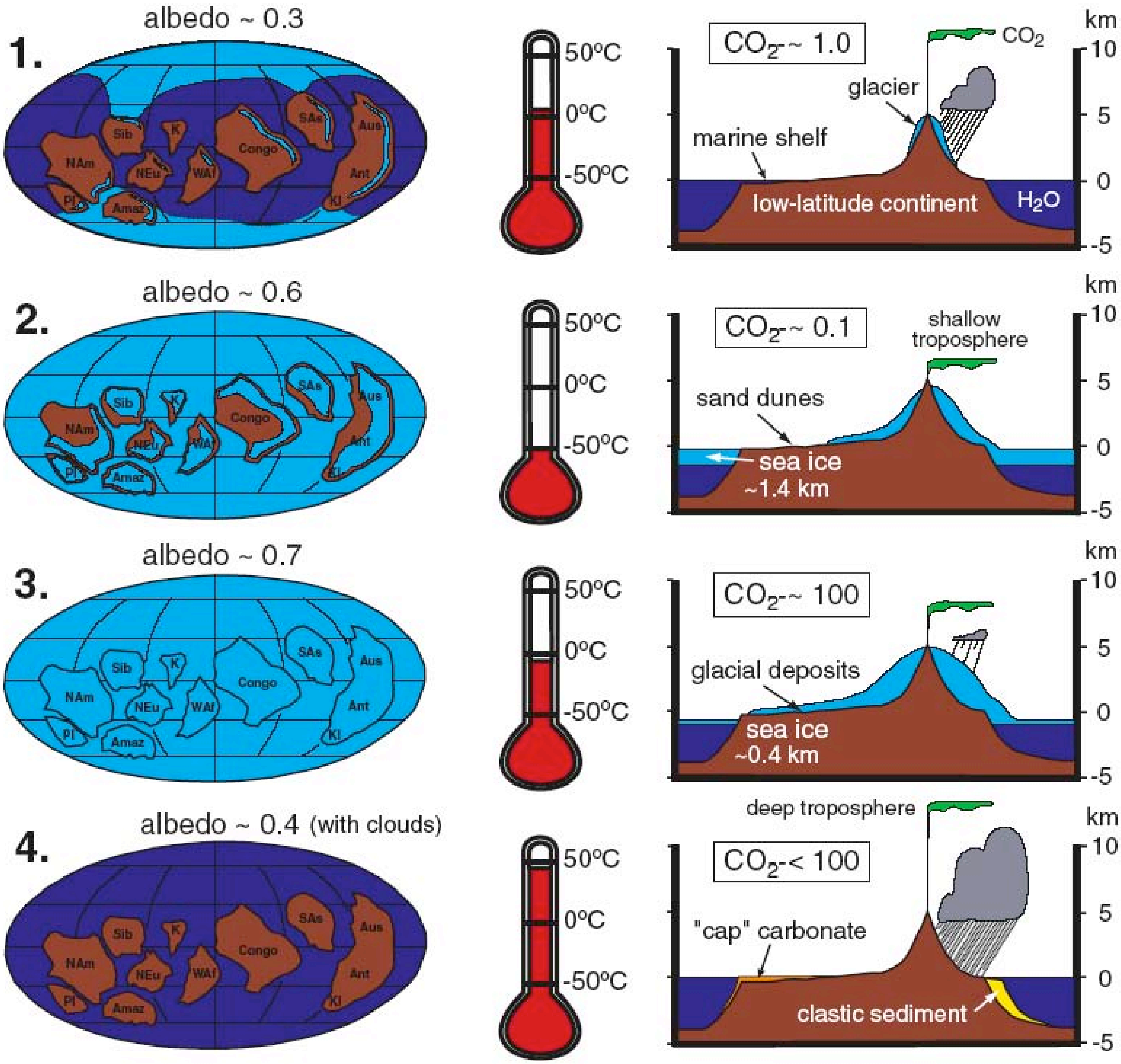
General Circulation Model (GCM) simulation

Chandler, M.A., and L.E. Sohl 2000. Climate forcings and the initiation of low-latitude ice sheets during the Neoproterozoic Varanger glacial interval.
J. Geophysical Research **105**, 20737-20756.



One problem: the authors of this study used a value for albedo which at its highest was only 0.44! Yet snow and ice is much higher: 0.6-0.9; sea-ice=0.62

