The Snowball Earth Hypothesis: Where It Came From, Where It's Going

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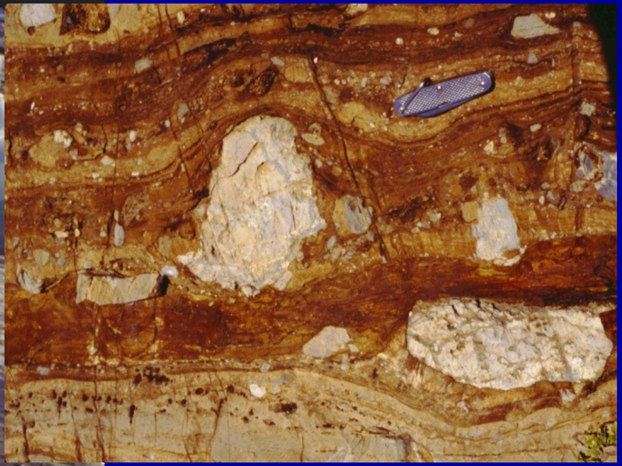
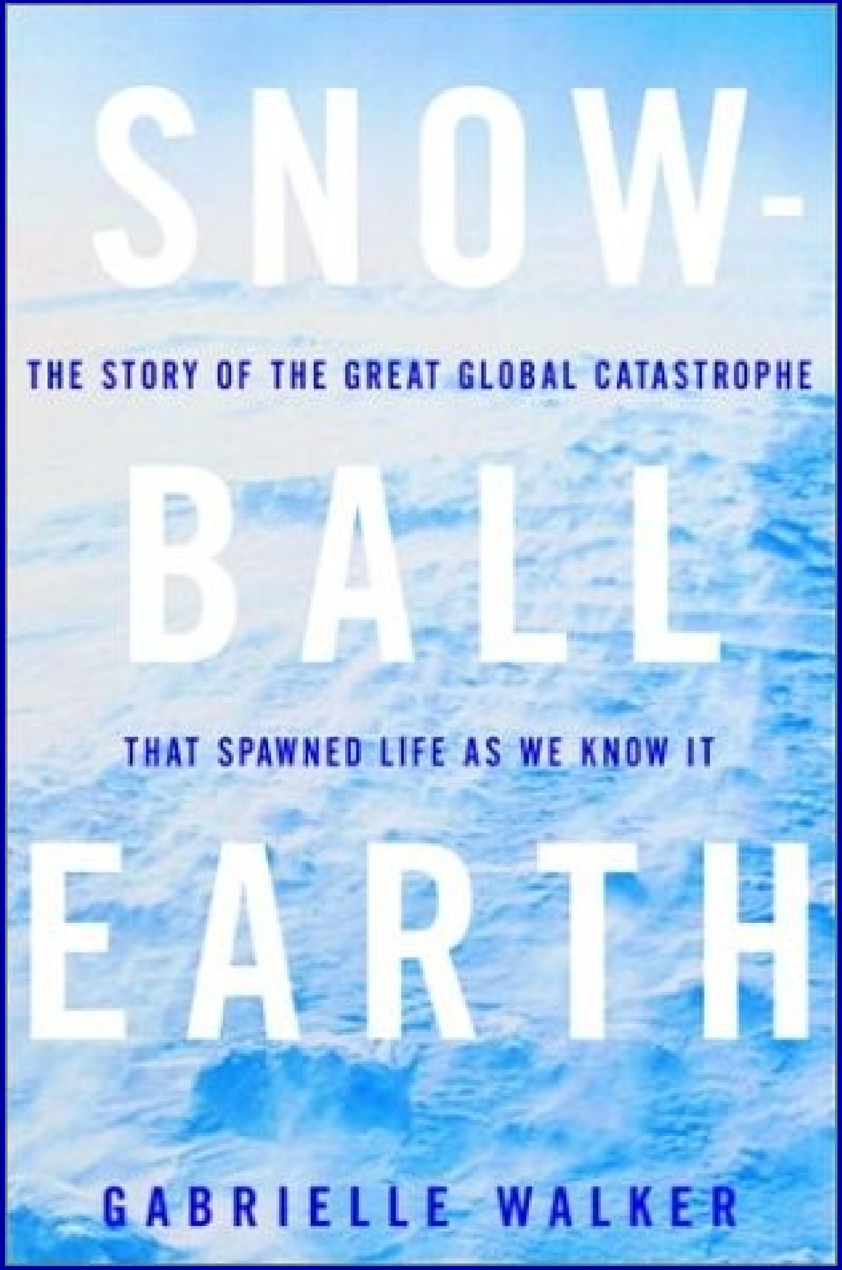
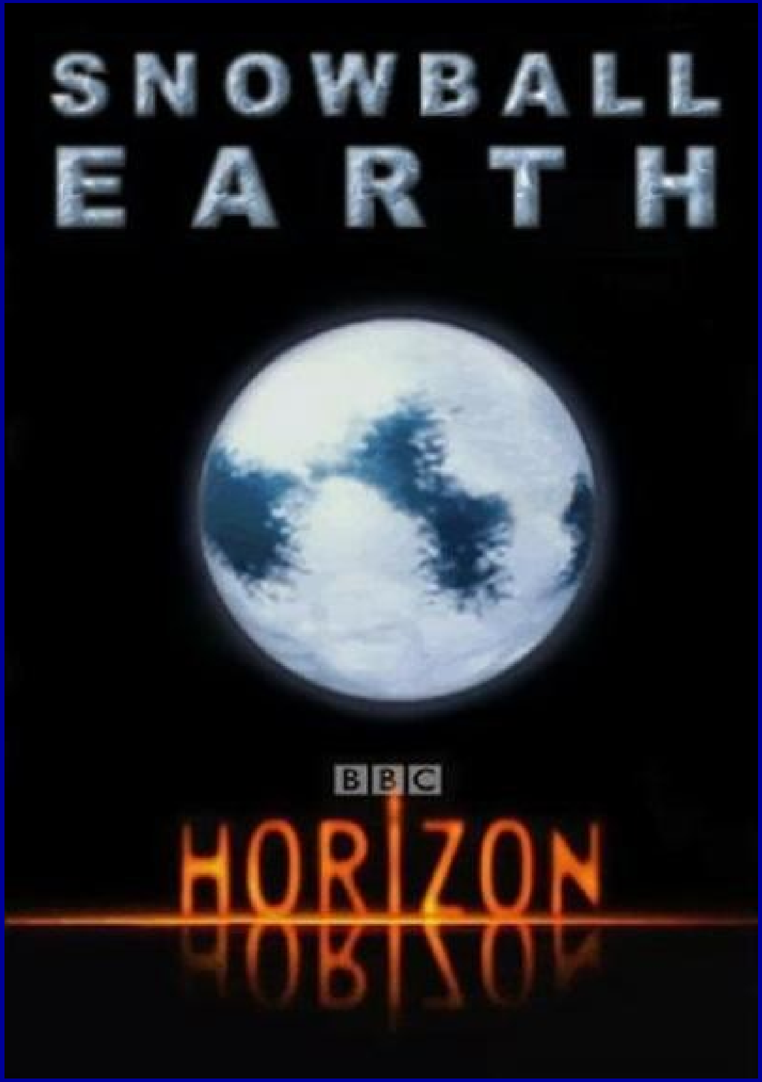
Low-Latitude Glaciation in the Neoproterozoic:
The World's Most Severe Ice Age?

