Snowball Earth:

Jeff Lewis

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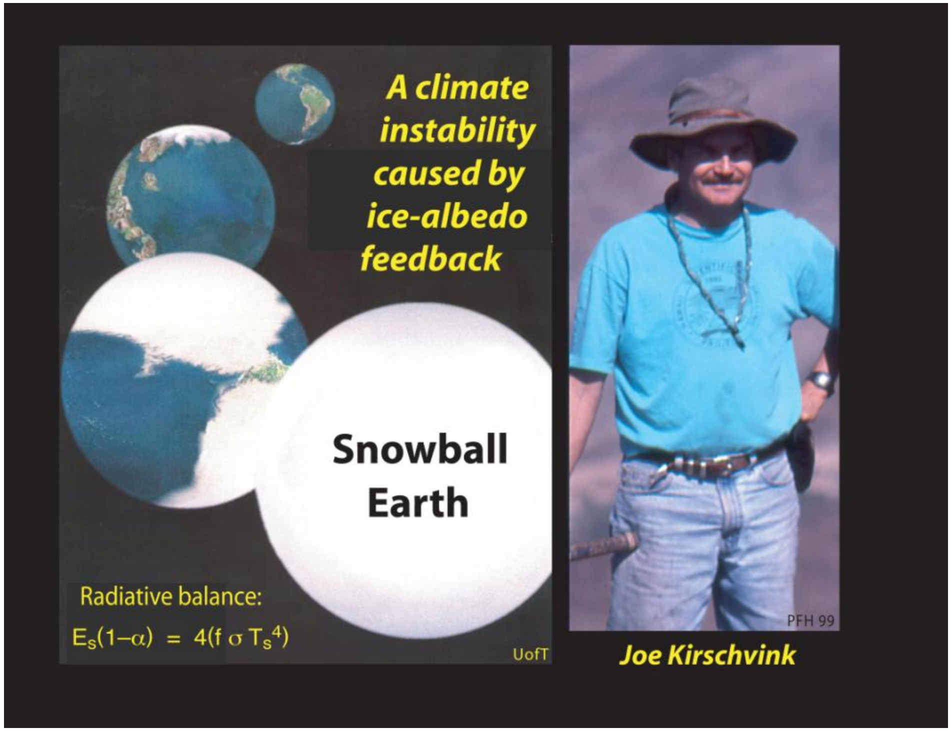
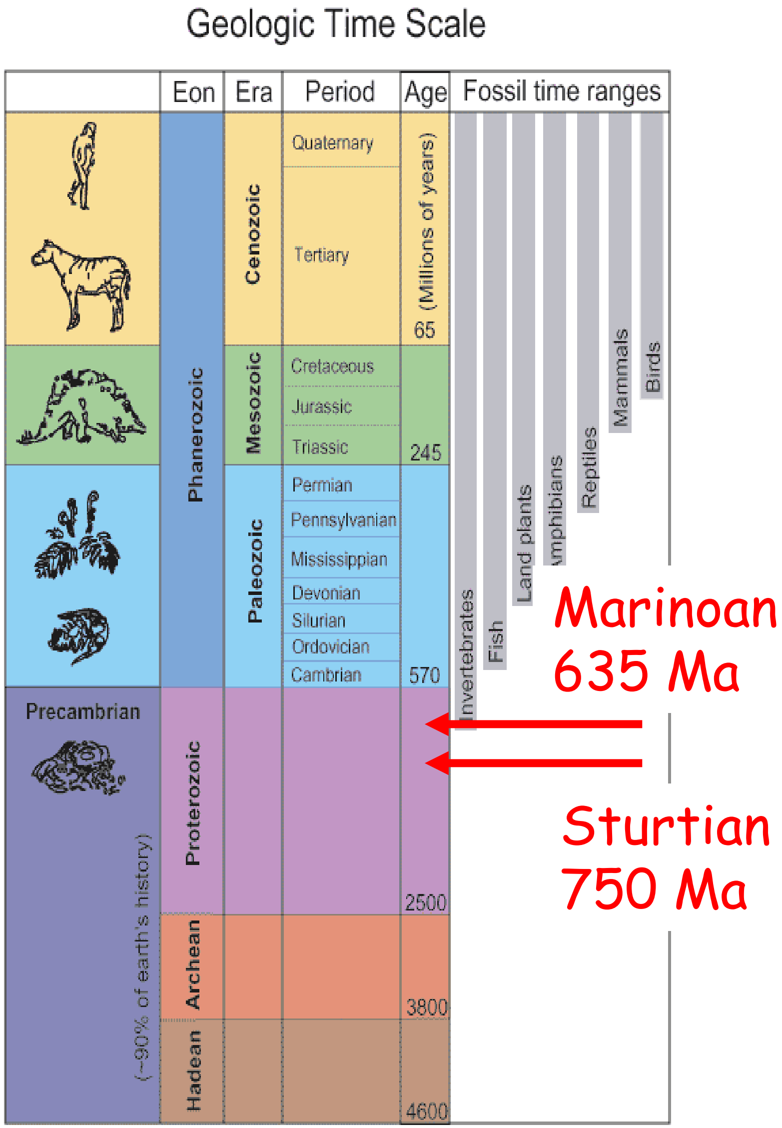
What is the Snowball Earth Theory?

- Entire planet was covered by snow and ice for prolonged periods between 750 Ma and 635 Ma

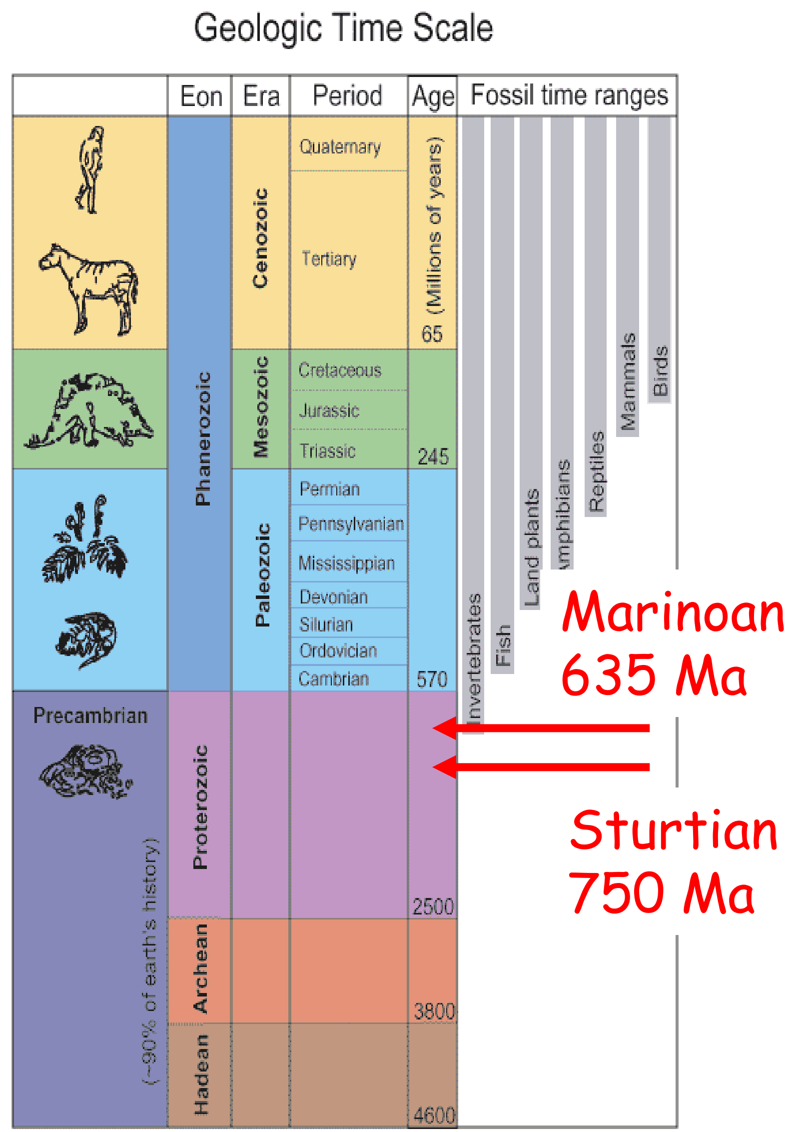




What is the Snowball Earth Theory?

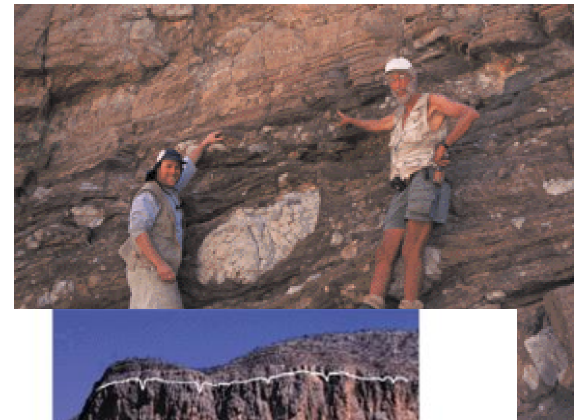
- It was proposed to explain the paradox of tropical glaciation at sea level in the Neoproterozoic

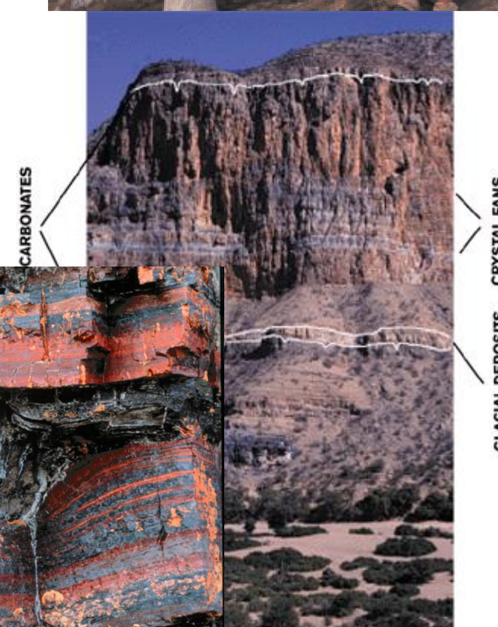
(Hoffman and Schrag 2000)

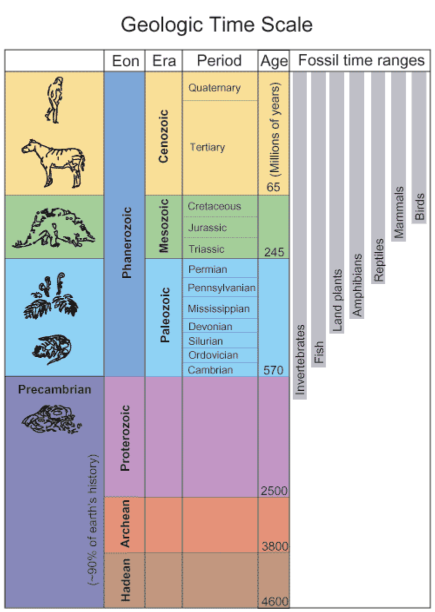


What is the geological evidence?

