
U3A Geology
Snowball Earth hypothesis

Introduction

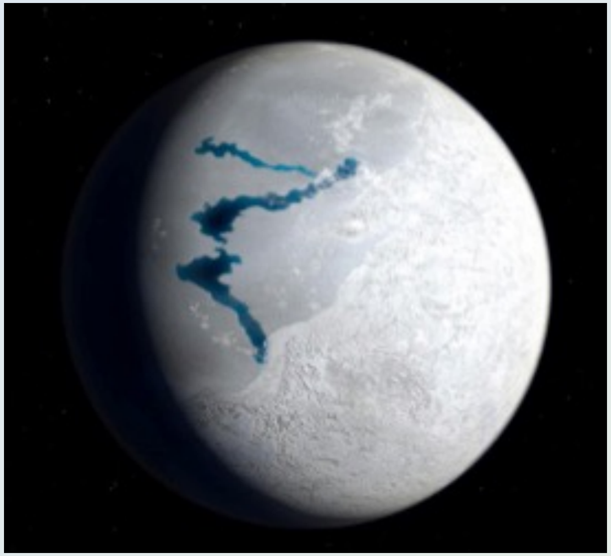
- Many climate researchers believe that there were periods in the Neoproterozoic era when the entire Earth was frozen
- controversial theory is called the "Snowball Earth" hypothesis
- it has evoked much discussion amongst the scientific community and given rise to many compromise and rebuttal theories
- there is however, compelling evidence to support the theory

Proterozoic Eon

Eon	Era	Period	Mya
	Cambrian (Palaeozoic)		545
PROTEROZOIC EON	Neopro-terozoic	Ediacaran	630
		Cryogenian	850
		Tonian	1000
	Mesopro-terozoic	Stenian	1200
		Ectasian	1400
		Calymmian	1600
	Palaeopro-terozoic	Statherian	1800
		Orosirian	2050
		Rhyacian	2300
		Siderian	2500

Snowball Earth

- 750-600 million years ago (Cryogenian-Ediacaran) Period) → considered most pervasively cold period in Earth's history
- there were 3 or 4 glaciations, 2 were global (Sturtian, Marinoan)
- over long periods during these times → whole Earth was frozen (?)
- this is the origin of the "Snowball Earth" hypothesis
- an alternative theory is "Slushball Earth" → equatorial oceans contained thin layers of watery ice in otherwise open sea



"Snowball Earth"

"Slushball Earth"

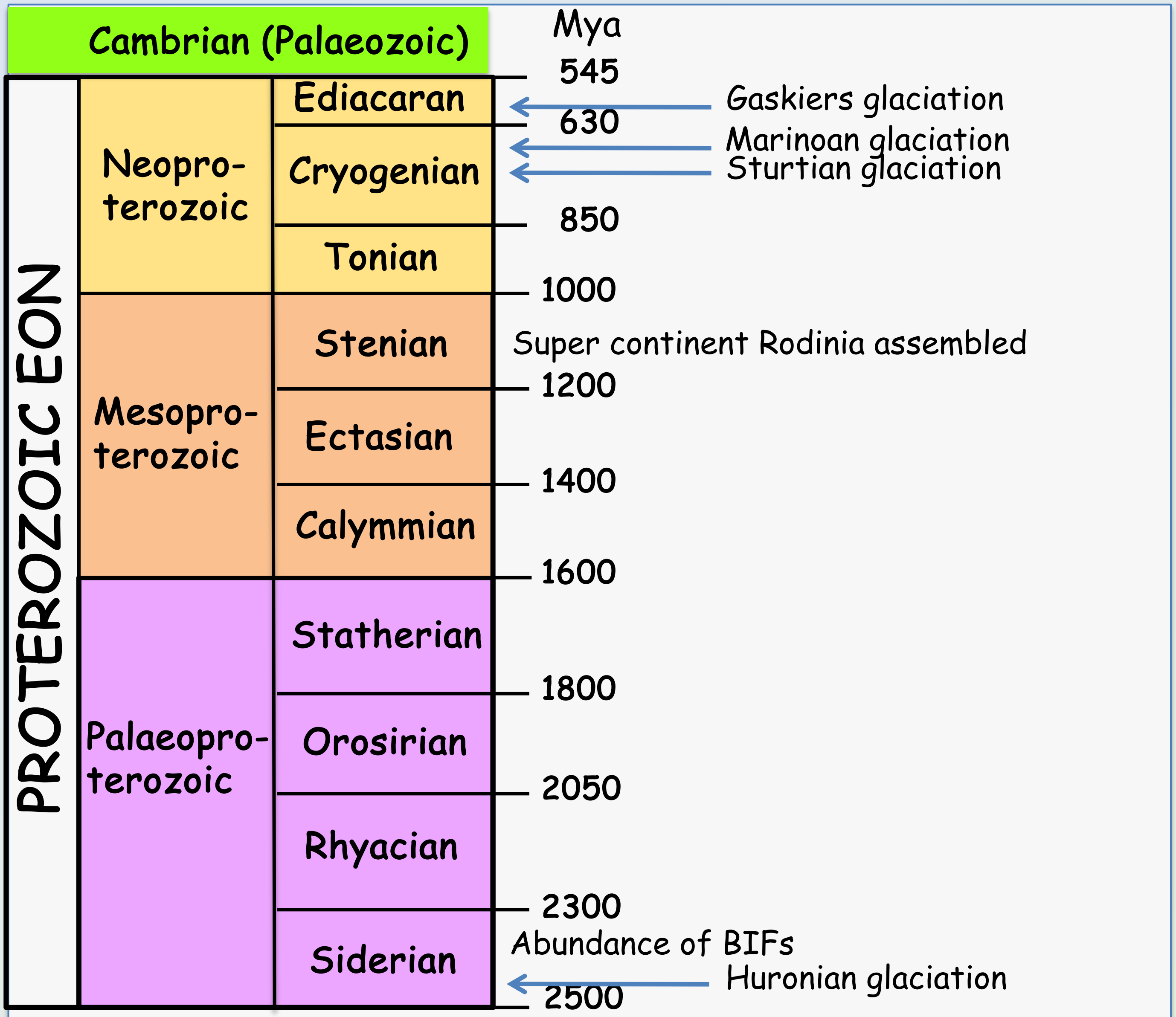
Evidence for past glaciations

- Louis Agassiz (early 19th century) noted → past alpine glaciations were more extensive than those of the time (evidence → glacial erratics, stranded terminal moraines → glacial retreat)
- Douglas Mawson (1920s) identified thick Neoproterozoic glacial sedimentary rocks in South Australia
- British geophysicist Brian Harland (1964) published a paper presenting palaeomagnetic data demonstrating that Greenland Neoproterozoic glacial deposits → deposited in tropical latitudes at sea level