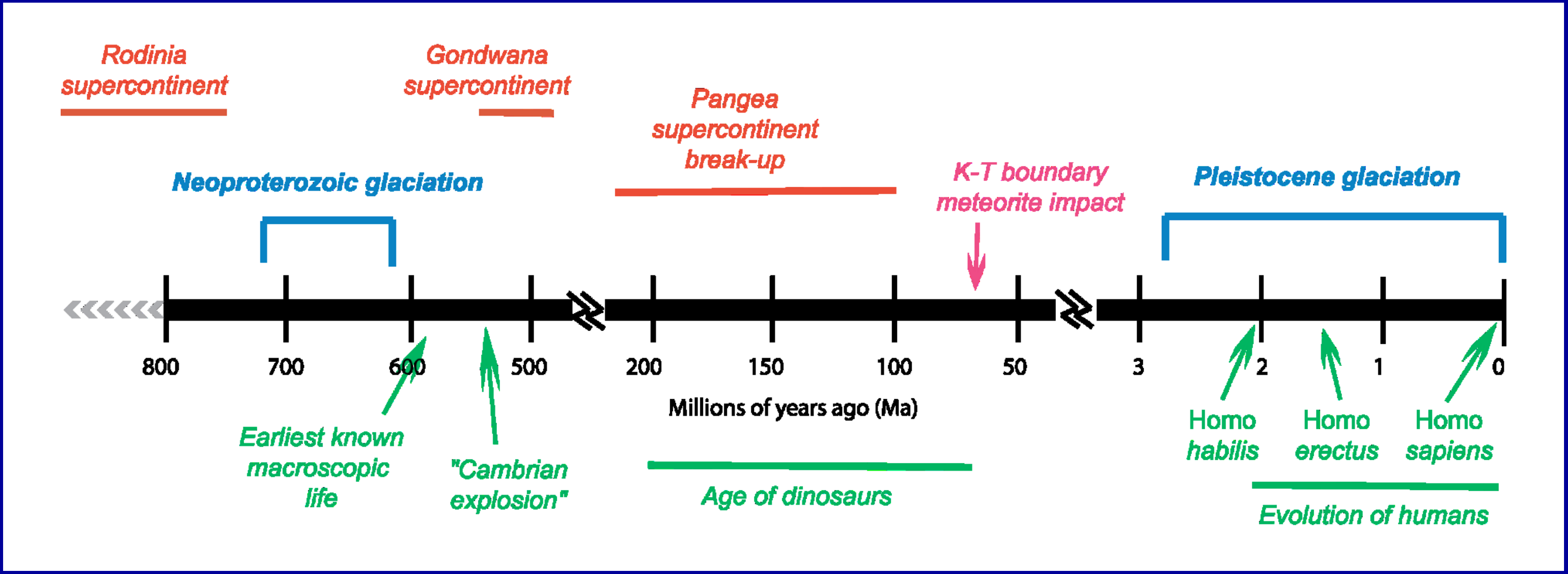



SNOW-
THE STORY OF THE GREAT GLOBAL CATASTROPHE
BALL
THAT SPAWNED LIFE AS WE KNOW IT
EARTH
GABRIELLE WALKER

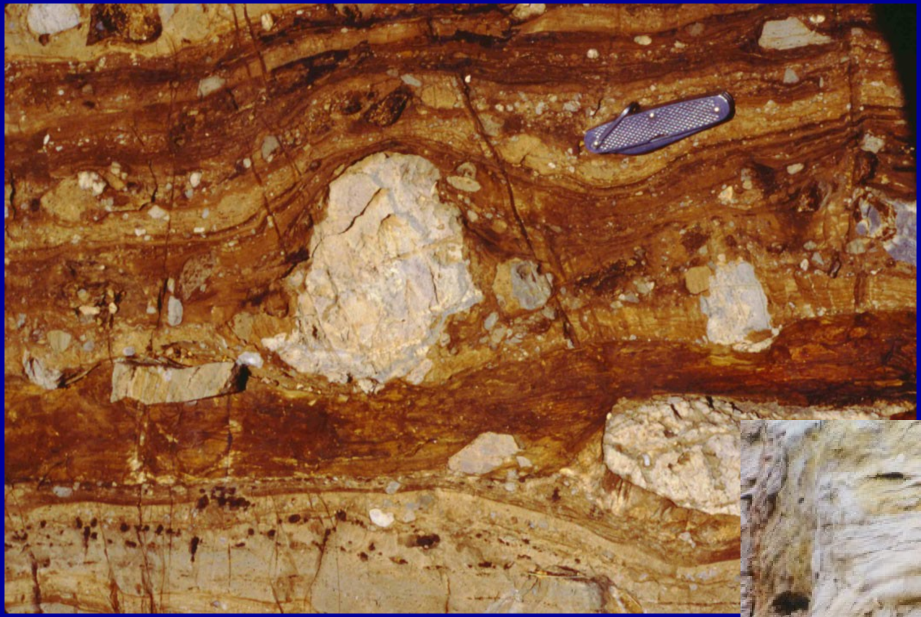
Media Blitz!