Hoffman and Schrag model



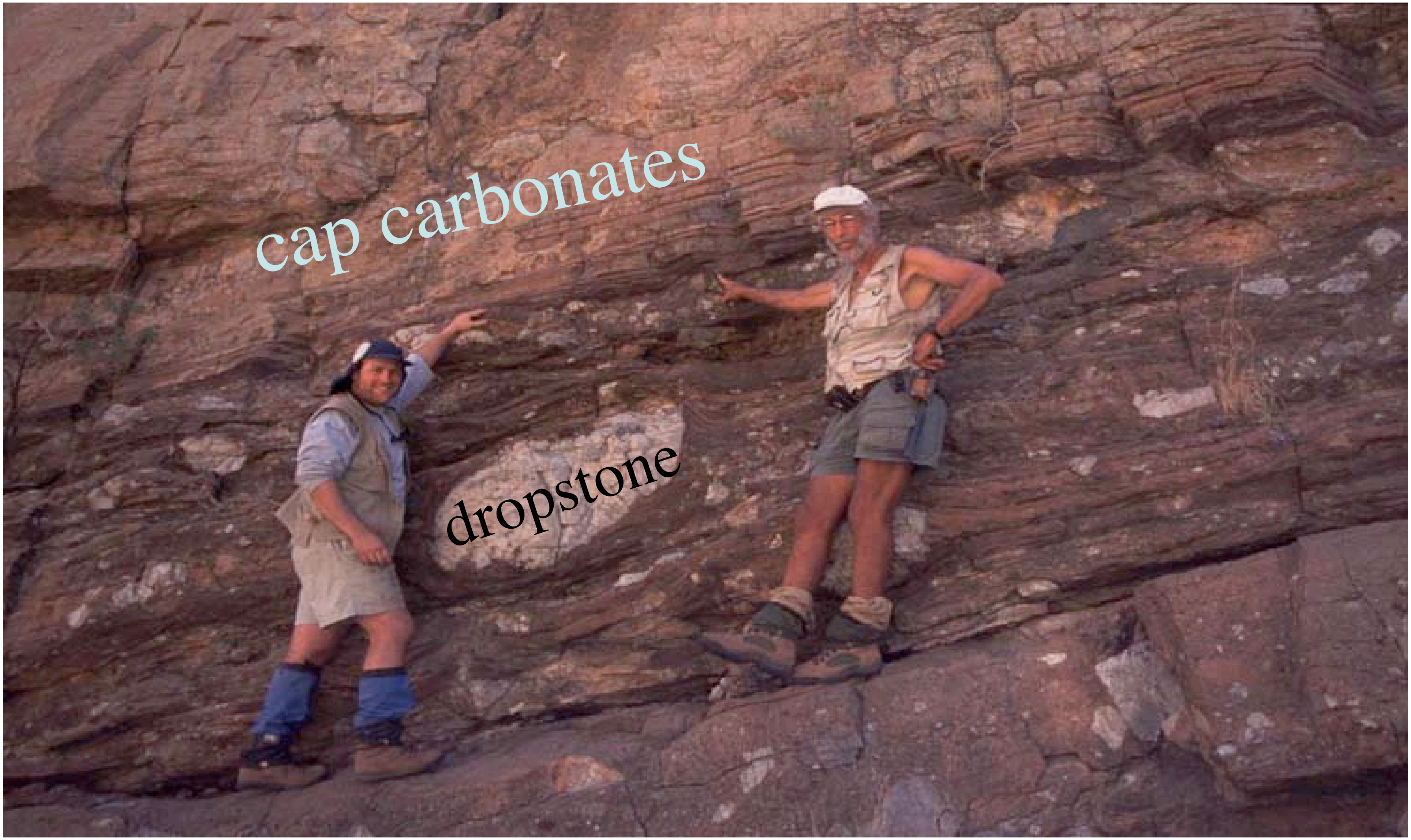
initiation

deep freeze

warm-up

fry up

Cap carbonates above dropstones



Carbon isotopes

See p.222, Kump. The delta notation is defined as:

$$\delta^{13}C = \frac{(^{13}C/^{12}C_{sample}) - (^{13}C/^{12}C_{standard})}{^{13}C/^{12}C_{standard}} \times 1000 \ (‰)$$

Value of volcanic gas $\delta^{13}C = -6‰$

Typical value of ancient marine carbonate $\delta^{13}C = 0‰$

Value of carbonate $\delta^{13}C$ just before Snowball glaciation -6‰
- attributed to loss of organic productivity by Hoffman and Schrag

Approximately, the same $\delta^{13}C$ value is seen in the cap carbonates

Cap carbonates

Variable thickness of carbonate, (limestone ($CaCO_3$) or dolomite ($MgCa(CO_3)_2$)), that sit on top of glacial dropstone and tillite deposits.

Cap carbonate formation is attributed to the loss of CO_2 buil up in the atmosphere during the glaciation, through weathering and deposition.

Eventually, biology recovers and values of $\delta^{13}C$ go back to normal.

Biology and the Snowball

Hoffman & Schrag speculate that refuges in a “Snowball Earth” led to speciation of eukaryotes, given that speciation is associated with geographical isolation.

Ediacaran fossils occur just after the last glaciation.
(these are the most primitive metazoans without shells/skeletons
- impressions of soft-bodied things like jellyfish, sponges, worms)

Later, the “**Cambrian explosion**” produced organisms with shells/skeletons

Others have suggested that a higher level of atmospheric O_2 was the key to the rise of animals. (This seems more likely to me; a “lack of Earth freezing over” as something that prevented multicellular life seems unlikely).