Evidence for Neoproterozoic glaciations

- Evidence for Neoproterozoic glaciations is widespread → found on every continent demonstrating glaciations → global phenomena
- palaeomagnetic evidence from Harland indicated that glaciations occurred at low palaeolatitudes → within 10° of the equator
- dropstones in marine sediments near the palaeoequator indicate sea level glaciation in tropics
- glaciers exist at low latitudes only in mountainous regions e.g. Mt Kilamanjaro in Tanzania, Mt Carstensz in Irian Jaya

Proterozoic Eon



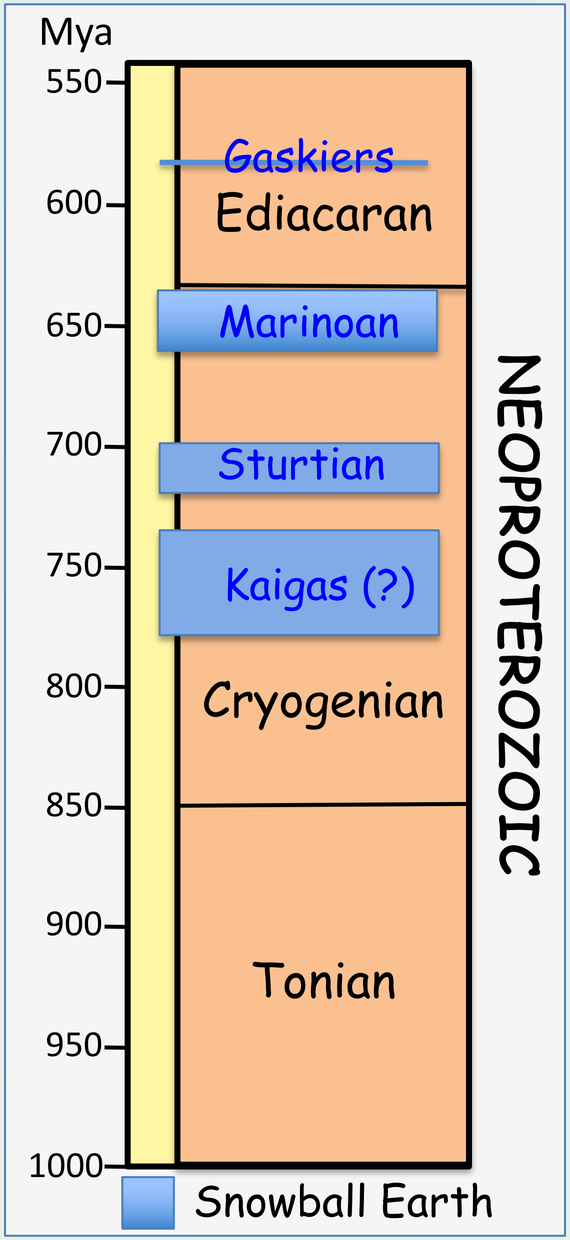
Proterozoic glaciation and glacial deposits

- Tillites provide evidence for glaciation
- two major periods of glaciation recognised in Proterozoic

  Early Proterozoic

  Neoproterozoic

- four glacial periods in Neoproterozoic (?)
- Kaigas glaciation → hypothetical
- Neoproterozoic glaciation gave rise to "Snowball Earth" hypothesis



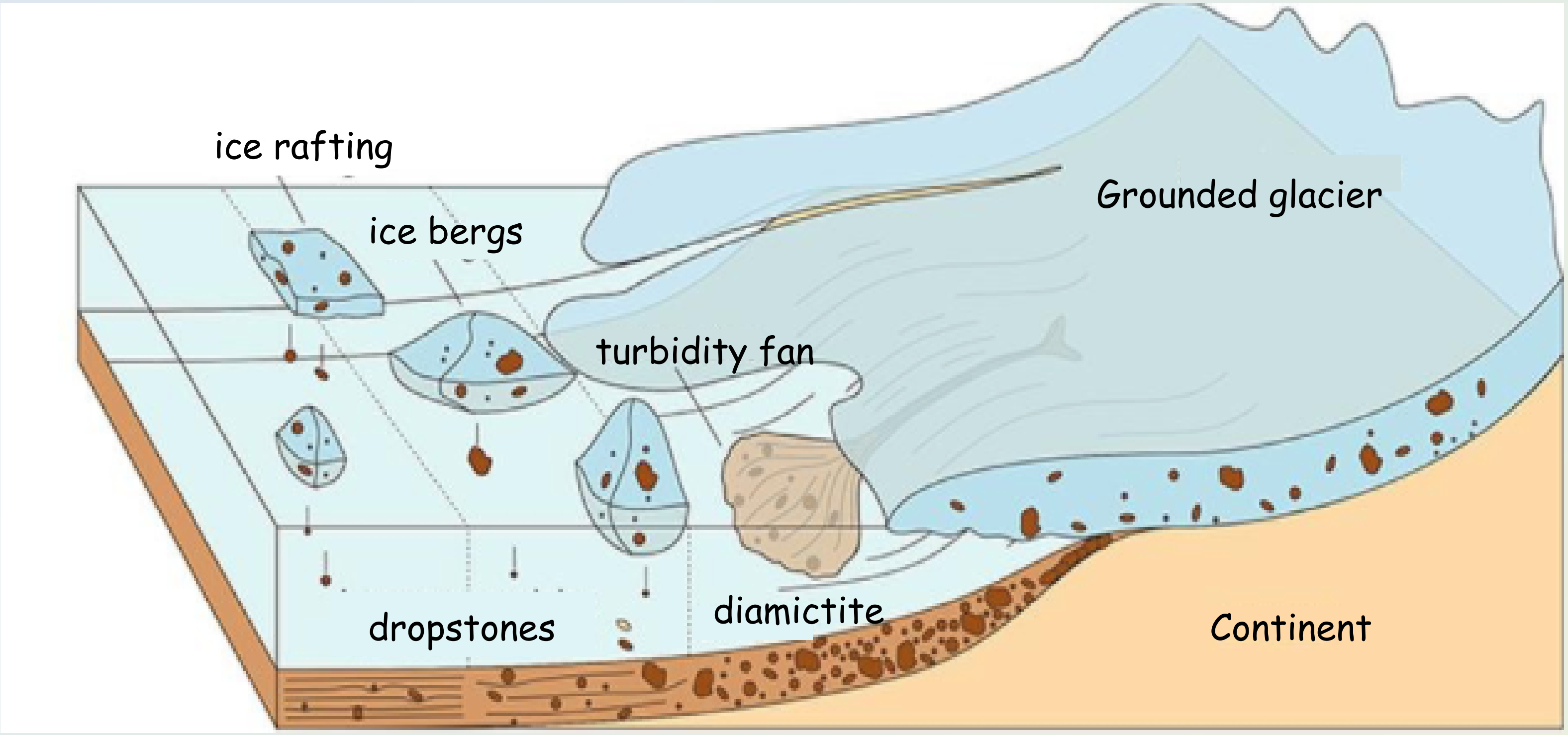
Proterozoic glaciations - Huronian

- Oldest recognised ice age in Earth's history was the Huronian glaciation → extended from 2400 to 2200 million years ago (Palaeoproterozoic)
- one of the longest and most severe ice ages in Earth's history
- some scientists believe that it was the first " Snowball Earth"
- however, lack of evidence for it being global in scale