1. Glacial deposits
2. Cap carbonates
3. Banded iron formations (BIF)
4. Timing of early life

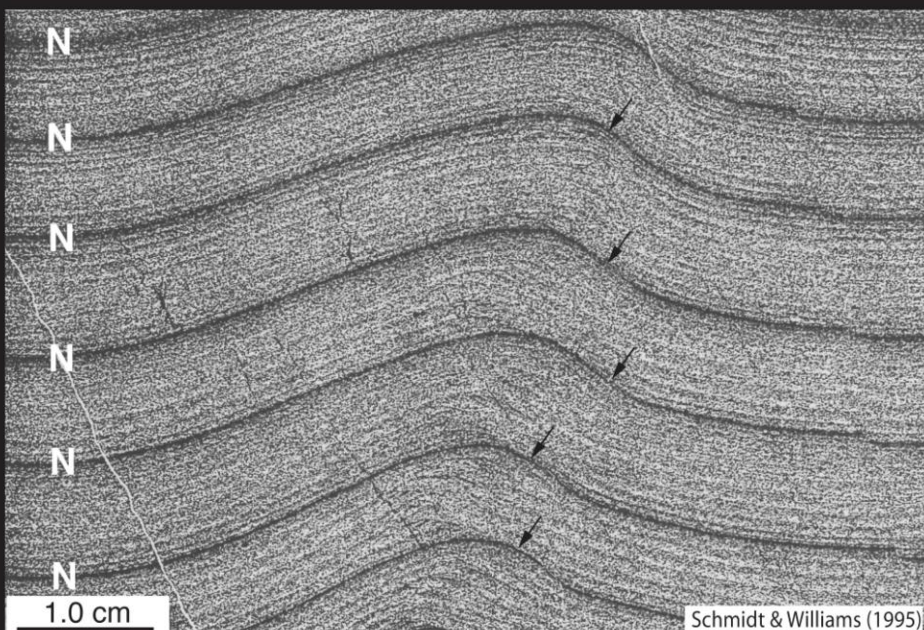




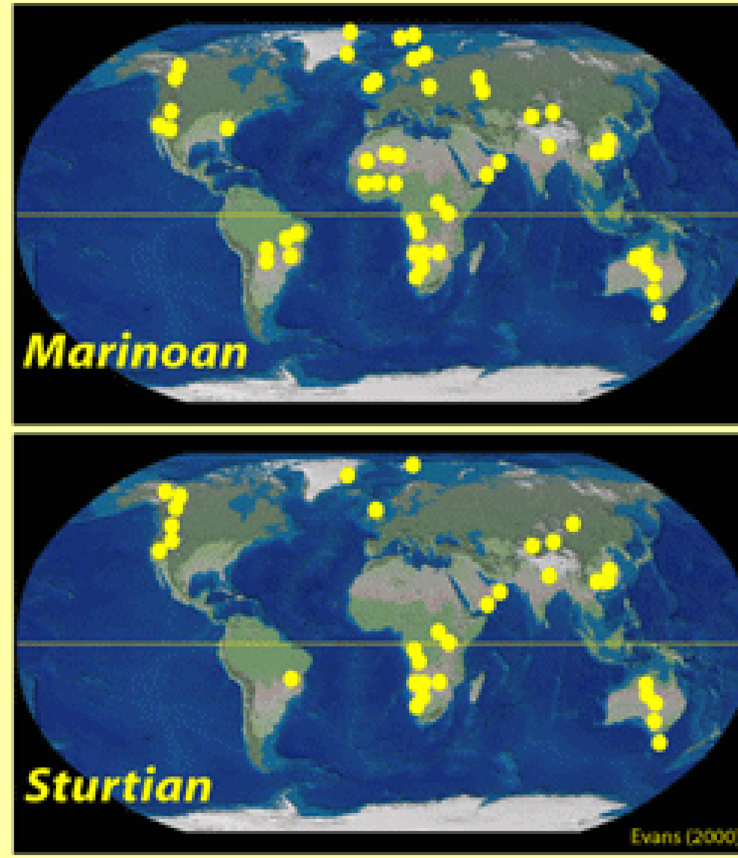


1. Glacial deposits

- Distributed on all continents
- Tidal rhythmites indicate that they formed at sea level



Fortnightly tidal bundles (N, neaps) in Elatina Fm synglacial siltstone, South Australia. Note syn-sedimentary fold with onlapping laminae (arrows). Low-inclination remnant magnetization carried by detrital hematite was acquired as folding progressed.



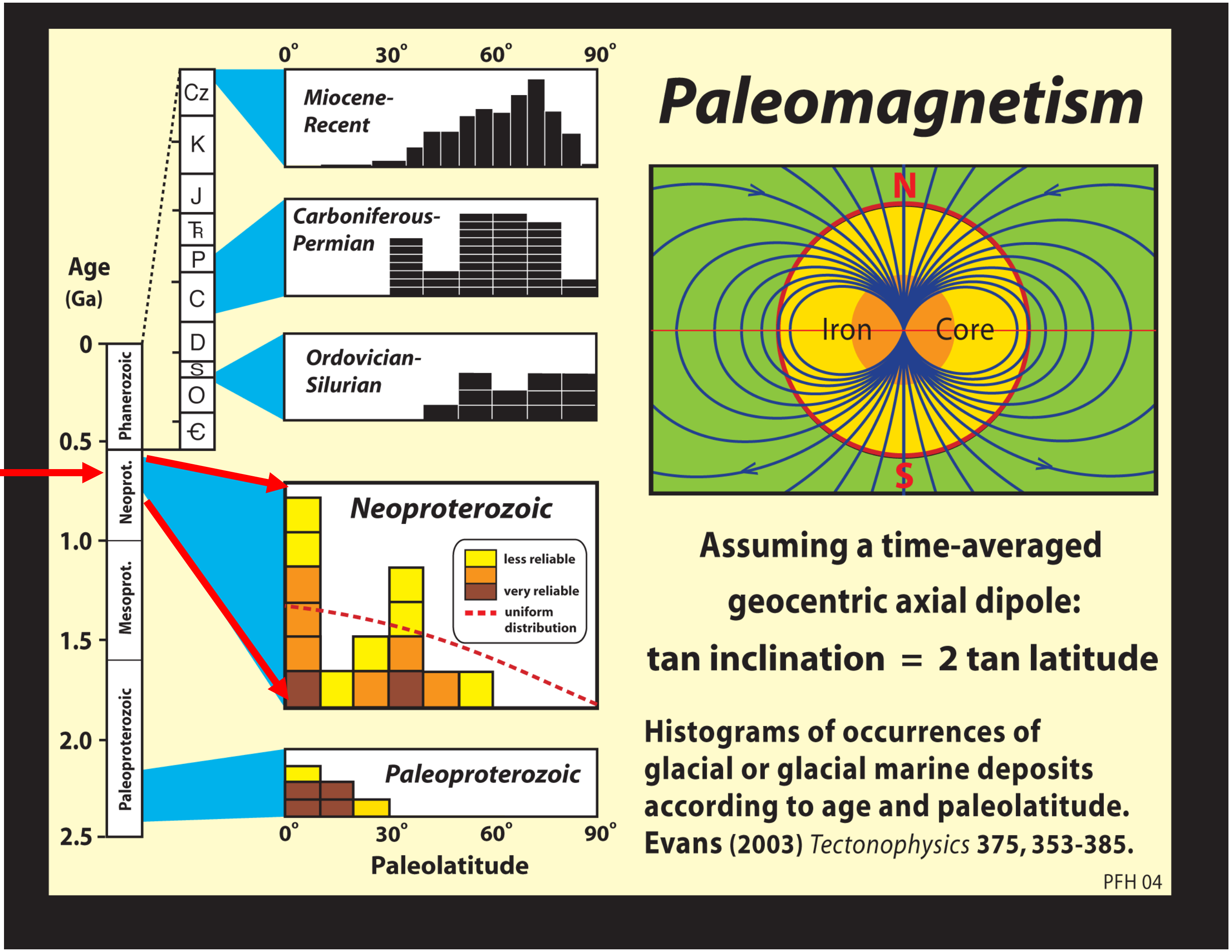
distribution of glacial deposits

(Hoffman and Schrag 2000)

1. Glacial deposits

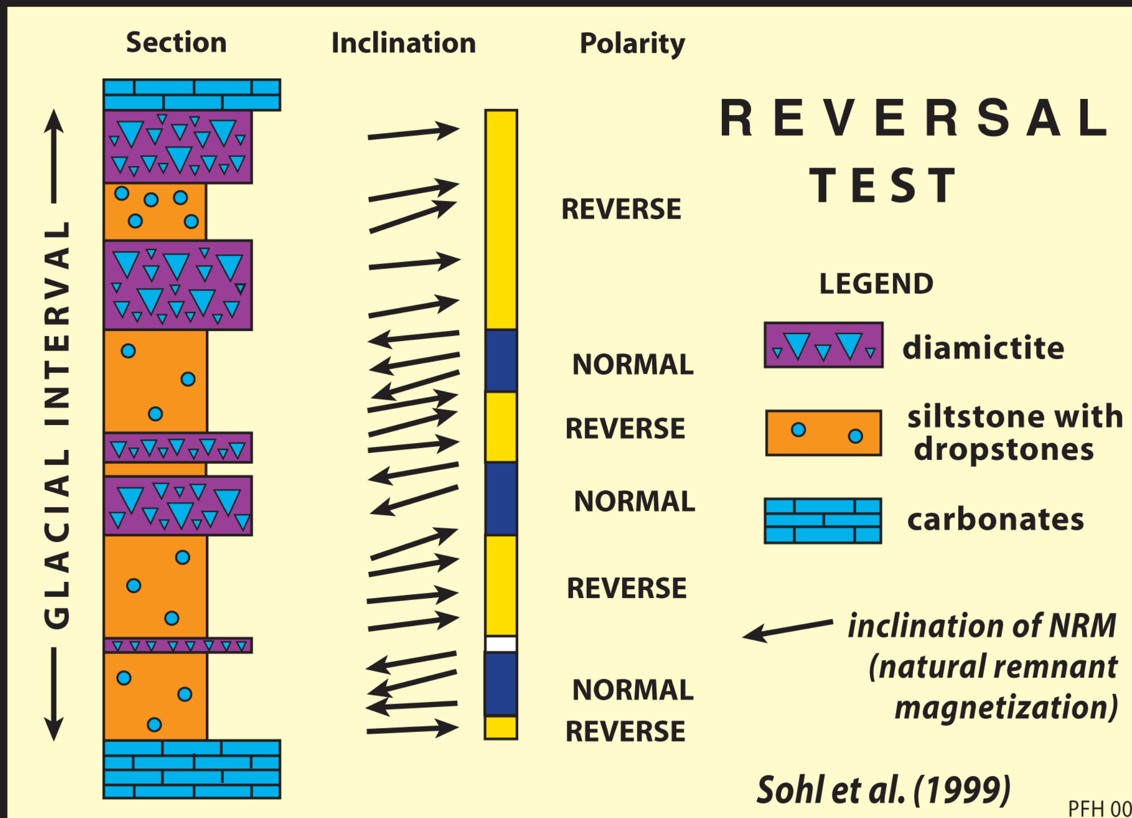
- Paleomagnetic data suggest they formed near the equator, none poleward of 60 degrees