SNOWBALL
EARTH
BBC
HORIZON

A step back in time

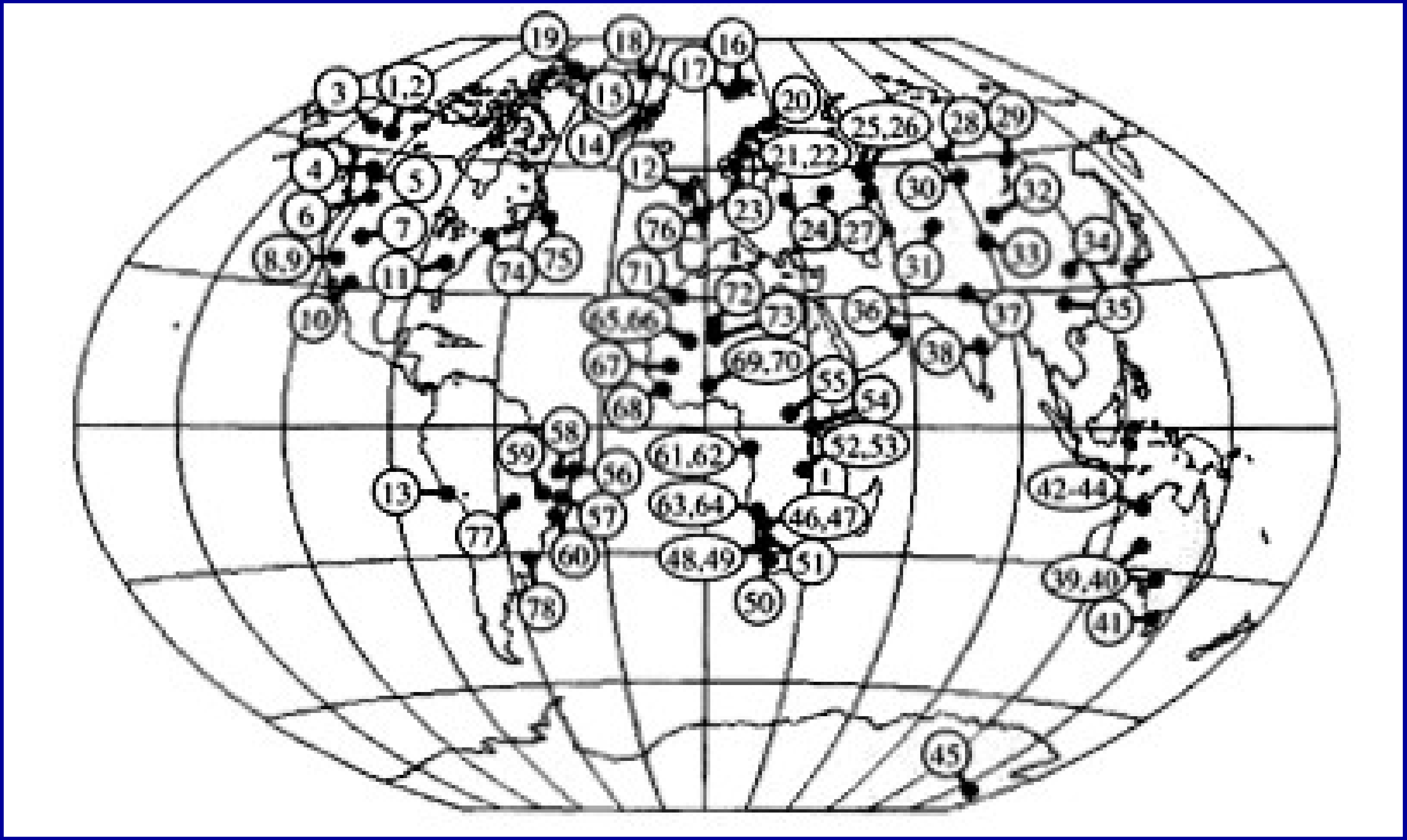


Signs of cold climates…



… followed by rapid warming?

Distribution of Neoproterozoic glacial deposits

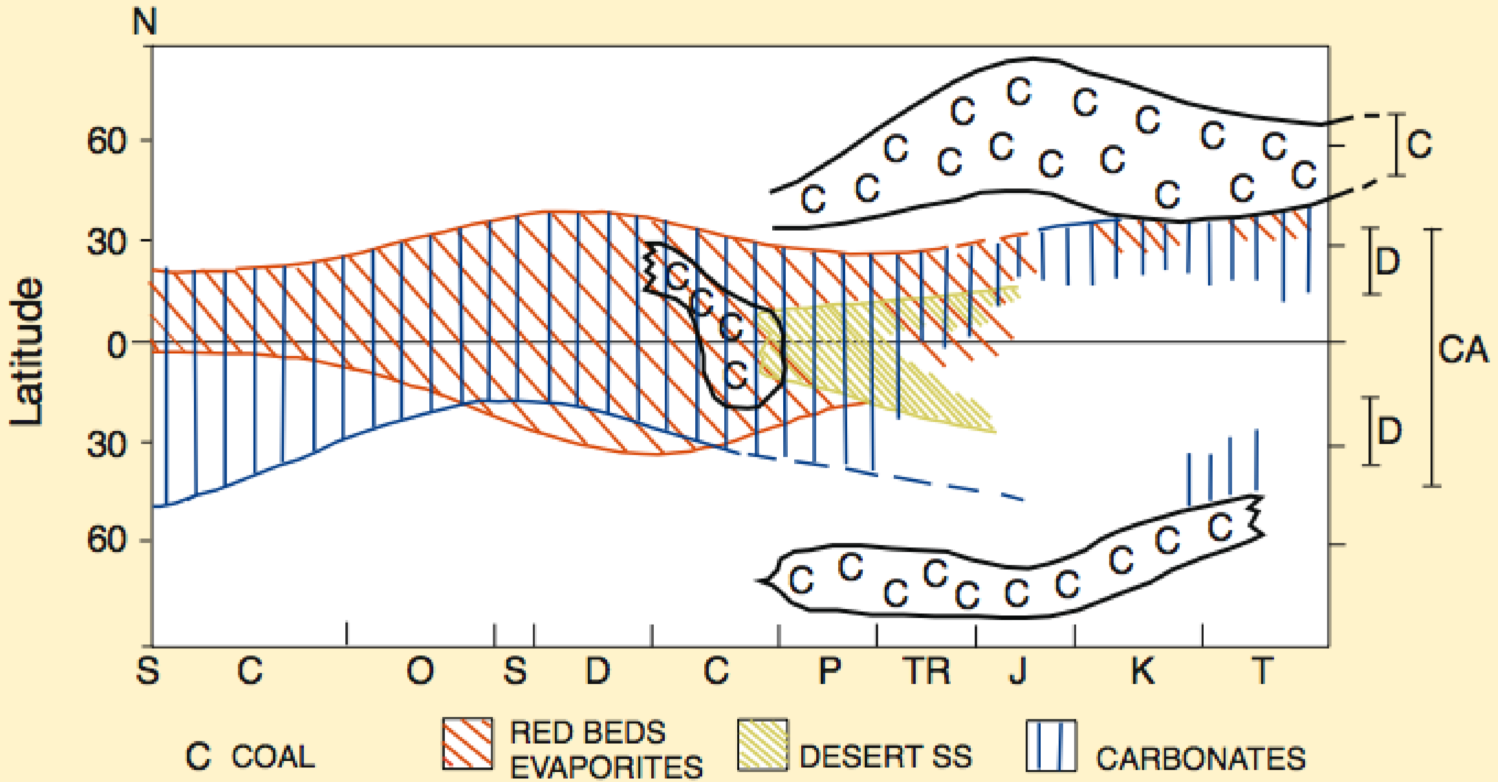


(Evans, 2000)

And so the debates begin…

- Harland (1964) proposes the existence of a "great Infracambrian glaciation"
- The community disagrees - vehemently!

Distribution of climate-sensitive sediments



(Briden and Irving, 1964)

The debates continue…

- Numerous debates over veracity of the glacial nature of sediments
- Astrophysicists and geophysicists weigh in
- Improvements in paleomagnetic techniques lead to many tests of "low-latitude glaciation"

Father of the Snowball Earth

The Original Snowball Earth Hypothesis (Kirschvink, 1992)

- Concentration of continental land masses at low to mid-latitudes led to global cooling by impacting planetary albedo

- Widespread pack ice led to ocean stagnation, resulting in the return appearance of banded iron formations for the first time in > 1 billion years

ELSEVIER

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EPSL

The Neoproterozoic (1000–540 Ma) glacial intervals: No more snowball earth?