Dropstone in Palaeoproterozoic siltstone, Canada

Formation of dropstones

Dropstones → cobbles and boulders dropped from melting glaciers or icebergs into soft sediments at the bottom of the sea or a lake



Huronian dropstones , China

Evidence for Neoproterozoic glaciations

- Evidence is widespread, found on every continent → global phenomena
- at least two, as many as four major glaciations with warmer intervals
- Sturtian → Cryogenian Period (~720-700Mya)

  Marinoan → Cryogenian Period (~660-635Mya)

  Gaskiers – short term glaciation Ediacaran Period (~582-580Mya)
- Sturtian and Marinoan glaciations are considered by many to be "Snowball Earth" episodes
- Neoproterozoic glacial erosion features formed at or near sea level at low latitudes

Some Neoproterozoic glacial deposits

Tillite, Greenland

Tillite, Oman

Tillite, Namibia

Tillite, Elatina Fm., Flinders Ranges, Australia

Snowball Earth

- American palaeomagnetist Joe Kirschvink (1992) proposed that some ice ages in Neoproterozoic were so severe → whole Earth froze
- Kirschvink called the hypothesis "Snowball Earth"
- evidence suggests sea ice extended from poles to equator at least twice during the Neoproterozoic
- what scenario could produce conditions that caused the Earth to completely freeze?
- why hasn't the phenomenon occurred more frequently?

Scenario

- Scientific modelling by Mikhail Budyko (USSR) and Michael Sellers (USA) in 1960s demonstrated that:

  combination of low atmospheric CO_2 and low solar input

  → cooling of the Earth's surface

  → ice would start to advance beyond polar regions

- when ice advanced to within 30° of equator → positive feedback called "ice-albedo feedback" → increase reflectiveness → further cooling

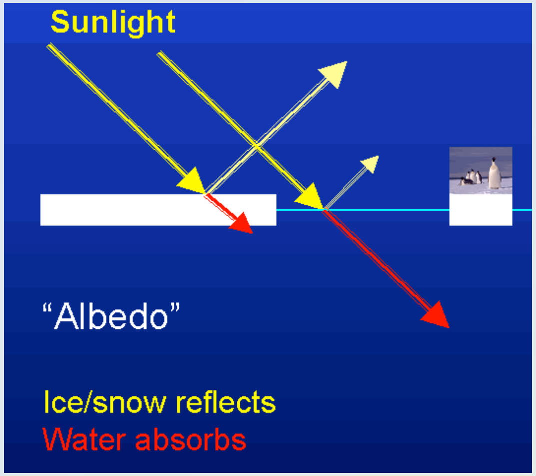
- runaway process with the whole Earth freezing

- without an escape mechanism → Earth should remain frozen

- Budyko and Sellers believed that it had never actually occurred

Ice-albedo feedback mechanism

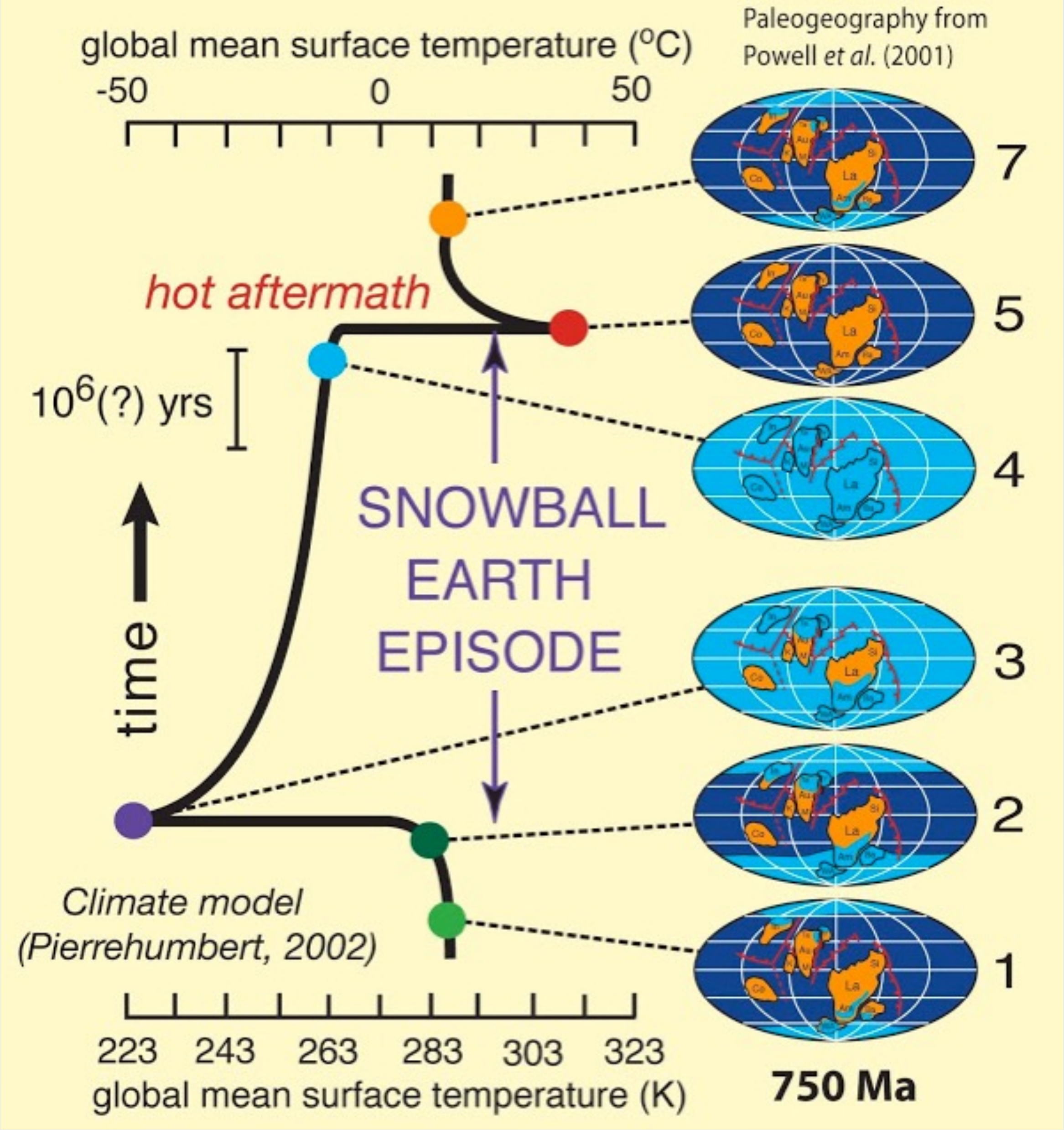
- Albedo – reflective power of a surface
  - 1.0 = total reflection
  - 0.0 = total absorption
  - albedo of ice/snow = 0.5 - 0.9
  - albedo of ocean surface = ~0.1