Snowball Earth



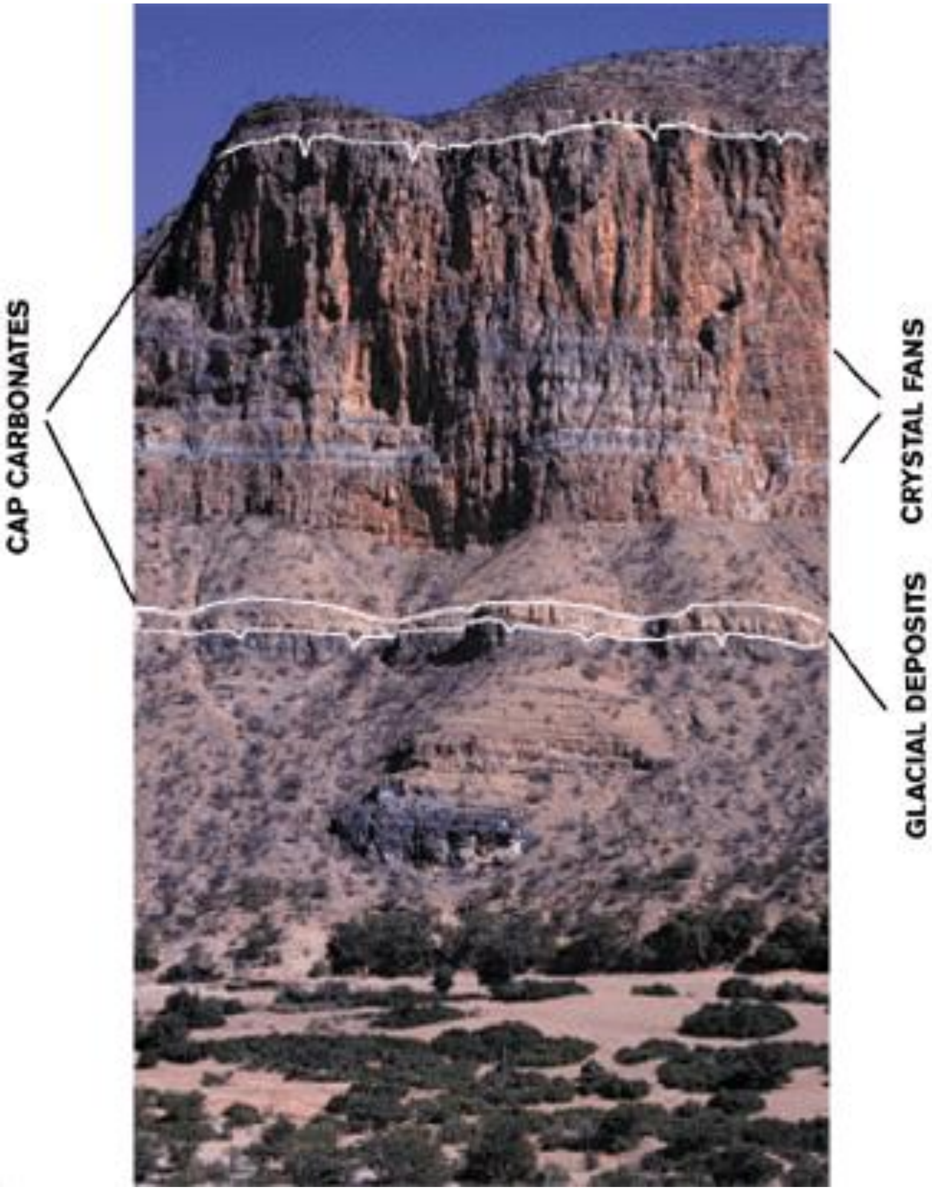
1. Glacial deposits

- Multiple magnetic reversals indicate that glaciation lasted several hundreds of thousands, to a few million years



Principal of the 'reversal test'. Stratigraphically coherent polarity reversals are assumed to represent reversals of the geomagnetic field, contemporaneous with sedimentation. Elatina Fm records up to six polarity reversals.

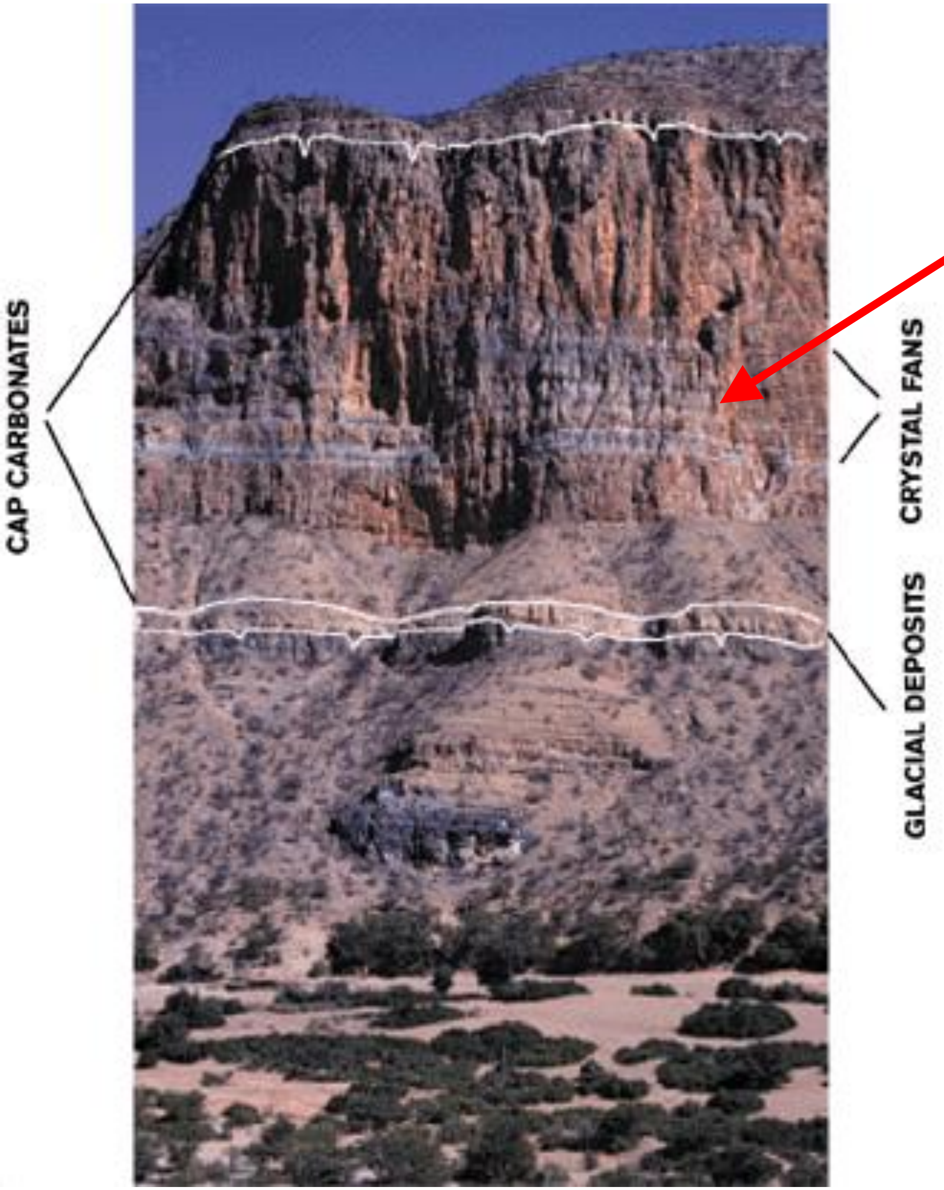
2. Cap carbonates



- Warm water deposit
- Associated with most Neoproterozoic glacial deposits
- Can be hundreds of meters thick

Younger Cryogenian cap-carbonate sequence in the Windermere Supergroup, Shale Lake section, Mackenzie Mtns, NWT, Canada

2. Cap carbonates



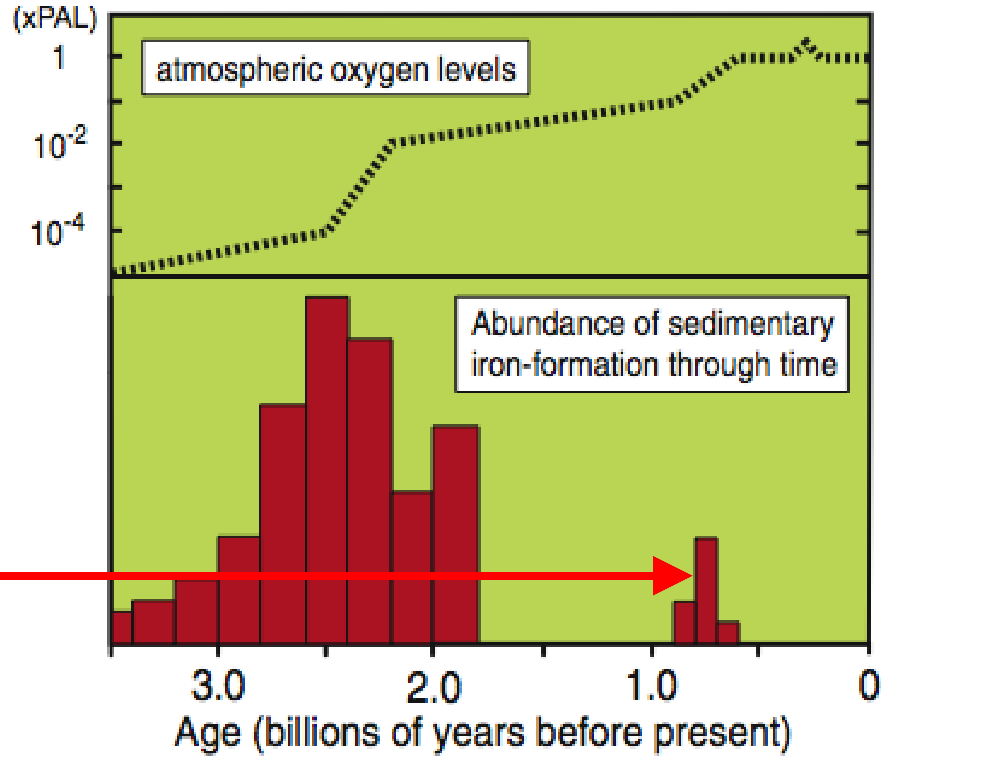
- Aragonite fans indicate rapid deposition under hot temperatures