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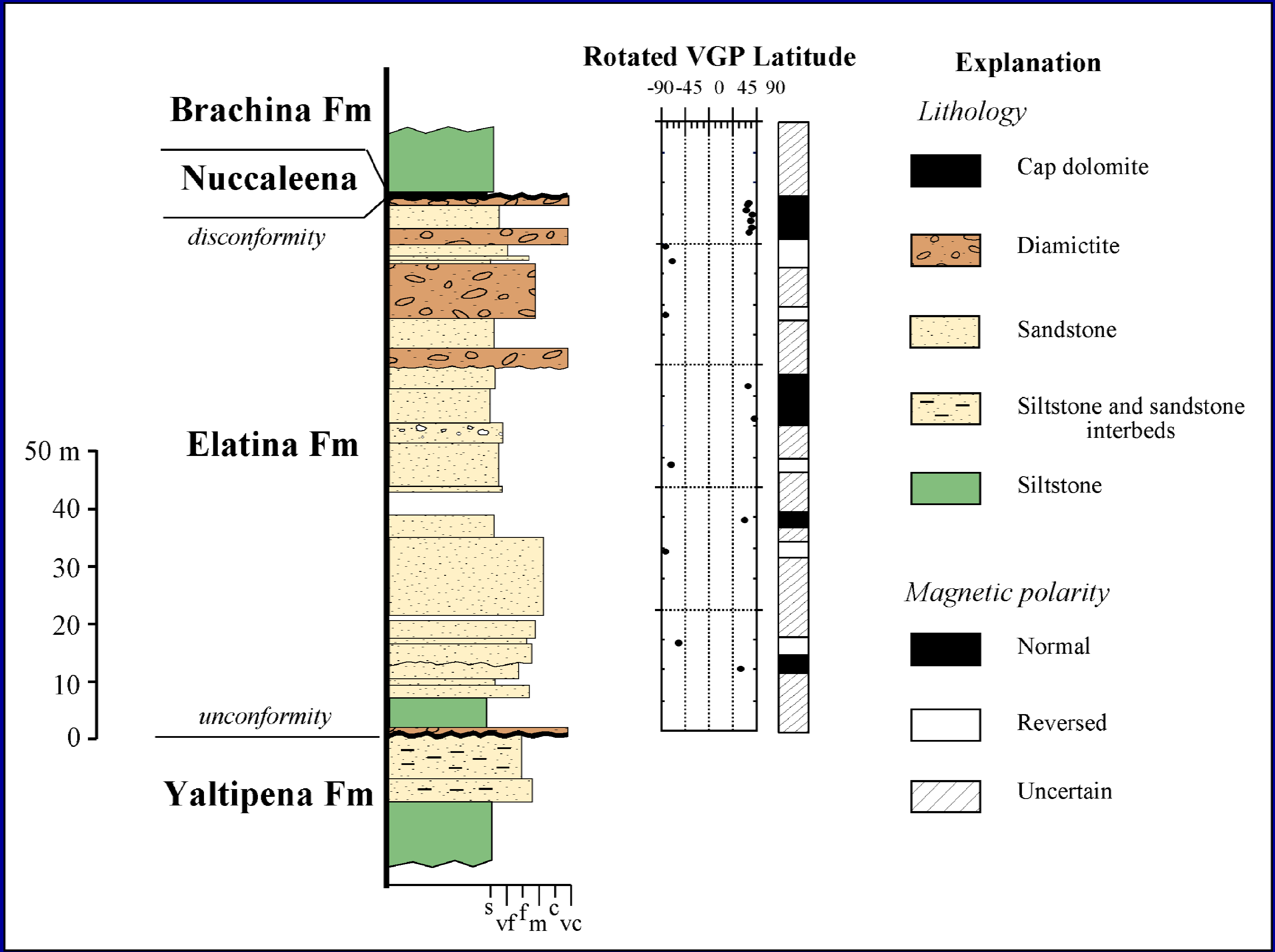
Abstract

The Neoproterozoic interval (1000–540 Ma) contains ample evidence for a series of glacial intervals. These include the 750–700 Ma Sturtian glaciation, the 625–580 Ma Marinoan–Vendian glaciation and the 600–550 Ma Sinian glaciation. Paleomagnetic evidence has suggested that many of these glaciations occurred at tropical latitudes ($\leqslant 25°$) and this led to a number of theories that attempt to explain the occurrence of these anomalously low latitude glaciations (e.g., an increase in the axial tilt of the earth, an equatorial low-orbit ice-ring, rapid equator to pole continental drift, incorrect identification of impact deposits as glacial deposits or secondary magnetizations misidentified as primary). New paleomagnetic data for Laurentia, China, Baltica and parts of Gondwana are combined with a reanalysis of previously published data to demonstrate that the Neoproterozoic glaciations may well all have occurred above 25° latitude. Climate models using a juvenile Sun of slightly lower luminosity, lower CO_2 levels and coupling to Milankovitch cycles suggest that ice sheets could extend to within $\pm 25°$ of the Neoproterozoic equator. Thus, the new paleomagnetic data and climate models offer an alternative explanation for the Neoproterozoic glaciations that is consistent with the waxing and waning of intermediate latitude ice sheets to form the conformable sequences of warm climate–cold climate strata.

Paleomagnetic Data – Trezona Bore Section, Flinders Ranges

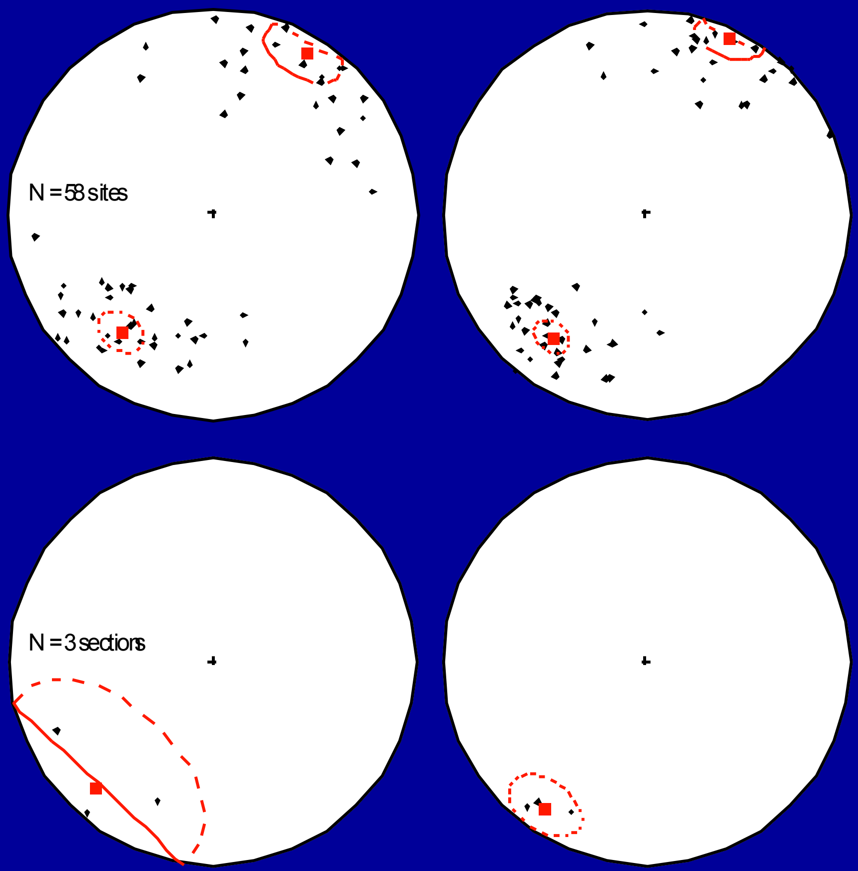


(Sohl et al., 1999)

Summary of Paleomagnetic Results from the Elatina Formation, Central Flinders Ranges, South Australia

A)

B)



In situ Tilt-Corrected

A) For 58 sites:

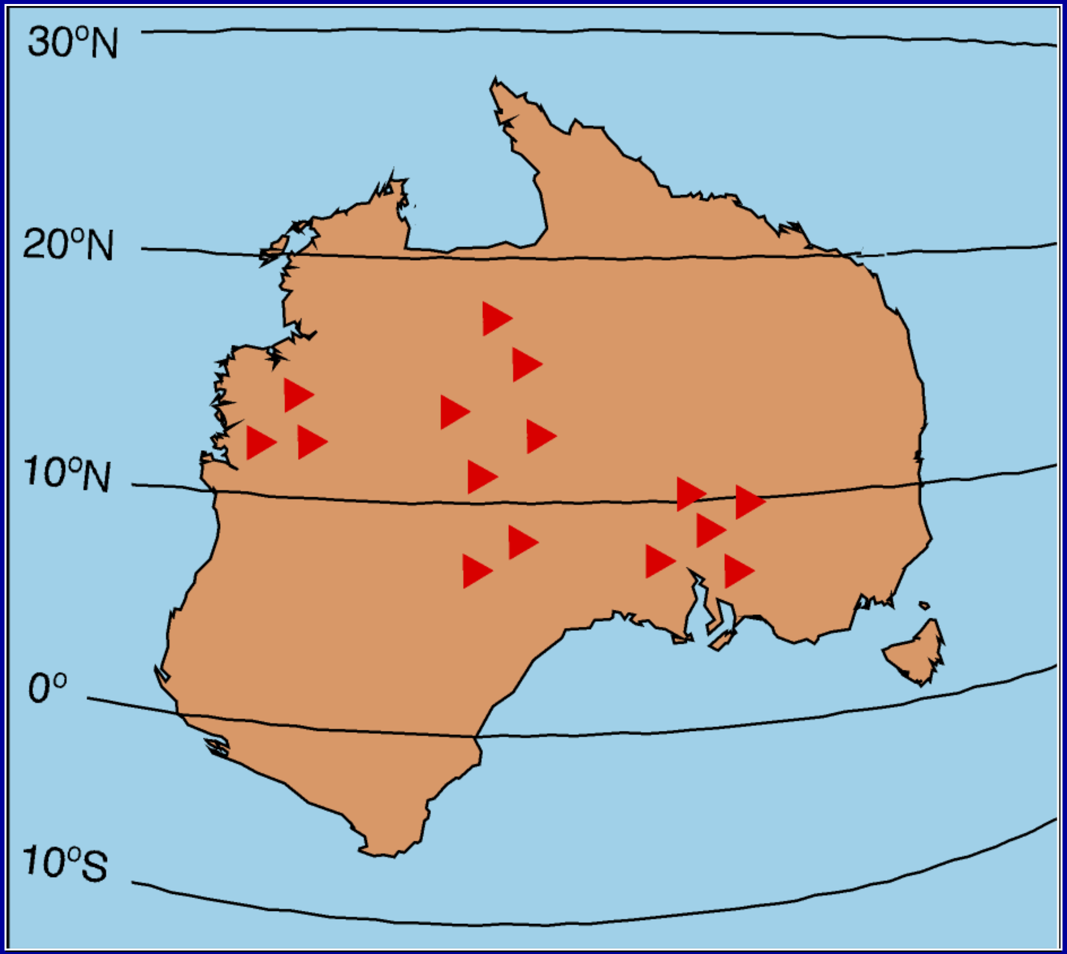
In situ	Tilt-Corrected
Dm = 213.9°	Dm = 212.1°
Im = -20.6°	Im = -16.9°
k = 7.1	k = 9.9
= 7.6°	= 6.2°

B) For 3 sections:

In situ	Tilt-Corrected
Dm = 223.1°	Dm = 214.9°
Im = -17.9°	Im = -14.7°
k = 11.5	k = 94.9
= 38.1°	= 12.7°

(Sohl et al., 1999)

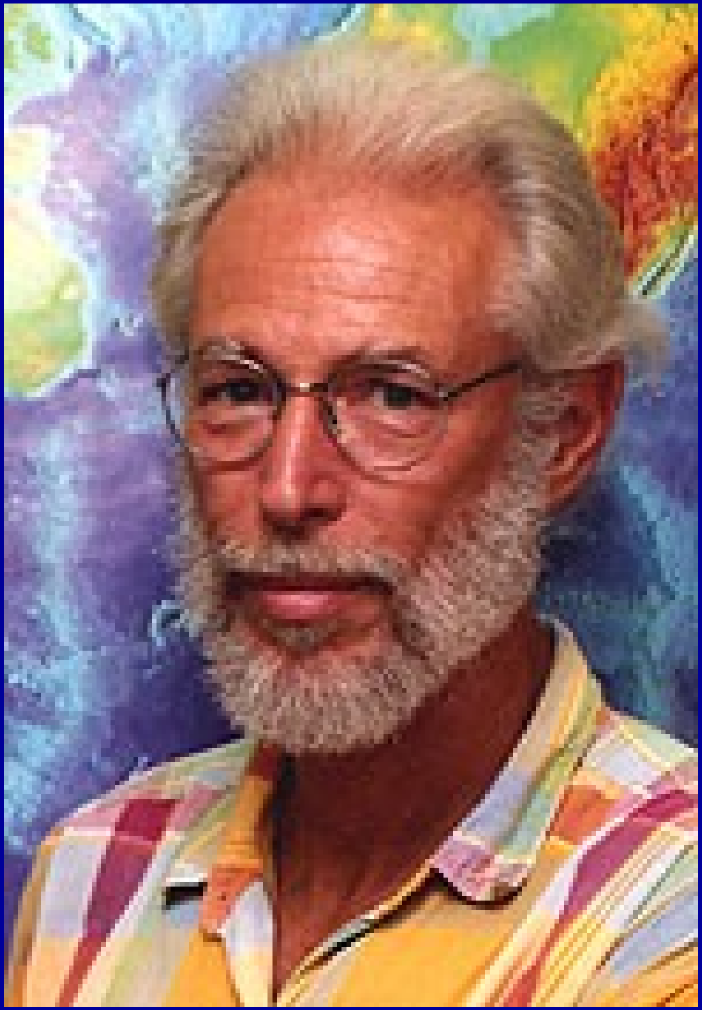
Paleolatitude of Australia During the Marinoan Glaciation




Location of glacial deposits

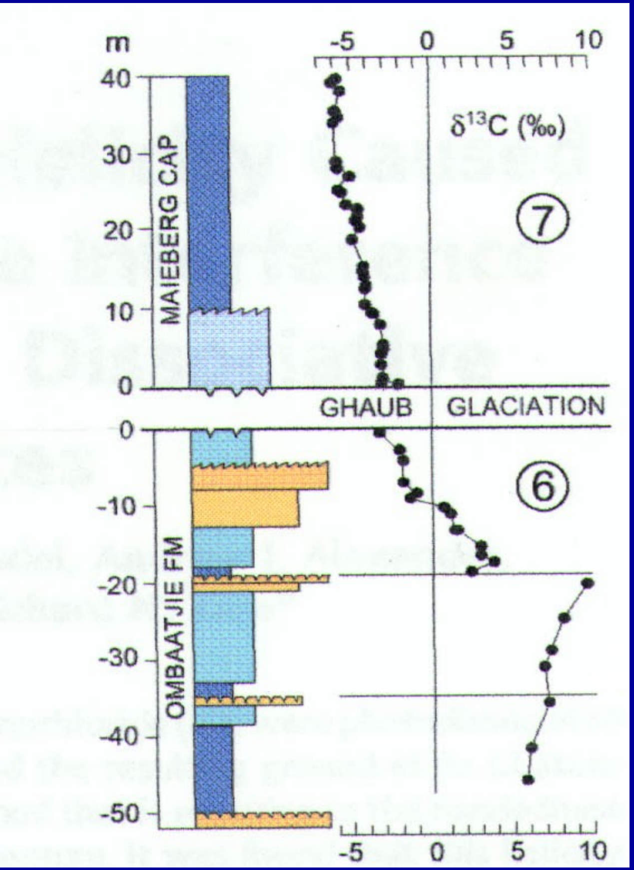
(Sohl et al., 1999)