- Ice-albedo feedback mechanism
  (1) cooling of atmosphere → increase in area of ice/snow → decrease in solar radiation absorption → further increase in cooling
  (2) warming of atmosphere → decrease in area of ice/snow → increase in solar radiation absorption → further increase in warming

- Earth's average temperature due to albedo and greenhouse effect =15°C
  - if Earth was ice covered → < -40°C
  - if Earth was water covered → 27°C

Global temperatures in Neoproterozoic



Possible causes for cooling of the Earth

- According to astronomers → Sun's radiation was weaker at the time and has gradually increased over Earth's history
- decrease in greenhouse warming due to a depletion in atmospheric methane (CH_4) after the Great Oxygen Event (GOE)

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

- drawdown in CO_2 due to a lull in volcanic activity → "Snowball Earth" not possible unless CO_2 was half present day levels
- configuration of continents probably a significant factor
- high obliquity of Earth's axis (?)

Great oxygenation Event (GOE)/Oxygen catastrophe

The GOE event refers to the period of rapid increase in the oxygen concentration in the atmosphere due to activity of photosynthetic cyanobacteria (about 2.3Ga)

Up until 2.45Ga O_2 almost totally depleted in atmosphere

2.45 – 1.85Ga O_2 produced by photosynthesis captured by Fe dissolved in the ocean and in organic sediments

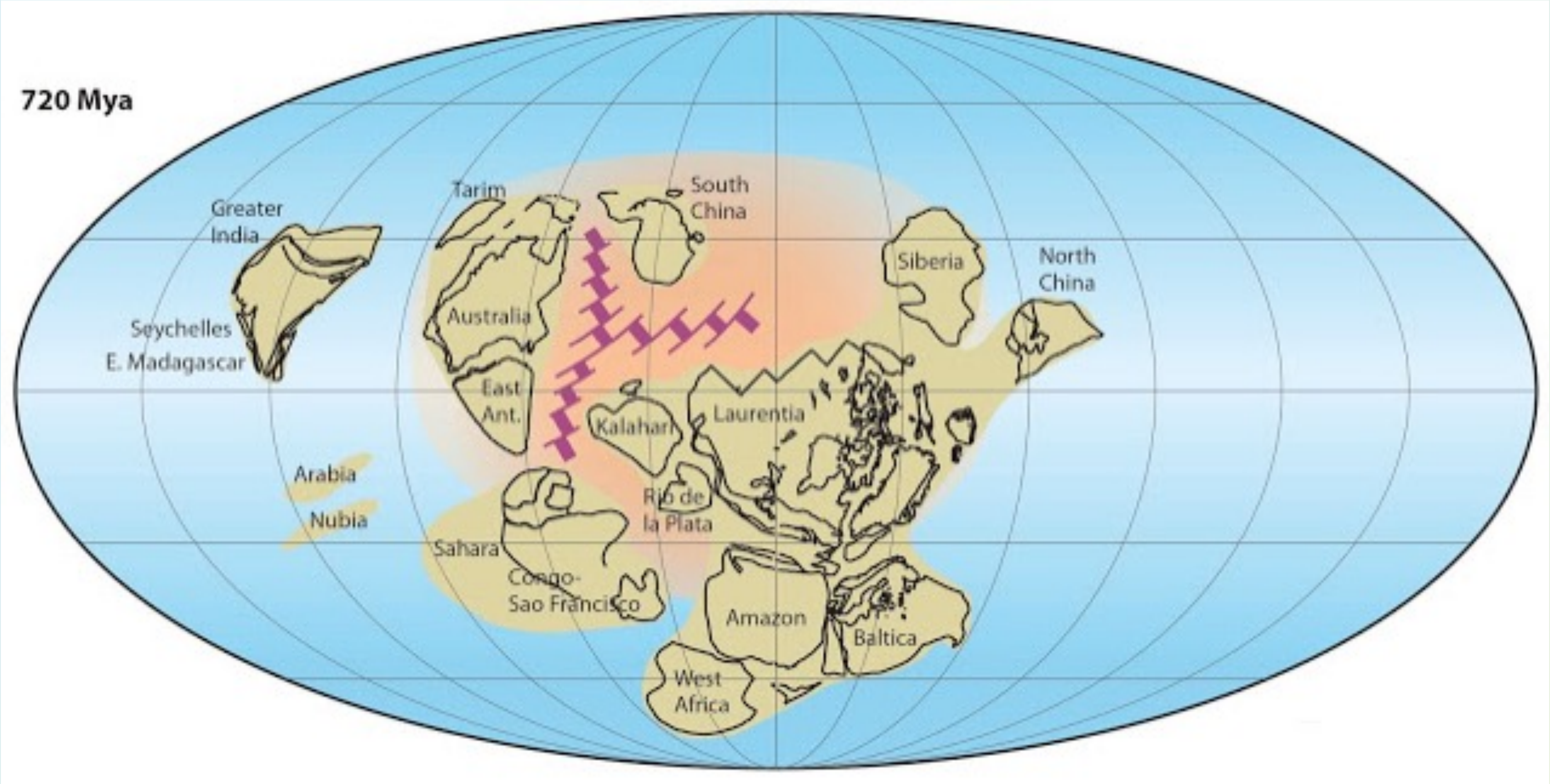
1.85 – 0.85Ga O_2 released to atmosphere oxidises land surface

0.85Ga → O_2 accumulates in atmosphere → oxidation of CH_4

Oxygen → responsible for forming iron ore deposits and the extinction of most anaerobic organisms

Neoproterozoic congfiguration of continents

- Majority of continents were at latitudes <30° almost none > 60°
- no landmasses at either of the poles
- oceans in tropics store energy whereas continents re-radiate energy
- lack of vegetation on continents → even greater degree of re-radiation



Alternative theories

- George Williams (1975) suggested → during Neoproterozoic, the Earth's tilt may have exceeded 54° → with tilt >54° the mean annual temperature around equator would be lower than at poles → tropics would still experience hot summers
- Richard Sheldon (1984) proposed that ice rings orbiting the Earth periodically collapsed into the atmosphere → shielding sunlight → causing global cooling

Evidence to support "Snowball Earth" hypothesis

(1) Global distribution of Sturtian and Marinoan glacial sediments

(2) Carbon stable isotope data (large positive and negative anomalies) after each event