3. Banded Iron Formation (BIF)

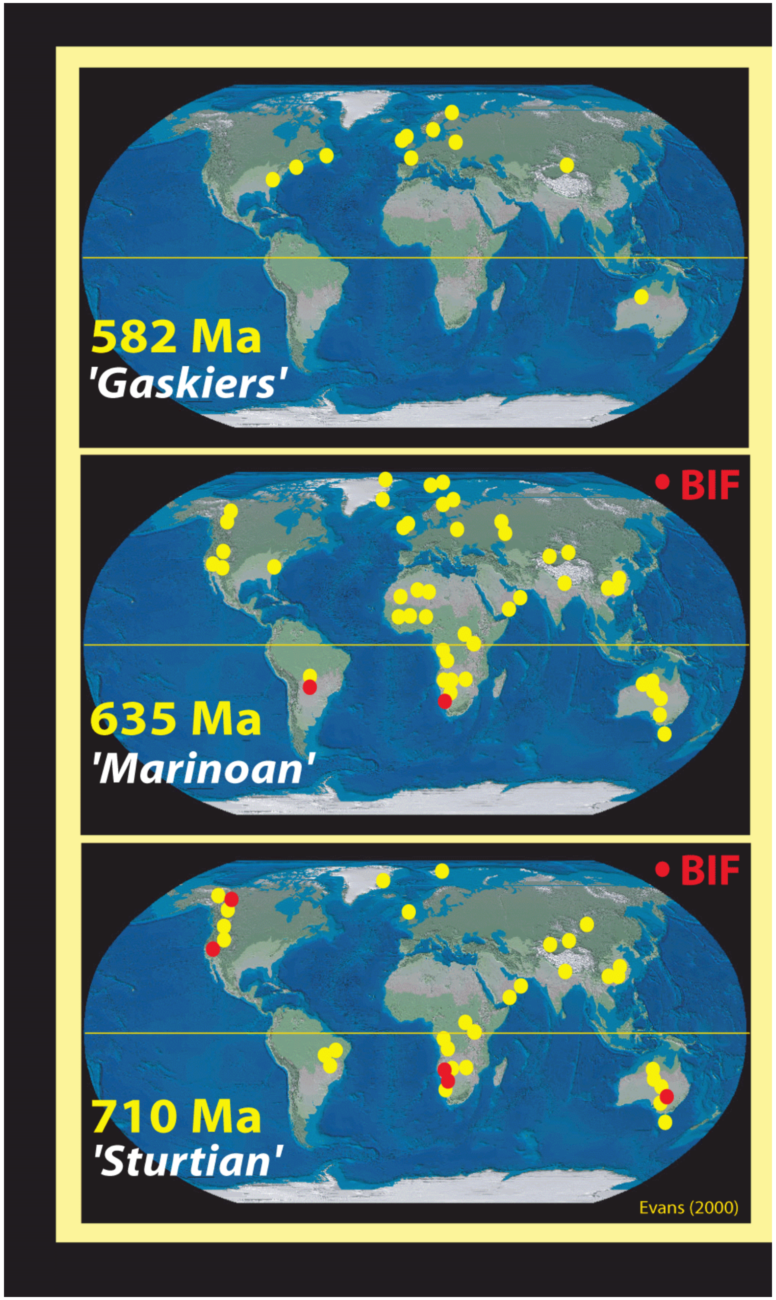
- Absent from the geologic record for a billion years

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.



3. Banded Iron Formation (BIF)



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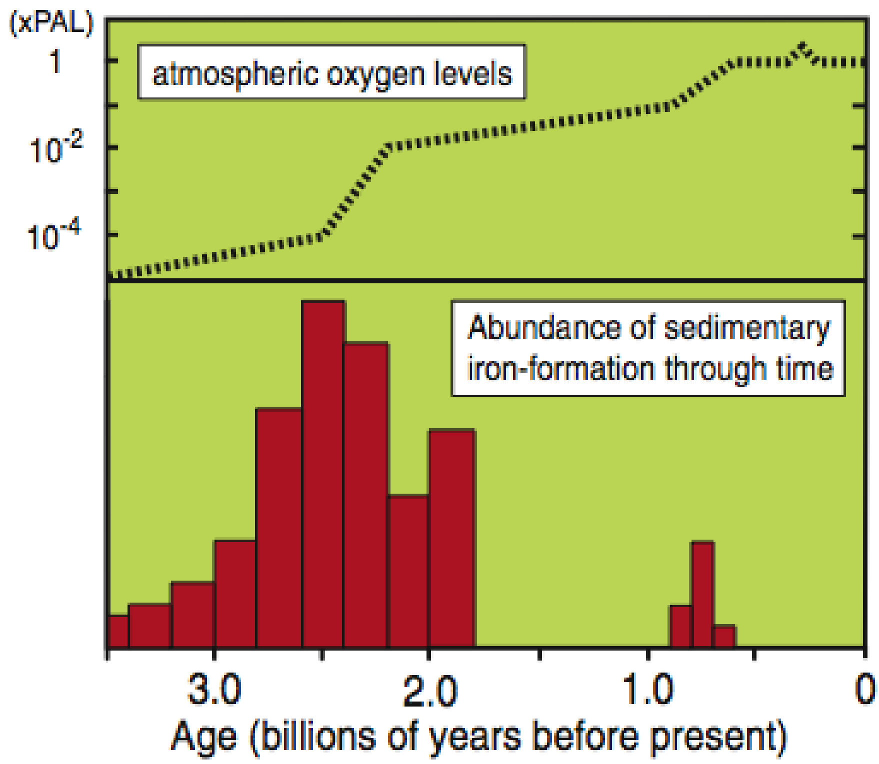
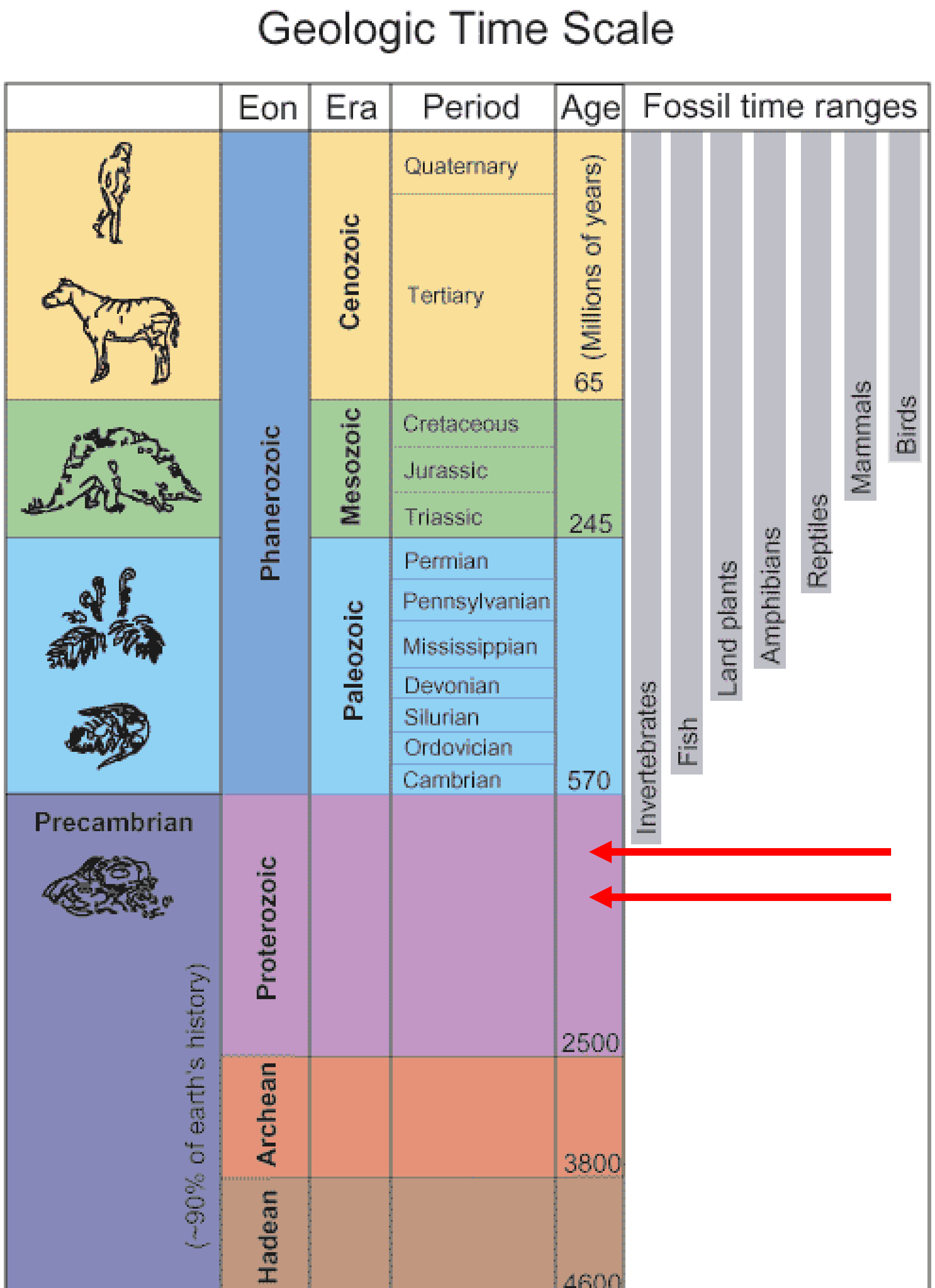