Founder of the “new” snowball Earth

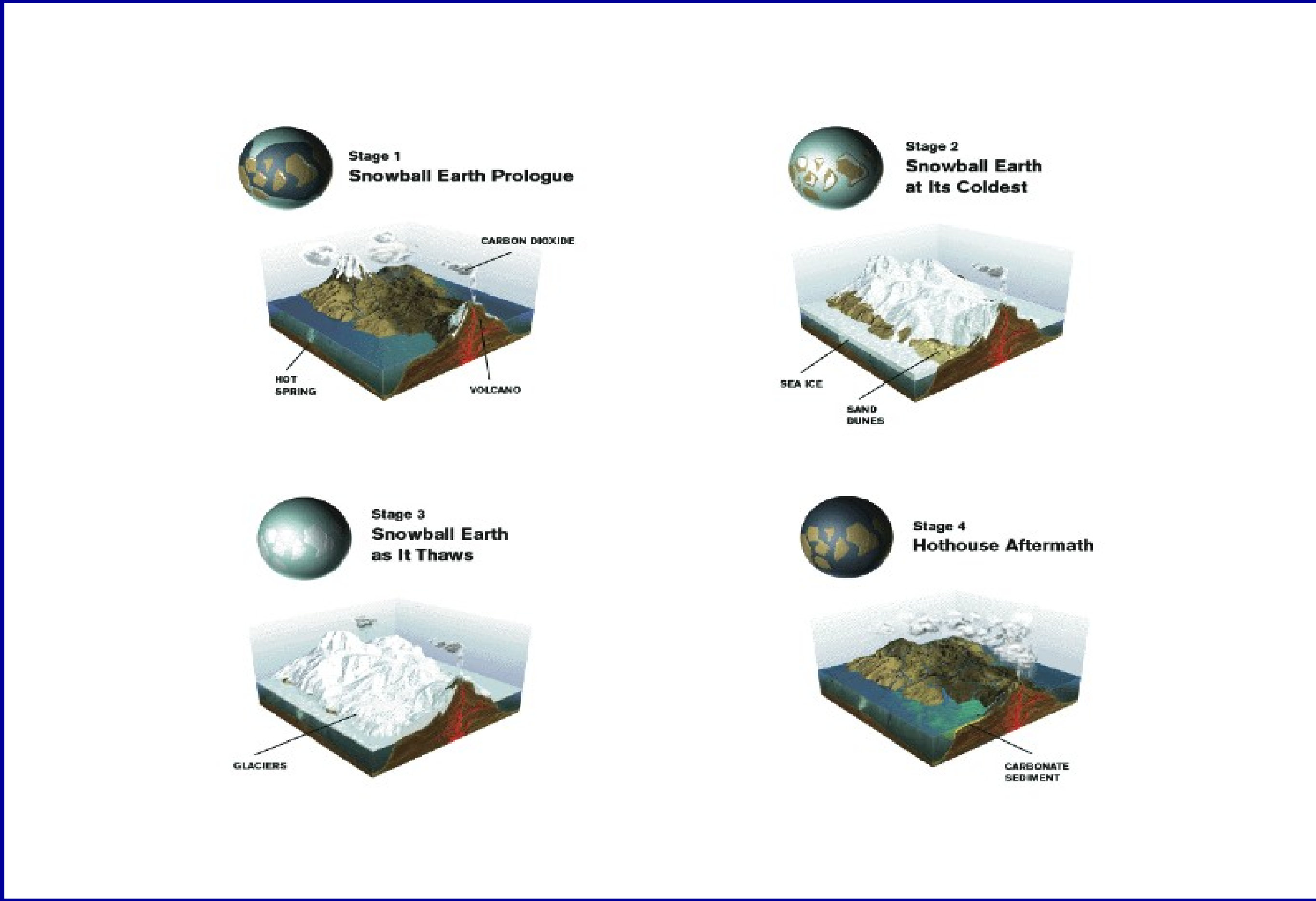


The New Snowball Earth Hypothesis (Hoffman et al., 1998)

- Primarily intended to account for carbon isotopic data ([illegible]^{3}C = 0 to -5‰) in cap carbonates
- Suggests that carbon isotopic values reflect mantle values in an ocean isolated from the atmosphere



The Snowball Earth (Hoffman and Schrag, 2000)



Snowball Earth Hypothesis: Freezing Phase

- Primary productivity in surface ocean ceases

- Surface ocean entirely frozen over (runaway ice albedo feedback; suggested by energy balance models)

- Atmospheric CO_2 increases to ~120,000 ppm owing to virtual shut-down of hydrological cycle and silicate weathering

Snowball Earth Hypothesis: Melting Phase

- Catastrophic melting of ice driven by greenhouse effect
- Renewed silicate weathering draws down atmospheric CO_2, and delivers needed alkalinity and base cations to ocean. **Precipitates Carbonate.** Cap carbonate records transfer of excess atmospheric CO_2 to the oceans
- Trend of increasing carbon isotopic depletion upwards in the cap carbonates is due to Rayleigh distillation

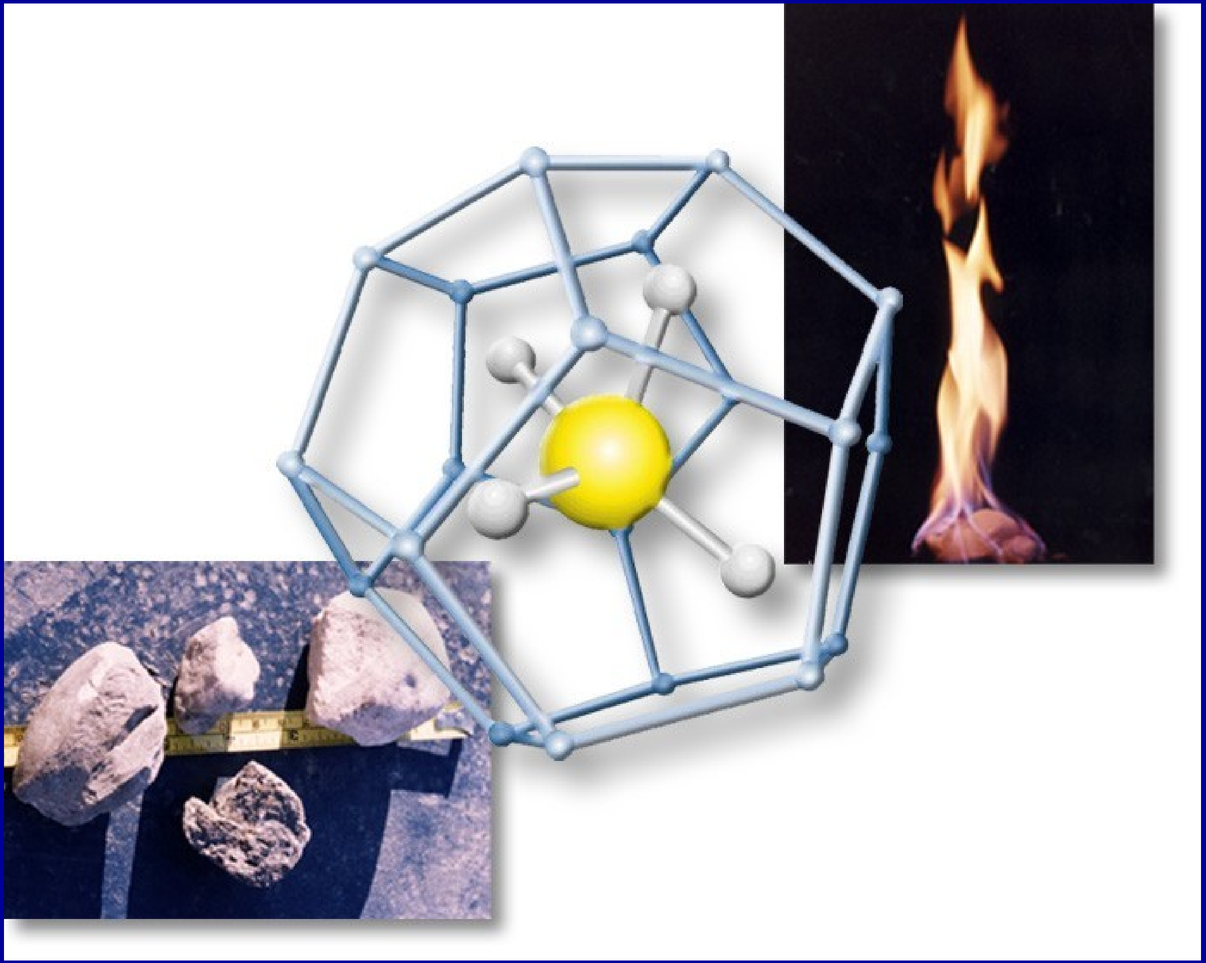
Problems with the new Snowball Earth

- Necessary continental configuration not applicable to both glacial intervals
- Estimate of duration of glacial interval based upon incorrect basin subsidence calculations
- No evidence for mass extinctions
- Glacial sediments cannot be created in absence of hydrologic cycle, and are too voluminous to be created solely at the end stage of glaciation
- Iron formations are limited in occurrence