(3) palaeomagnetic evidence of glacial sediments forming near equator

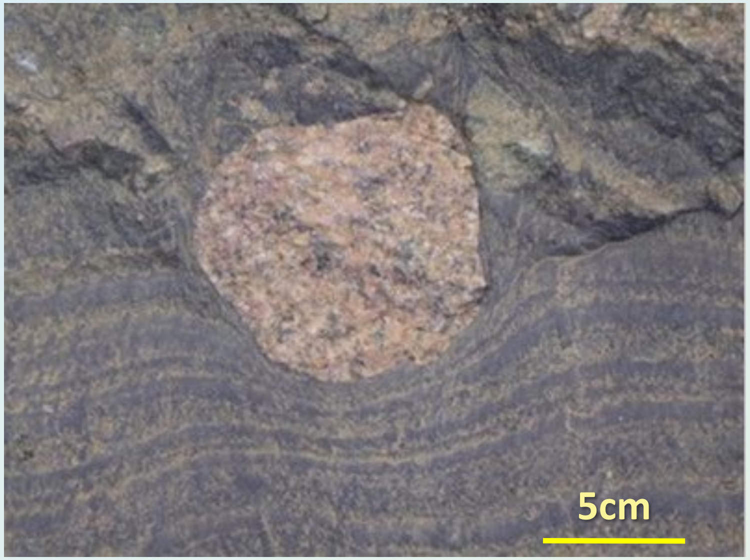
(4) reappearance of BIFs after 1,200 Mya (interbedded with glacial sediments)

(5) deep flooding of previously shallow water shelves after meltdowns

(6) global occurrence of cap carbonates → "super greenhouse" aftermath

Neoproterozoic glacial sediments

Ice-rafted dropstone, Namibia



Dropstone, Northern Flinders Ranges, SA

Tillite, Canada

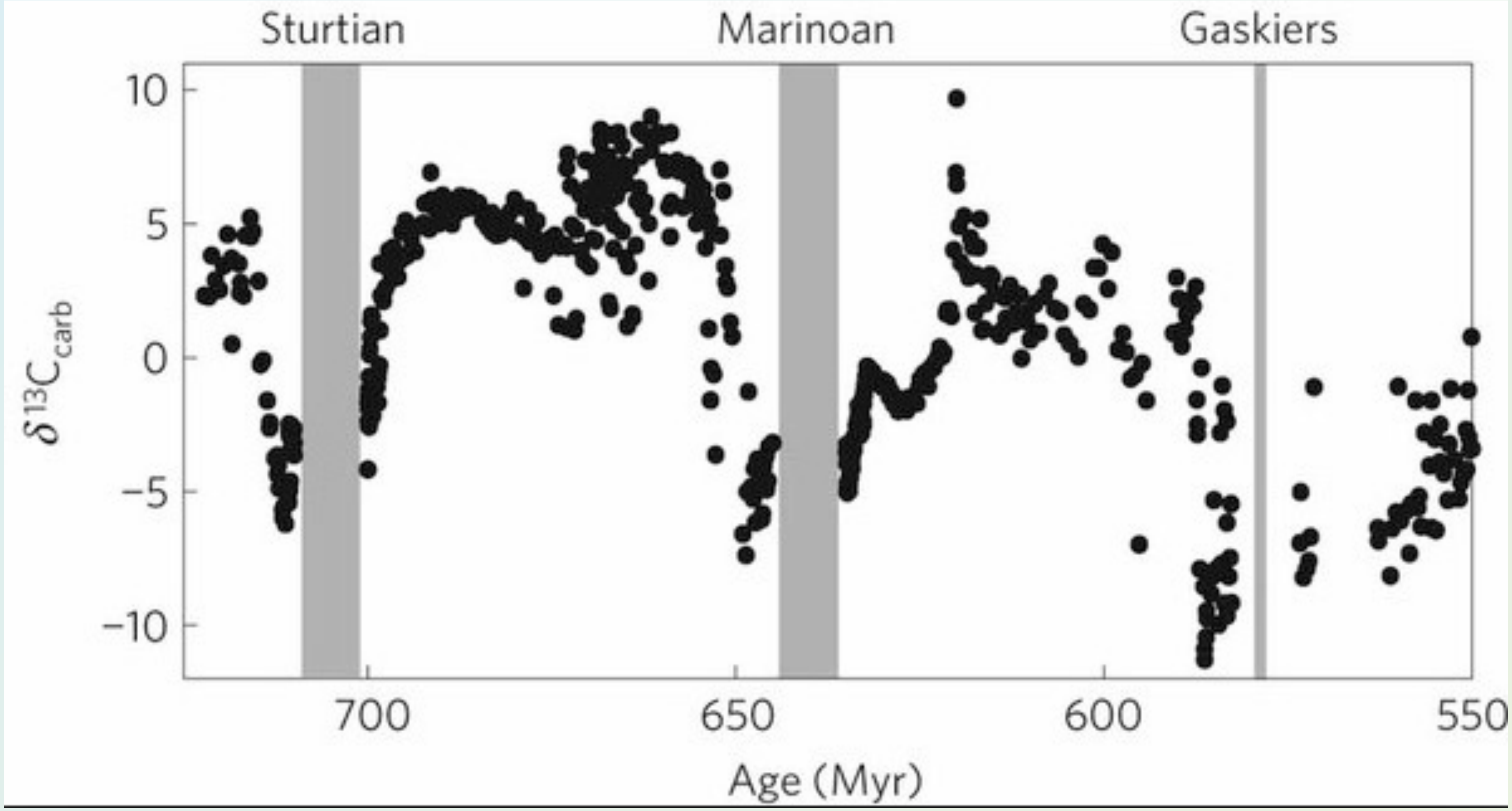
Tillite, Flinders Ranges, SA

Carbon isotope evidence for "Snowball Earth"