4. Timing of early life



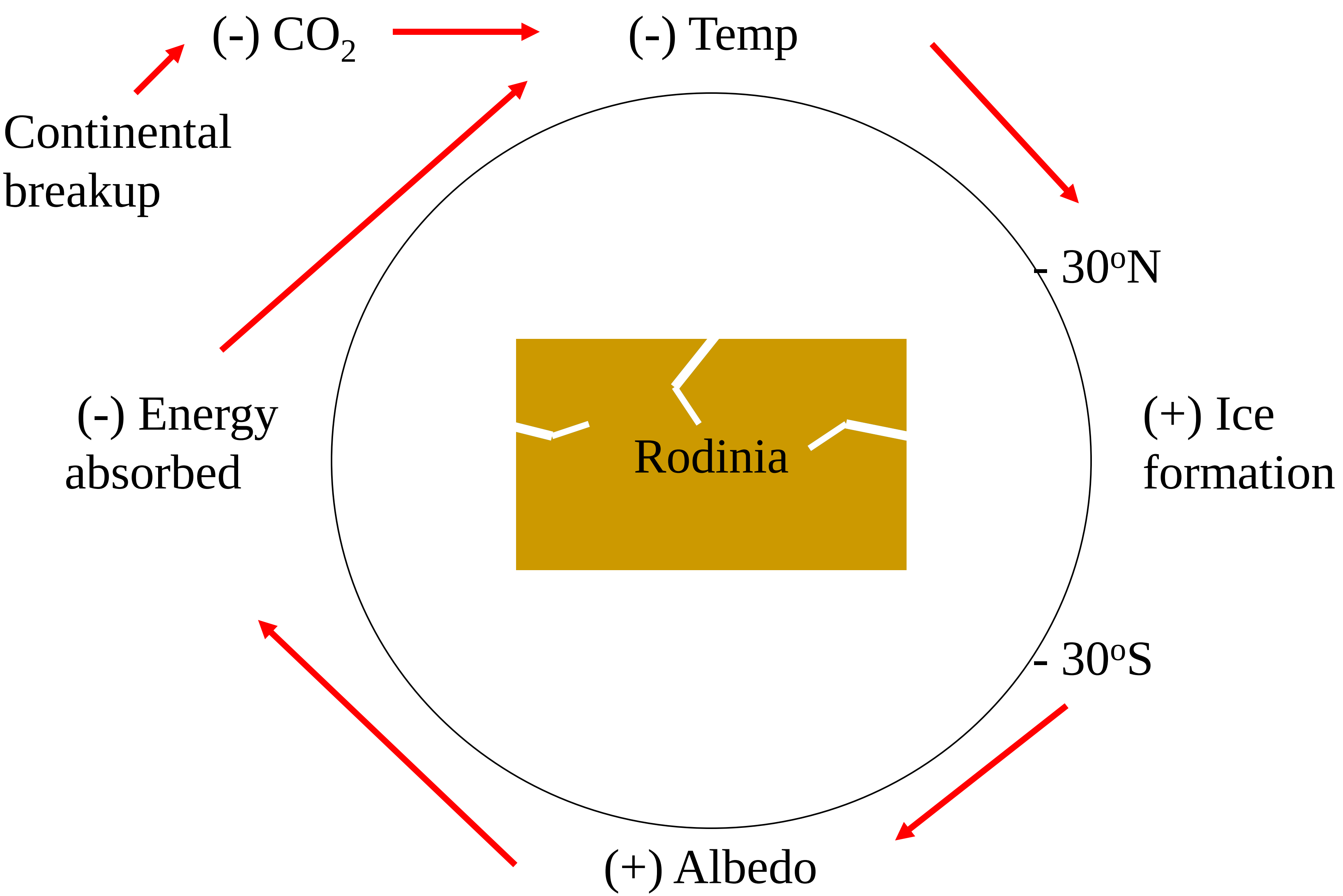
- DNA calculations put the beginning of multicellular life near the end of the Snowball period

Snowball Earth

~750-635 Ma

Mechanism: runaway icehouse

as advocated by Paul Hoffman



Runaway icehouse

as advocated by Paul Hoffman

How to get out of the snowball?

Runaway icehouse

as advocated by Paul Hoffman

How to get out of the snowball?

- The atmosphere is cut off from the ocean (no drawdown of CO_2)
- Volcanic outgassing of CO_2 accumulates in the atmosphere
- It would take ~ 10 million years to overcome the ice house
- Would need roughly 350 times present CO_2 levels (~0.12 bar)

What are the strengths and weaknesses of the Snowball Earth Theory?

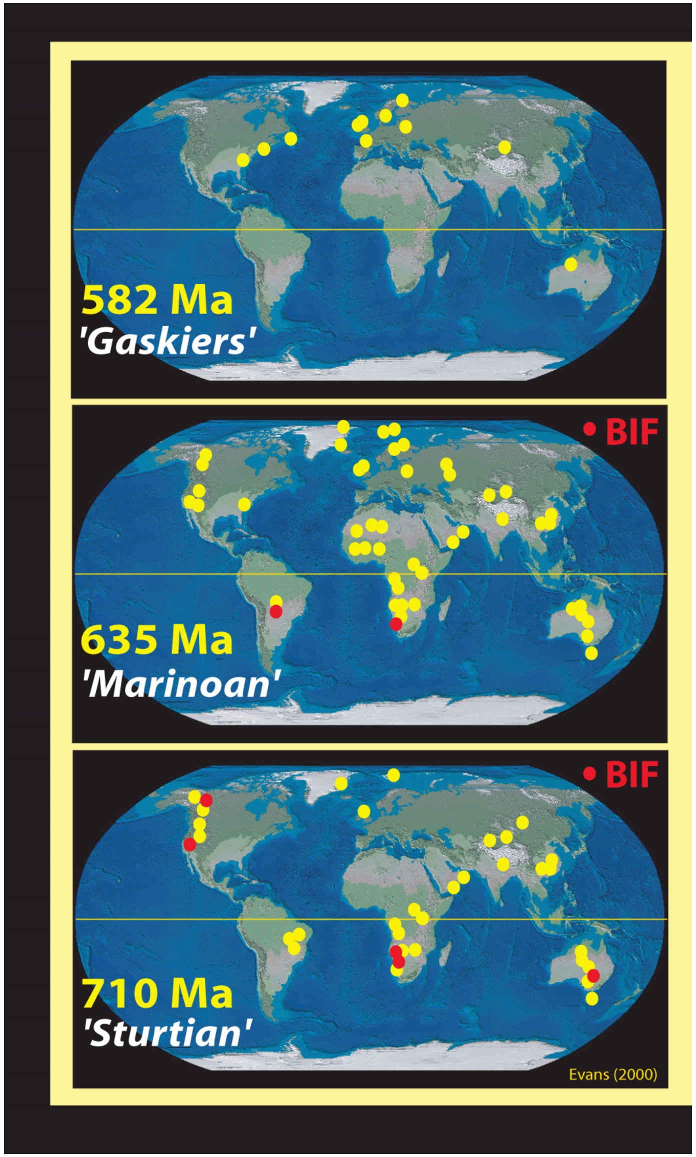
1. Glacial deposits

Strengths

(Hoffman and Schrag 2000)

- Glaciation on all continents
- Glaciation at sea level
- Glaciation near the equator
- The glaciations could have lasted for up to 10 million years