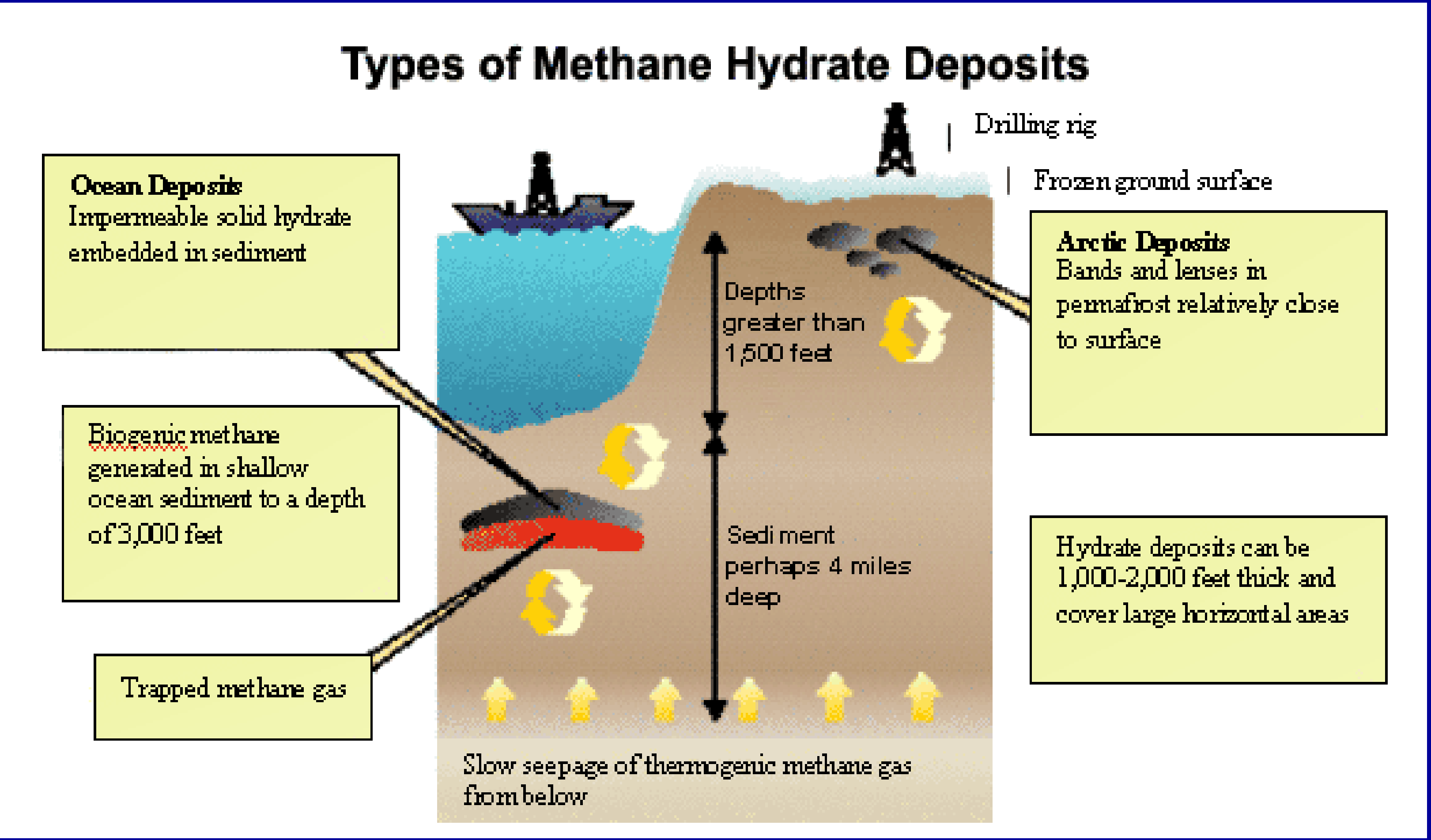
Is a "hard" Snowball Earth really necessary?

One alternative explanation for carbon isotope excursions - the methane clathrate hypothesis - negates the need for a totally frozen surface ocean

Methane hydrate



(Mahajan, 2007)

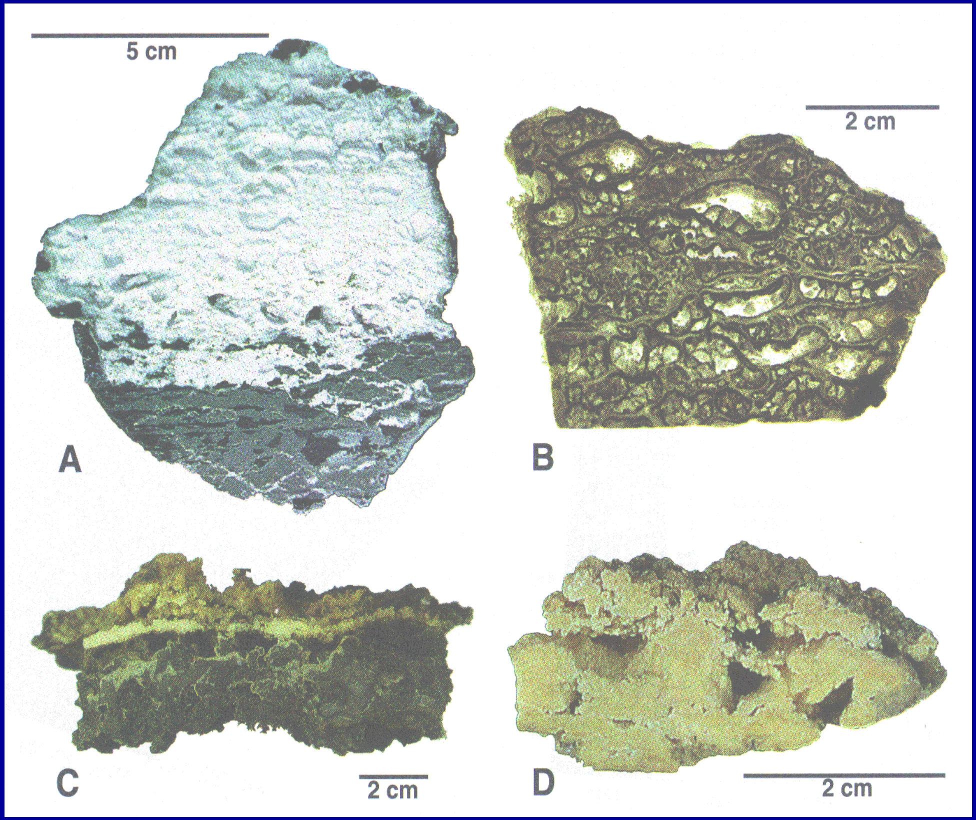


(Courtesy USGS)