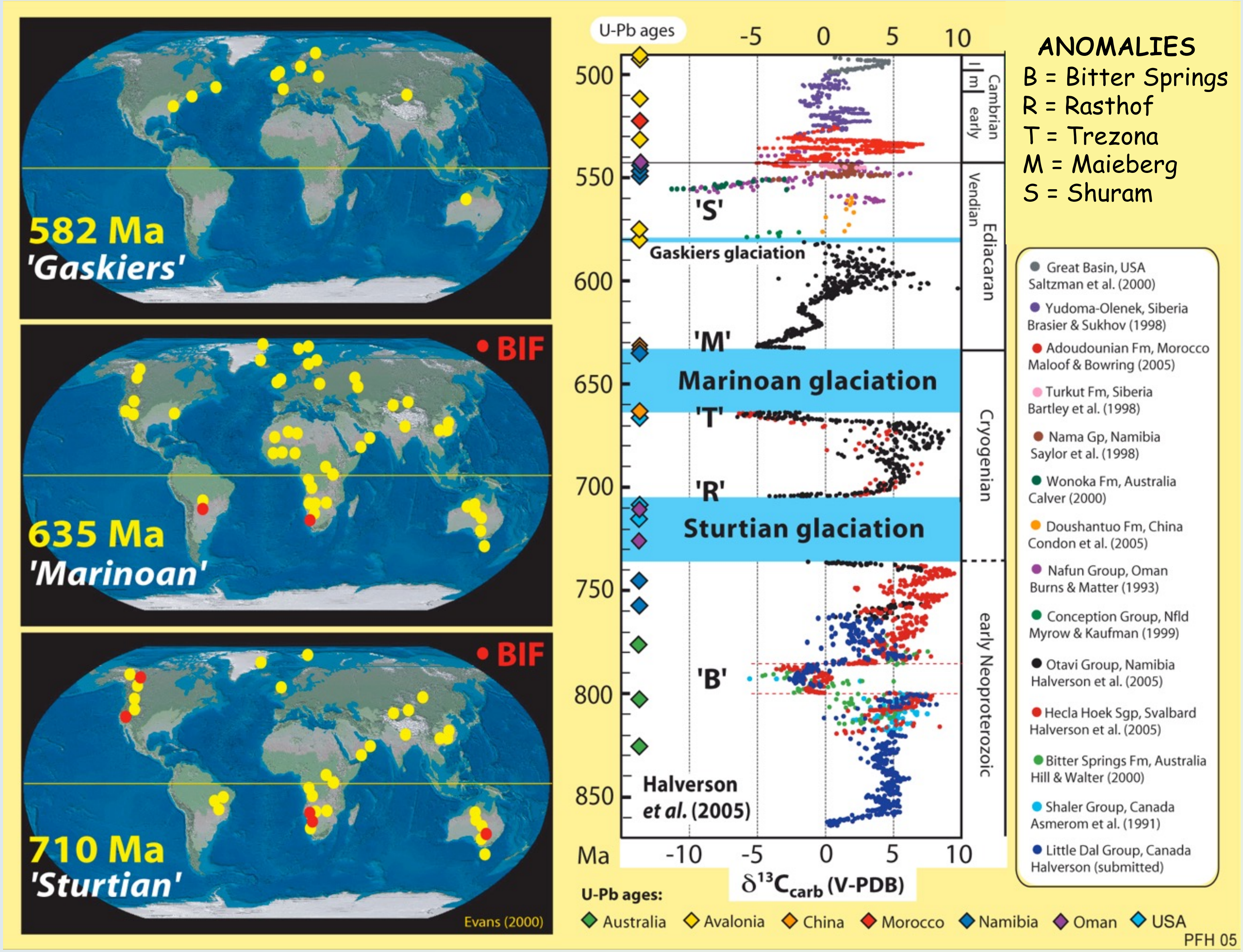
- Carbon isotopic signatures from Namibia → collapse in biological activity
- there are two stable isotopes of carbon in seawater ^{12}C and minor ^{13}C
- photosynthesis preferentially incorporates ^{12}C photosynthesizers are depleted in ^{13}C relative to concentrations in primary, volcanic C
- organic component of lithified sediments → depleted in ^{13}C (lower $^{13}C/^{12}C$ corresponding seawater → enriched in ^{13}C (higher $^{13}C/^{12}C$)
- during periods of "Snowball Earth" → $^{13}C/^{12}C$ in carbonates precipitated out of seawater → anomously low → implies shutdown of photosynthesis during "Snowball Earth" events

Carbon isotopes in the Late Neoproterozoic rocks

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



Carbon isotopes in carbonate rocks



Palaeomagnetic evidence

- Palaeomagnetic evidence from studies in Namibia (Hoffman 1998)

  → glaciations occurred at low latitude 760-600Mya

- glaciations began and ended abruptly

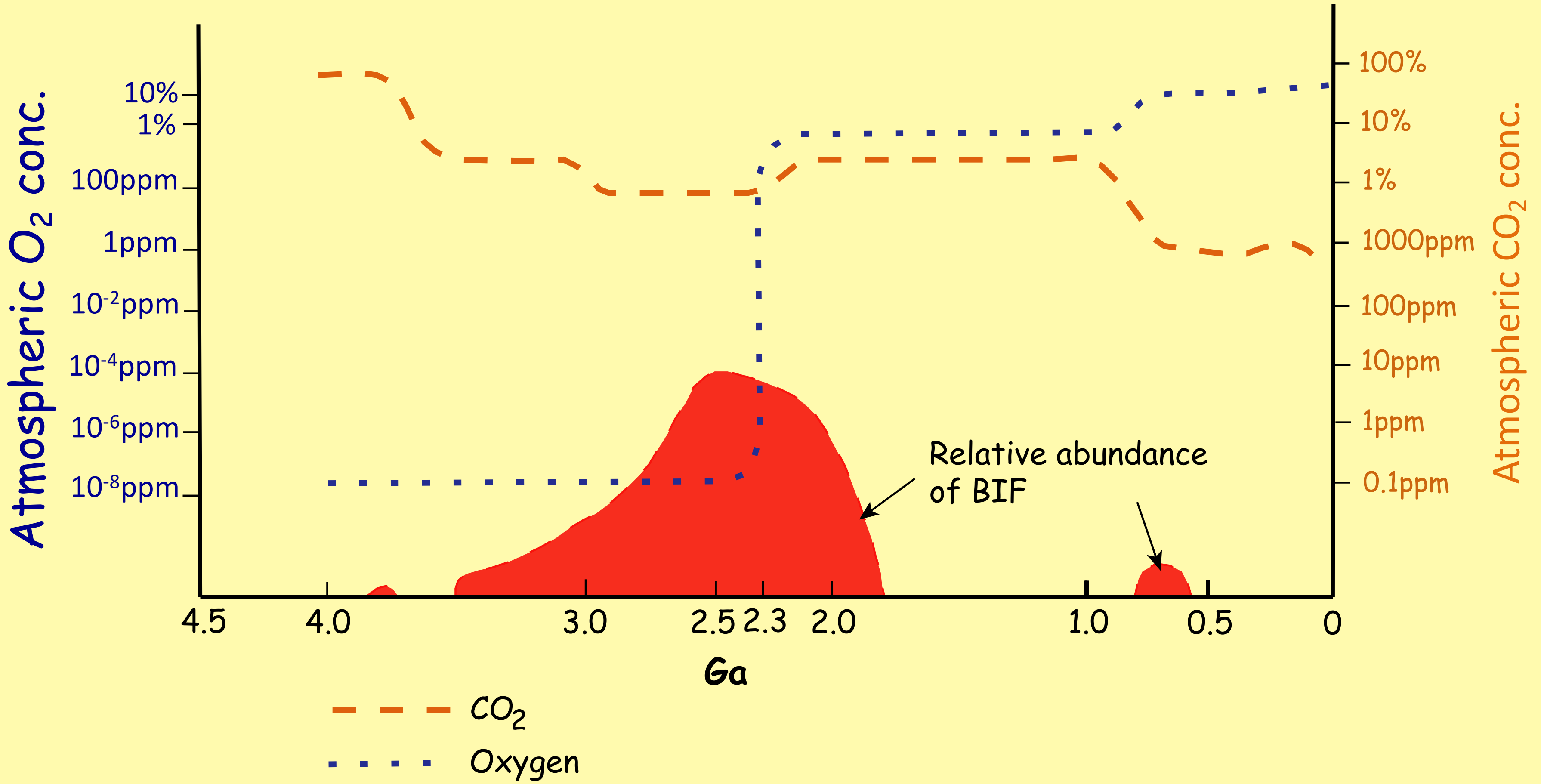
- contrasts with Permo-Carboniferous "ice age" → glaciers never further north or south of 35° latitude