1. Glacial deposits



Weaknesses

Gaskiers

- Glaciation is not global

Marinoan

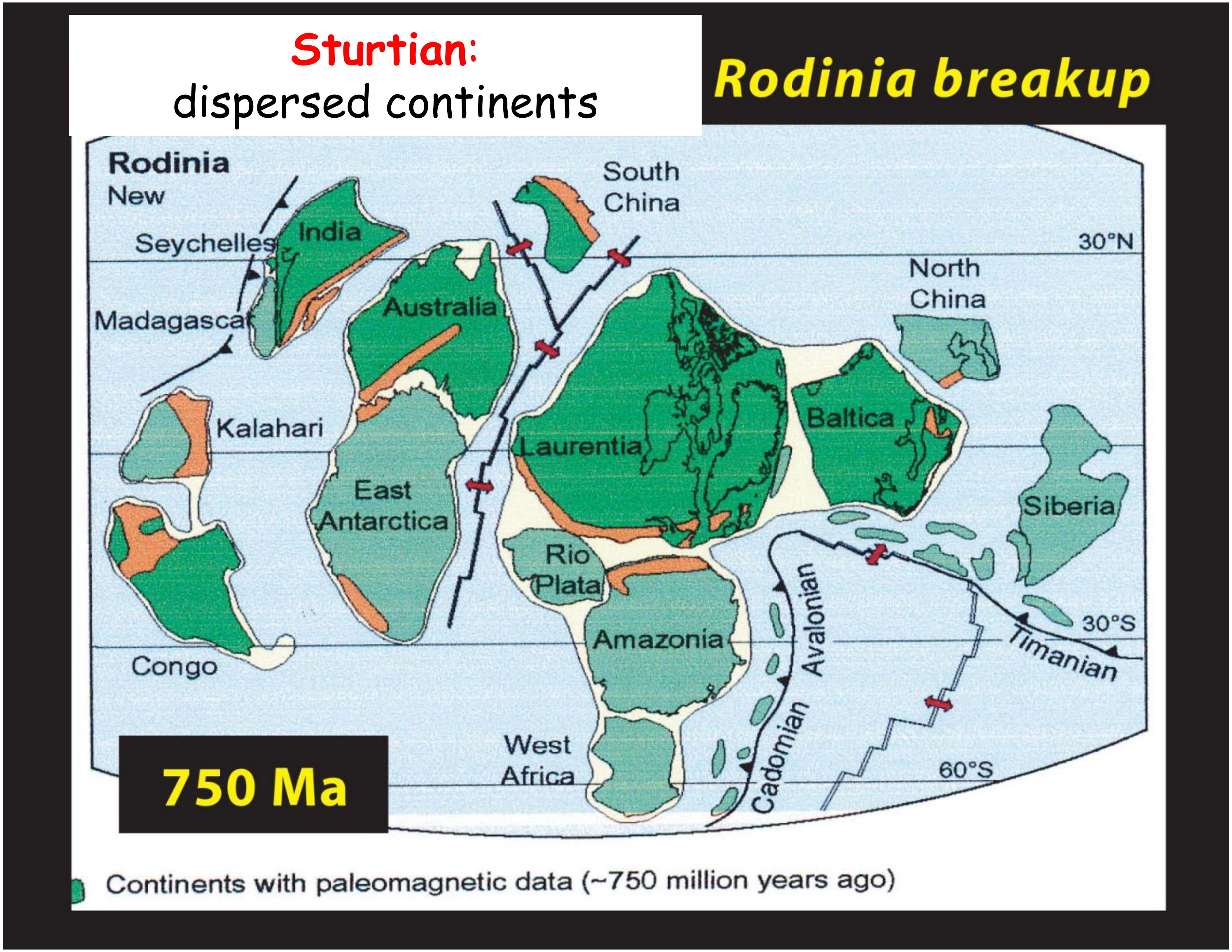
- Glaciation is global and synchronous

Sturtian

- Glaciation is global but not synchronous

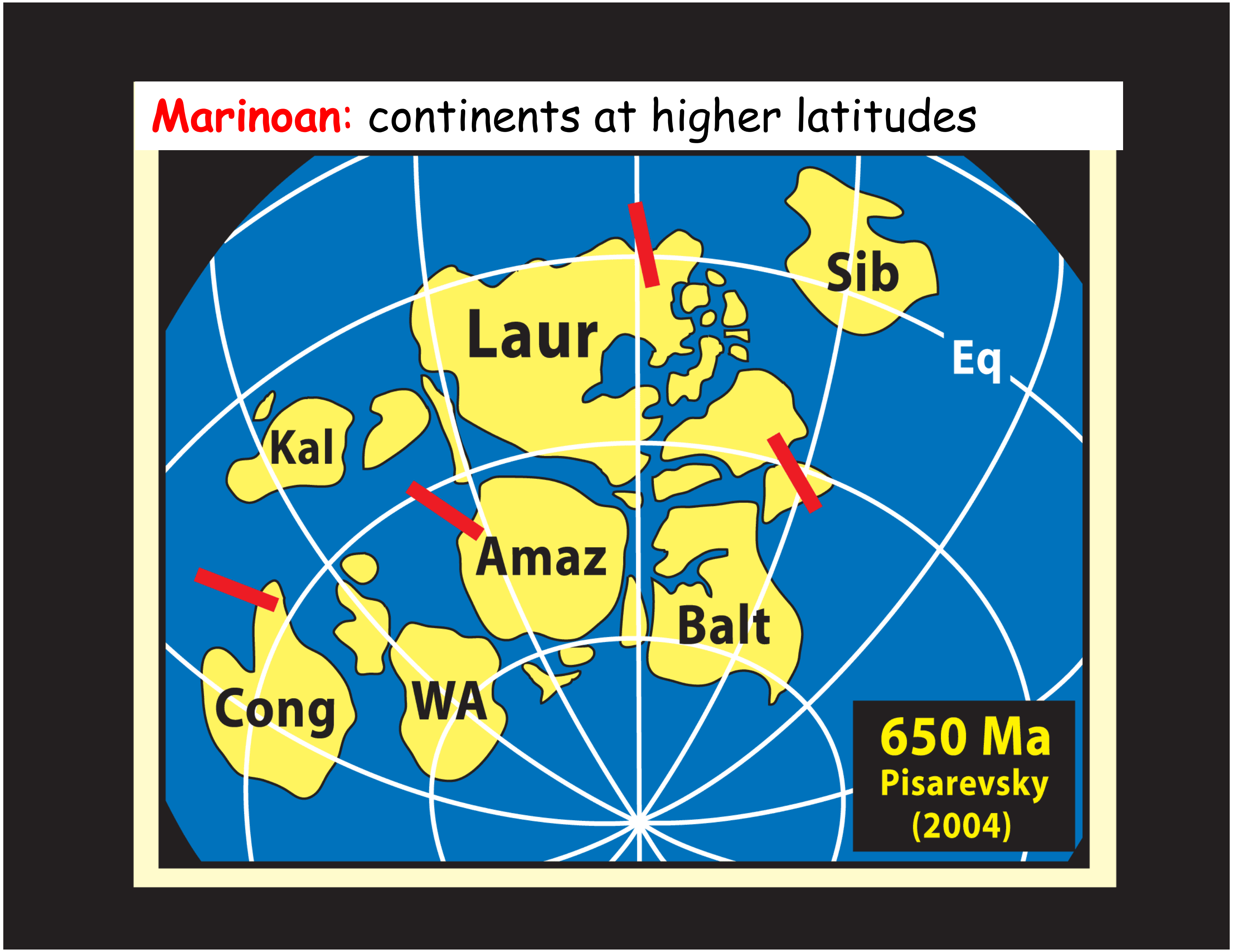
1. Glacial deposits

Weaknesses

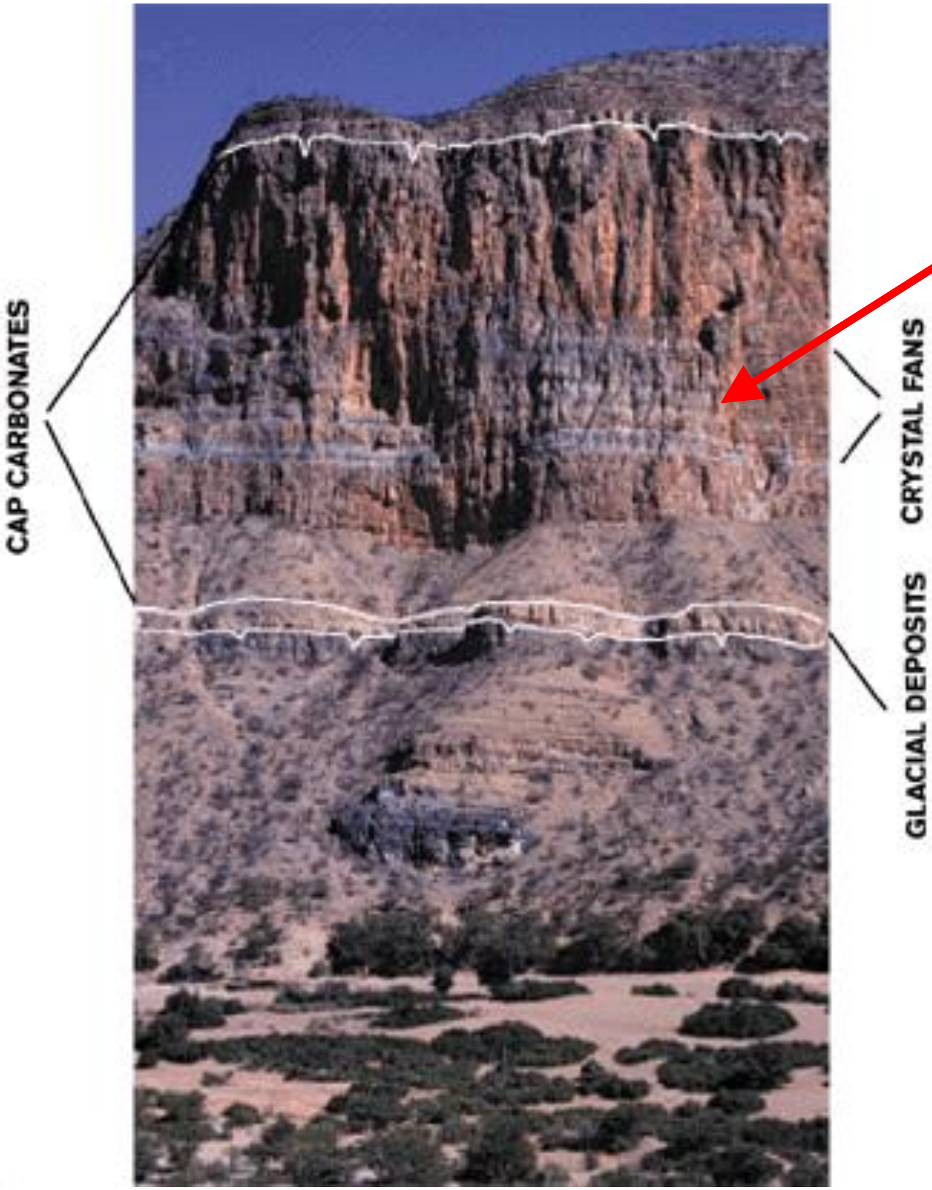


1. Glacial deposits

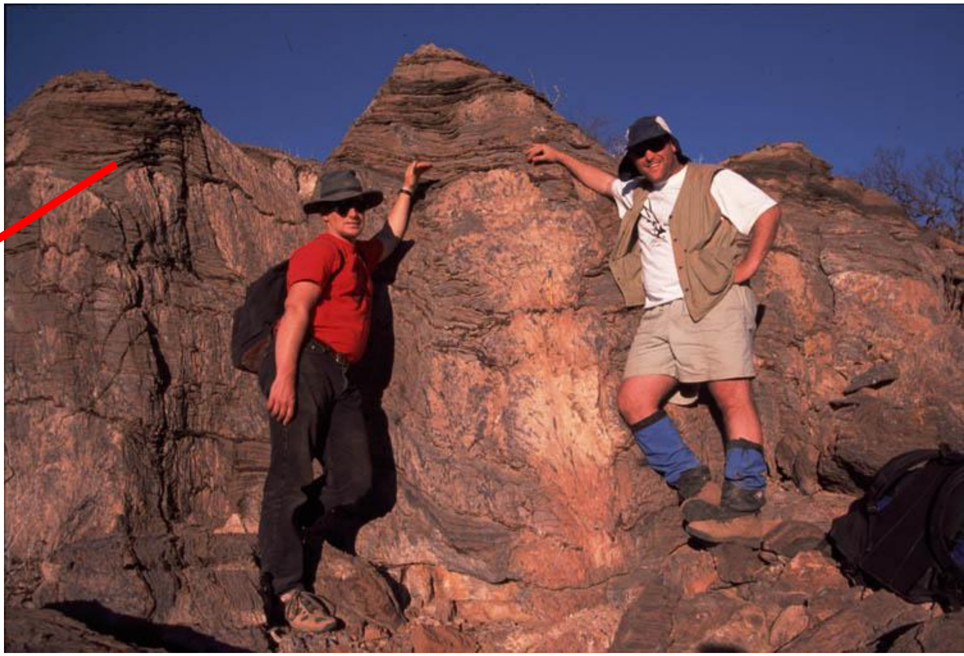
Weaknesses



2. Cap carbonates



Strengths



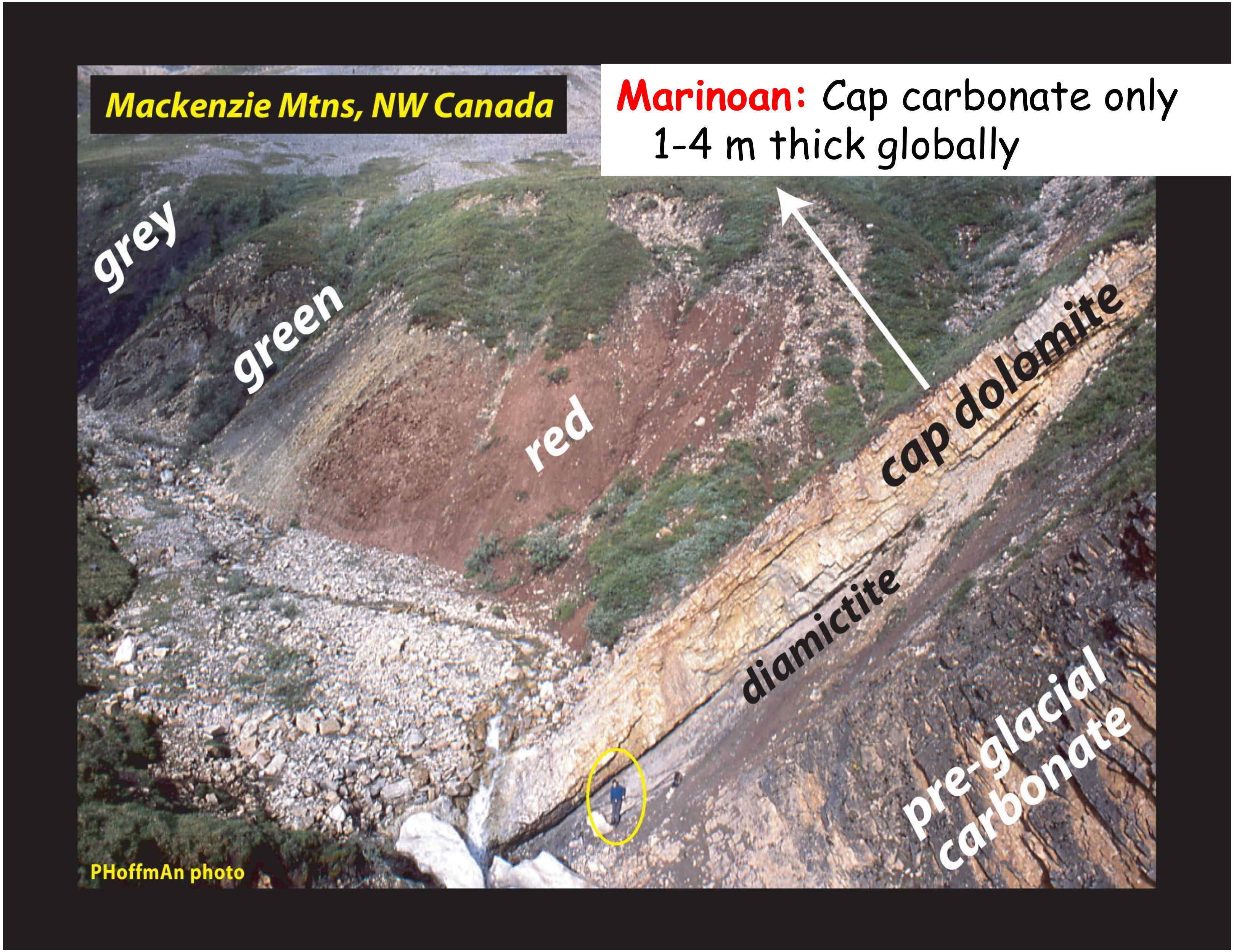