Methane Hydrate Hypothesis (Kennedy et al., 2001)

- Methane hydrates may have been more abundant during the Proterozoic ice ages than any other time in Earth history
  - Coldest intervals in Earth history
  - Abundant area available for permafrost development
  - Rapid flooding of continental basins and shelves

Modern Cold Seep Features

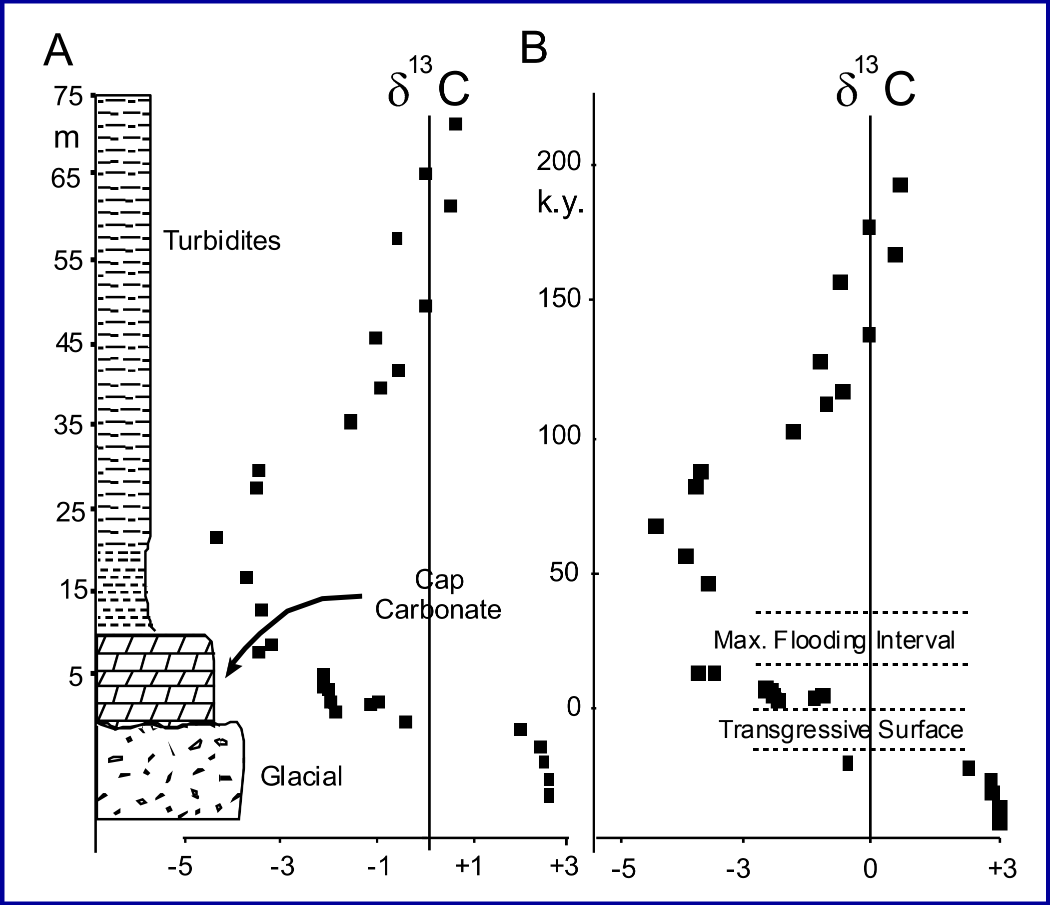


Recovered secondary hydrates from the Cascadia Margin
(Bohrmann et al., 1998)

Cold Seep Facies in Cap Carbonates

- Brecciation
- Cement-lined cavities
- Internal sediment fill
- Deep water depositional setting

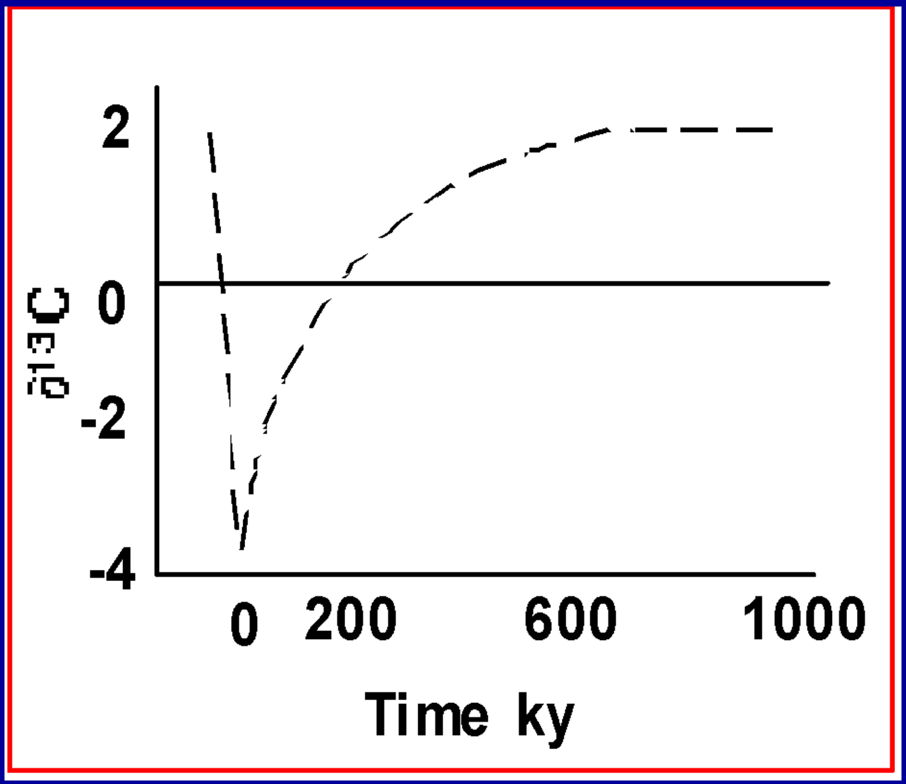
Isotopic Evidence from the Congo Craton



Stratigraphic Section   Time Model

- Values indicate a rapid excursion and long-term recovery
- Cap carbonate deposition occurred over a brief interval (likely <10 k.y.)

Isotopic Evidence for Clathrate Destabilization



(Kump, 1991)

Predictions:

- Rapid release of depleted ^{13}C (~-60‰) produces an instantaneous drop in marine ^{13}C
- Return to normal values takes several residence times of C (>100,000y)

But wait - there's more!

- New paleomagnetic data from cap carbonate in Australia presents a different time scale for the end of glaciation
- New age dates suggest that there may be only one true Neoproterozoic snowball glaciation
- Climate models present a range of possible environmental conditions, depending on the model and starting assumptions

Using the GISS GCM to simulate Neoproterozoic climates

Forcings investigated include decrease in solar luminosity, continental configuration, atmospheric CO2 levels, and ocean heat transports

QuickTime™ and a
Compact Video decompressor
are needed to see this picture.

GISS GCM Simulation results

Only most extreme combination of forcings permits the growth of ice sheets on land; surface ocean does not freeze over

Summary

- The "hard" Snowball Earth hypothesis (Hoffman et al., 1998; Hoffman and Schrag, 2000) is incorrect on key points

- A "slushball" Earth likely presents a better portrait of the environment circa 640 million years ago