- glacial features (e.g. dropstones, tillites) → glaciers existed at sea level in tropical regions

Evidence from banded iron formations (BIFS)

- BIFs of same age as Neoproterozoic glaciations occur at a number of localities around the world
- formation of BIFs requires oxygen depleted waters → cannot form today → precipitate in the presence of oxygen from photosynthesis
- BIFs widespread in the Archaean and Palaeoproterozoic (2500-1800Ma)
- Neoproterozoic → ocean oxygen levels relatively high → should preclude solution of iron → occurrence of BIFs enigmatic
- during "Snowball Earth" episodes, ocean oxygen levels → depleted → photosynthesis severely reduced and ocean decoupled from atmosphere
- Ocean oxygen levels increase post "Snowball Earth" → iron precipitates

Formation of BIF in Precambrian



Dropstone in Neoproterozoic BIF, Canada

Cap carbonate enigma

- Carbonate sediments (dolomites and limestones) that immediately overlie Neoproterozoic glacial sediments globally
- they are called cap carbonates
- these sediments normally only form in warm tropical seawater
- occur globally → Namibia, China, South Australia, North-western Australia, Canada, India, Oman, Greenland
- critics of "Snowball Earth" → use presence of cap carbonates to support their opposition to theory
- what could cause such an abrupt change in climate?
- how could icy Earth have thawed so quickly when completely covered?
- what possible escape mechanism could reverse freezing of the Earth?

Neopoterozoic cap carbonates

Dolomite caprock, King Island

Dolomite caprock, Namibia

Dolomite caprock, Kimberley region, WA

Recovery mechanism (Kirschvink)

- Effected by rapid buildup of CO_2 → volcanic activity continued unaffected by Earth freezing → continued to produce CO_2
- when CO_2 >10% of atmosphere → greenhouse effect → thaw Earth
- if outgassing rates were similar to today → build up of CO_2 would only take a few million years
- CO_2 removal mechanisms (photosynthesis, precipitation, silicate weathering) all severely suppressed
- photosynthetic activity reduced → most photosynthetic biota would die, also atmosphere decoupled from ocean

Recovery mechanism (Kirschvink)

- Freezing of ocean → inhibits evaporation → arid climate → flushing of atmosphere/silicate weathering would cease
- melting → proceed rapidly with the help of reverse ice-albedo feedback
- surface melt darkens ice → greater absorbance of solar radiation

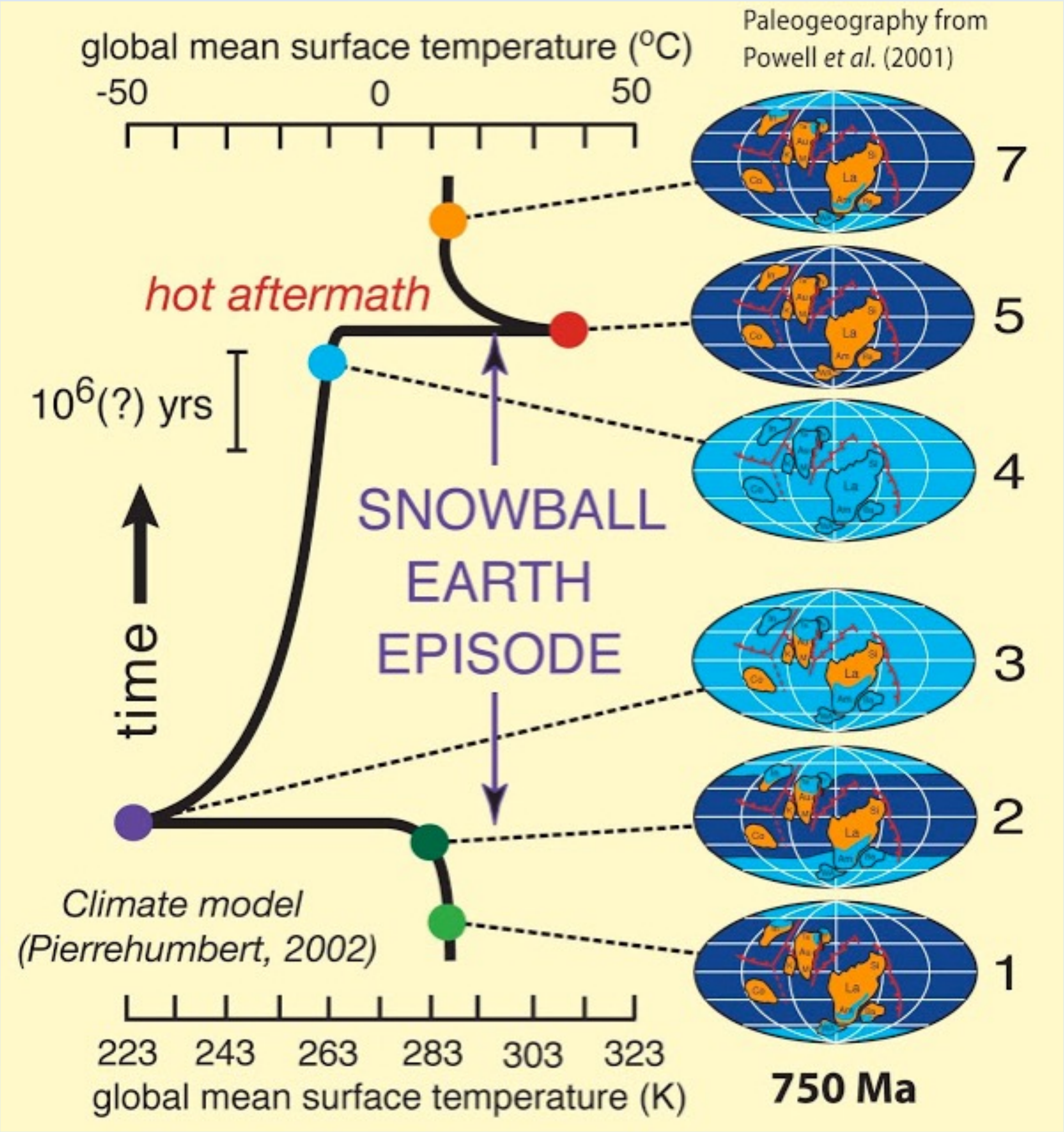
Solar absorption = 90% open water

60% bare ice

30% fresh snow

- once melting starts → evaporation would increase humidity → "super-greenhouse" effect until CO_2 balance restored
- meltdown could occur in as little as 2000years

Global temperatures in Neoproterozoic



Controls on CO_2 balance

- Normally two mechanisms keep atmospheric CO_2 in balance:

  (1) photosynthesis

  (2) dissolving of CO_2 by rainwater

- if the ocean was frozen photosynthesis would largely cease → removing major CO_2 removal mechanism