- An atmosphere super saturated with CO_2 would lead directly to rapid deposition of carbonate

$$Ca^{2+} + 2HCO_3^- \leftrightarrow CaCO_3 + CO_2 + H_2O$$

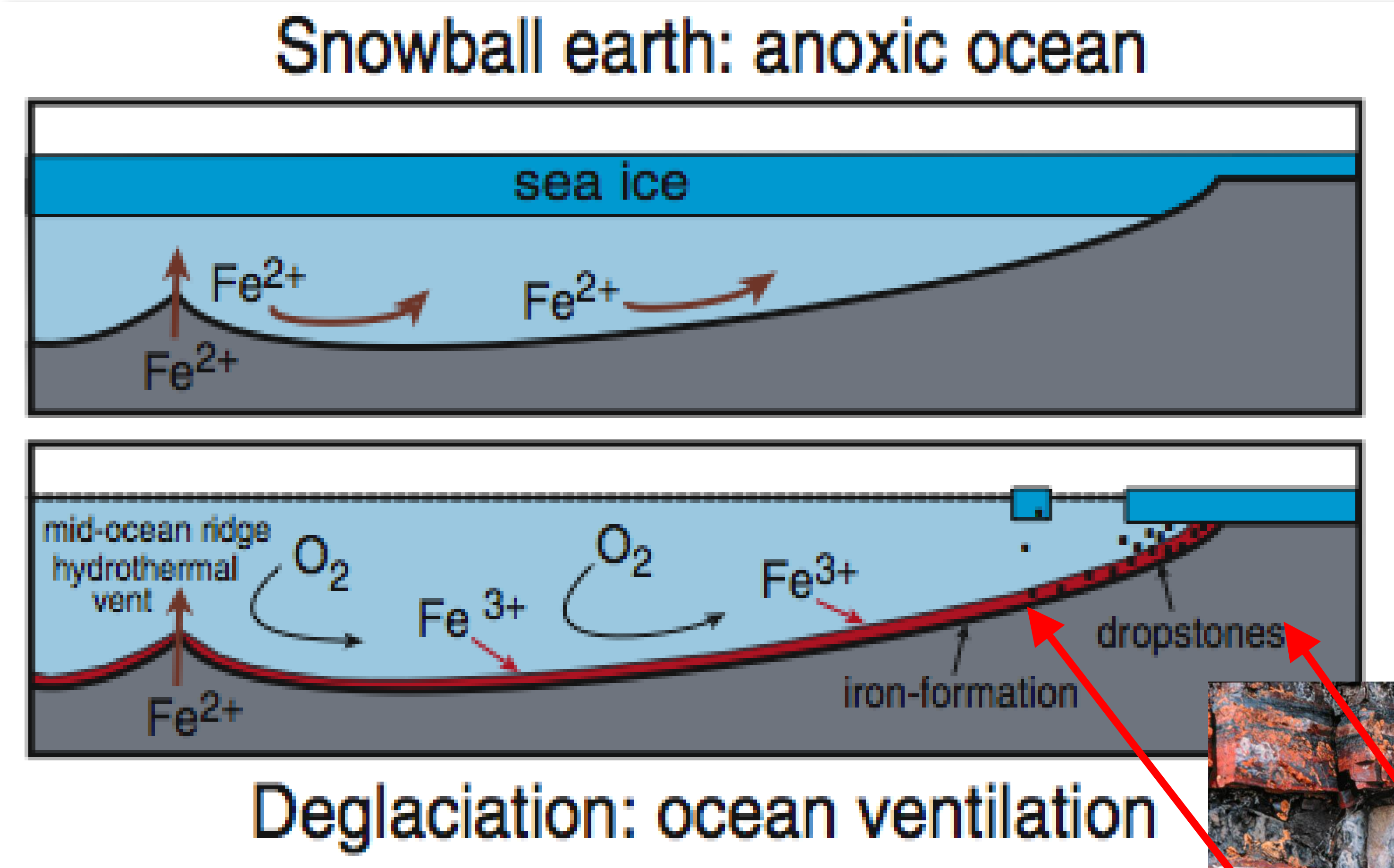
2. Cap carbonates

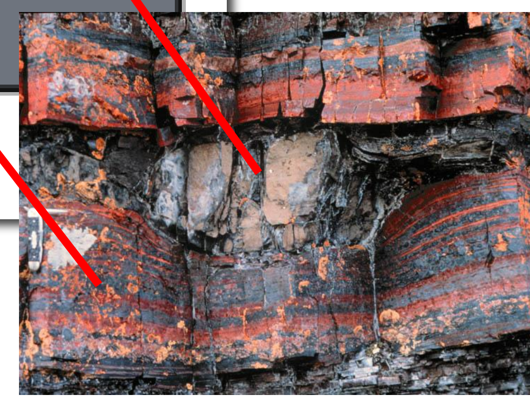
Weaknesses

Marinoan: Cap carbonate only 1-4 m thick globally



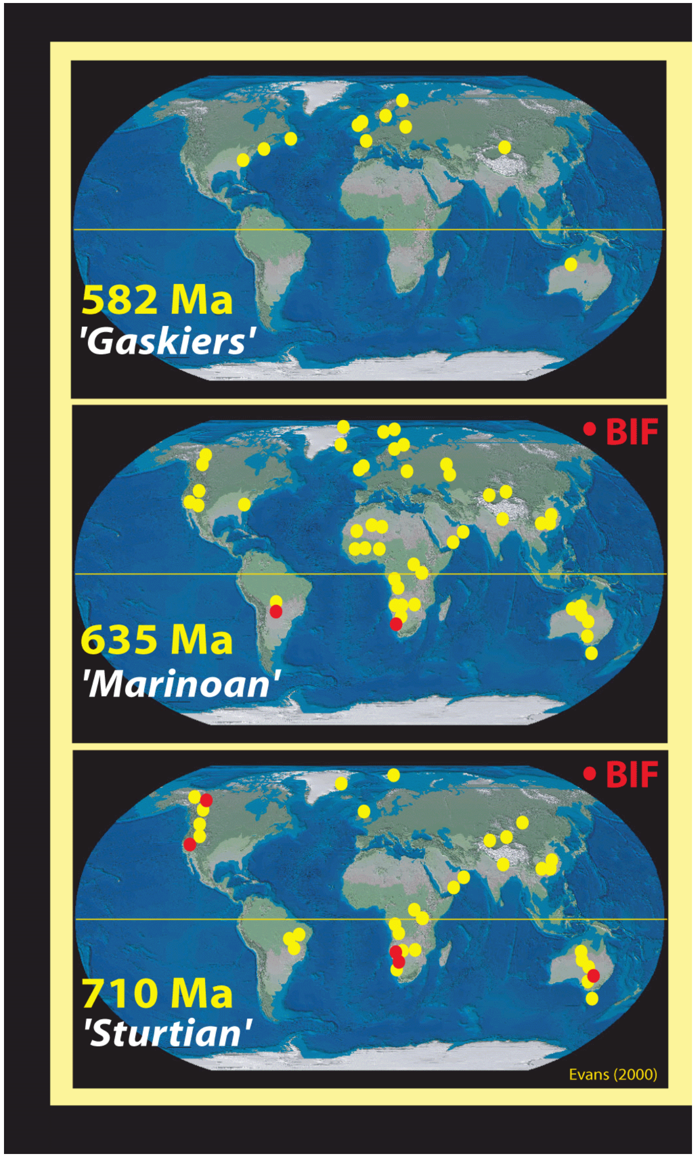
3. Banded Iron Formation (BIF) <u>Strengths</u>





- an anoxic ocean in contact with the atmosphere would precipitate iron to form the BIFs