- freezing of the ocean would severely inhibit evaporation from oceans leading to arid climate → without rain, flushing of CO_2 would cease

- once the tropical ocean begins to open → photosynthesis and increasing rainfall would begin the reduction of atmospheric CO_2

Origin of cap carbonates

- Post "Snowball Earth", Earth's surface heated due to high atmospheric CO_2 increased humidity
- elevated sea temperatures → increased evaporation → torrential rain flushes CO_2 from atmosphere → carbonic acid

$$H_2O + CO_2 \leftarrow \rightarrow H_2CO_3$$

Carbonic acid

- carbonic acid active in weathering rocks → releasing calcium

$$H_2CO_3 + CaSiO_3 \leftarrow\rightarrow CaCO_3 + H_2O + SiO_2$$

calcite

- carbonates form layers atop glacial sediments → cap carbonates
- recent theories involving methane release have proposed alternate origins

How did life survive "Snowball Earth"

- Scientists doubted that eukaryotes would survive a "Snowball Earth"
- evidence → marked decline in diversity of eukaryotes during glaciations
- salinity, high pressure and heat flux → prevented ocean from freezing to sea floor
- hydrothermal-vent and springs biotas could survive if ocean was frozen
- a recent model has predicted a 200km wide equatorial zone where ice thickness ~2metres → would permit light penetration
- ocean circulation and mixing processes → can keep local patches of water open (polynyas) → support phototrophic life
- Psychrophiles (cold-living organisms) discovered in Antarctica thrive at low temperatures (-20°C to +10°C)

How did life survive “Snowball Earth”

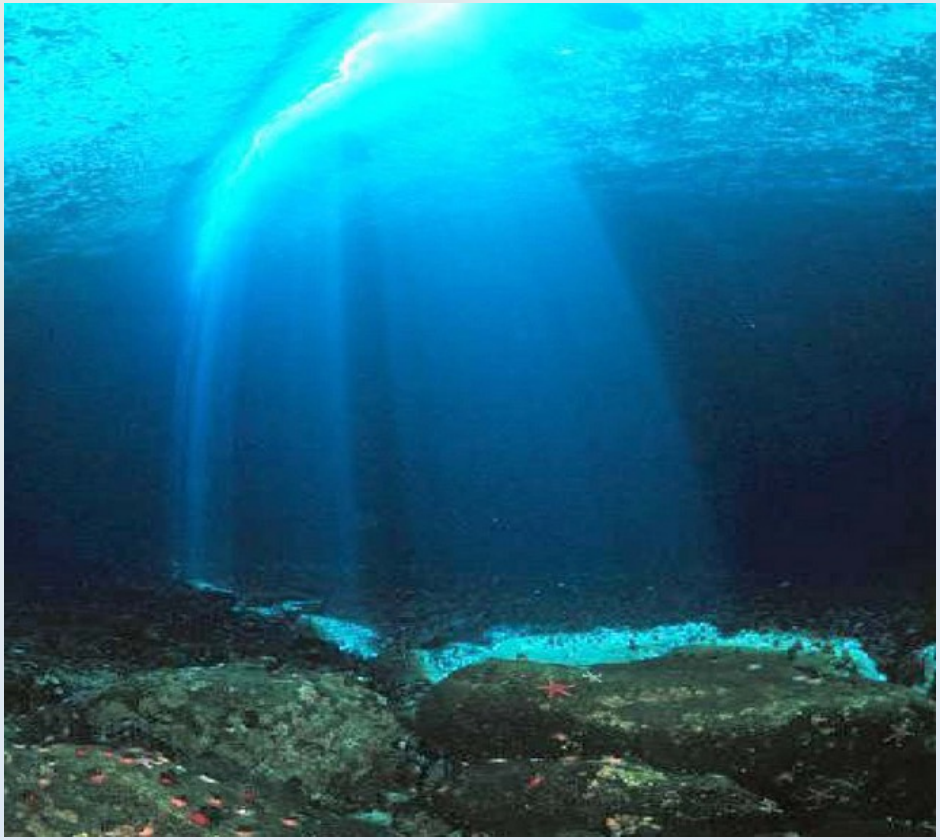
Hydrothermal-vent biota

Polynyas Canadian Arctic

Light penetration through sea ice

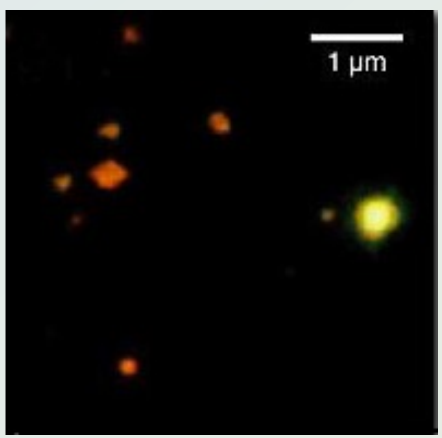
- Light penetration through 2 metres ice thickness

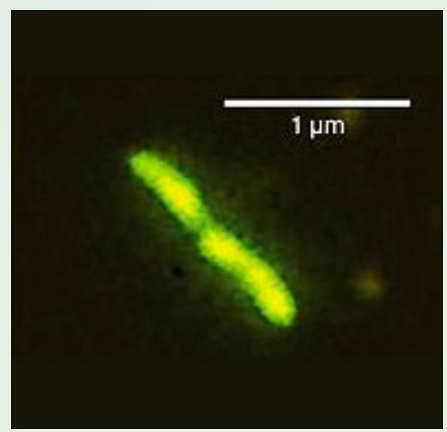
  → sufficient for limited photosynthesis
- light can also penetrate via cracks in ice and polynyas
- ice on land → rigid; sea ice mobile → crack formation



Psychrophiles

- Psychrophiles → micro-organisms capable of growth and reproduction under cold conditions (-20°C to +10°C)
- present in polar ice fields and snow fields
- most psychrophiles are bacteria or archaea
- derive their energy from photosynthesis or chemoautotrophy





Microscopic images of bacteria in ice from Vostok, Antarctica

Arguments against Snowball Earth hypothesis

Most arguments against the "Snowball Earth" hypothesis can be easily rebutted e.g.

(1) Global glacial deposits are probably not the same age everywhere and are no more extensive than for Phanerozoic glaciations
More and more evidence suggests that they are synchronous

(2) The sedimentary character and great thicknesses of Sturtian and Marinoan glacial deposits locally point to fast flowing wet based glaciers that should be absent if the ocean was totally covered in ice and the climate cold and dry.
Up to 90% of total ice drainage from Antarctica is routed through corridors of fast-flowing wet-base glaciers.

(3) Indicators of open water e.g. wave ripples, ice-rafted debris and biomarkers of phototropism are found within Sturtian and Marinoan glacial strata
Most glacial sediments and glacial features form as glaciers retreat when there was open water

(4) Caprocks are invariably dolomites whereas high Ca/Mg ratios in seawater favour the formation of limestones
Dolomites are probably secondary in origin