3. Banded Iron Formation (BIF) Weaknesses

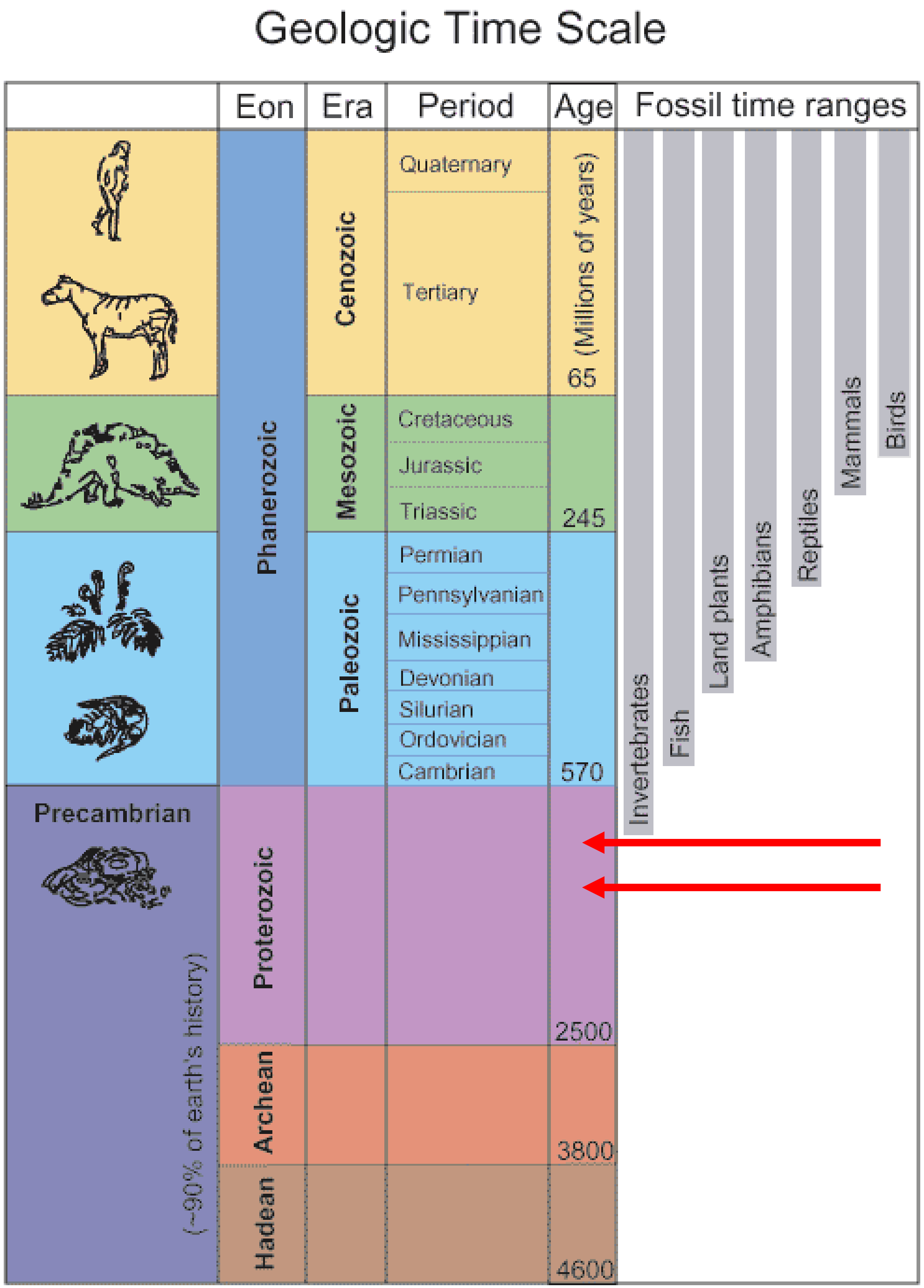


Gaskiers
- No BIFs

Marinoan
- Very few BIFs

Sturtian
- BIFs

4. Timing of early life



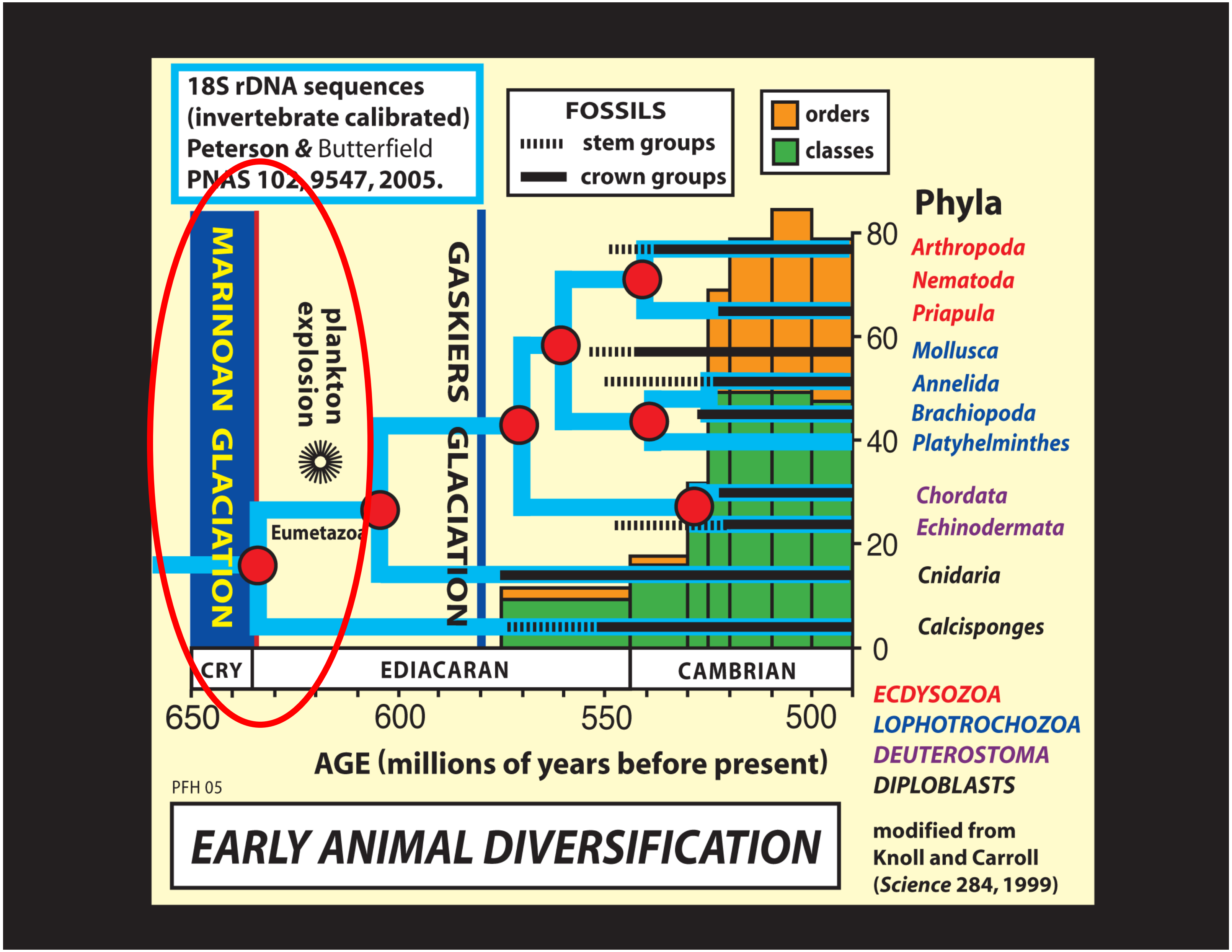
Strengths

- After Snowball Earth there would be new habitats for life to radiate into

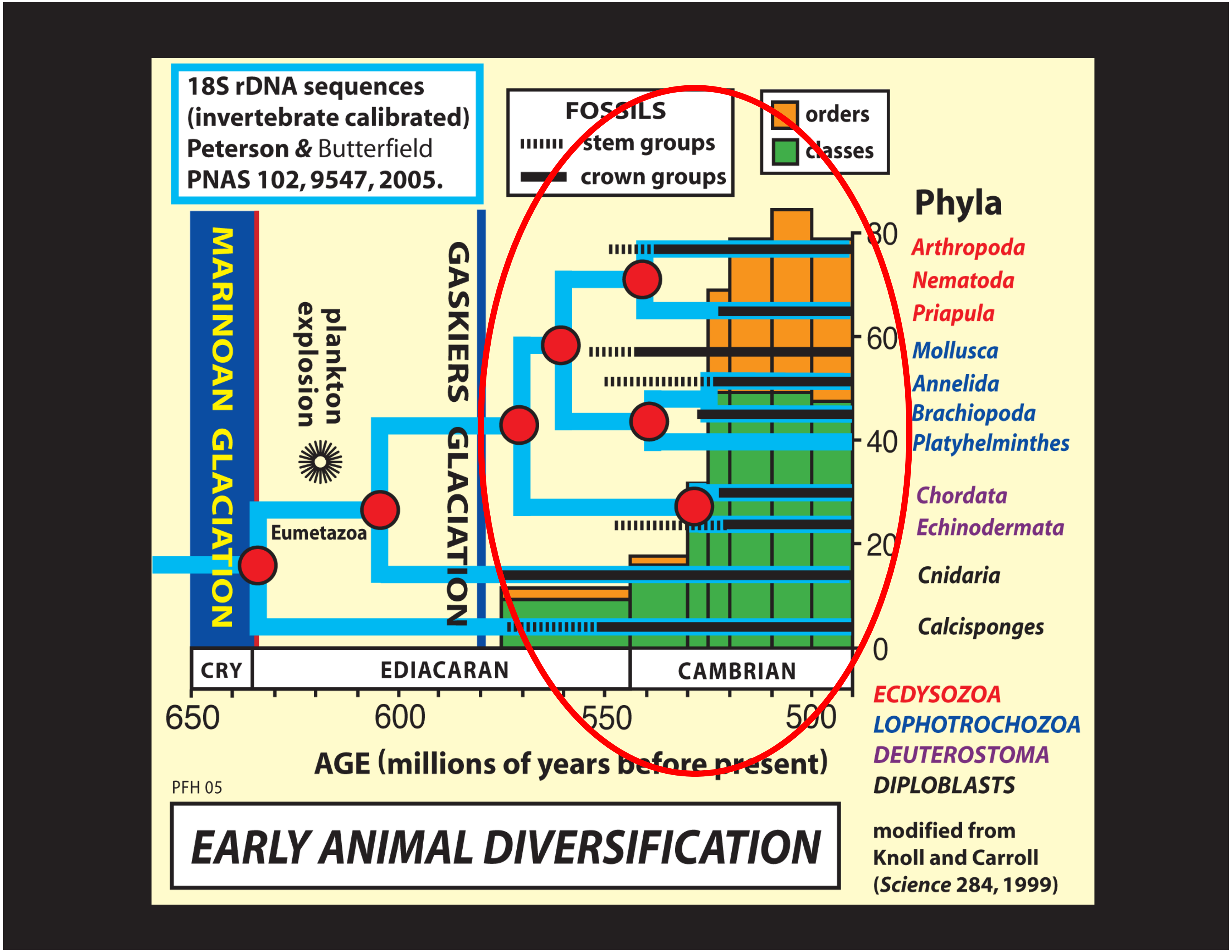
Snowball Earth

~750-635 Ma

Strengths   4. Timing of early life



Weaknesses 4. Timing of early life



Weaknesses 4. Timing of early life

How could photosynthetic life survive globally ice covered oceans?

Conclusions

Possibly two Snowball Earth episodes (750 Ma and 635 Ma)

Sturtian (750 Ma)	Marinoan (635 Ma)
Equatorial glacial deposits	Equatorial glacial deposits
Equatorial continents	Higher latitude continent
Thick cap carbonates	Thin cap carbonates
Many BIFs	Very few BIFs
Glaciation not synchronous	Glaciation is synchronous

Weakness of Snowball Earth: photosynthetic life

Strength of Snowball Earth: a single mechanism can explain many anomalous deposits


For more information:
snowballearth.org

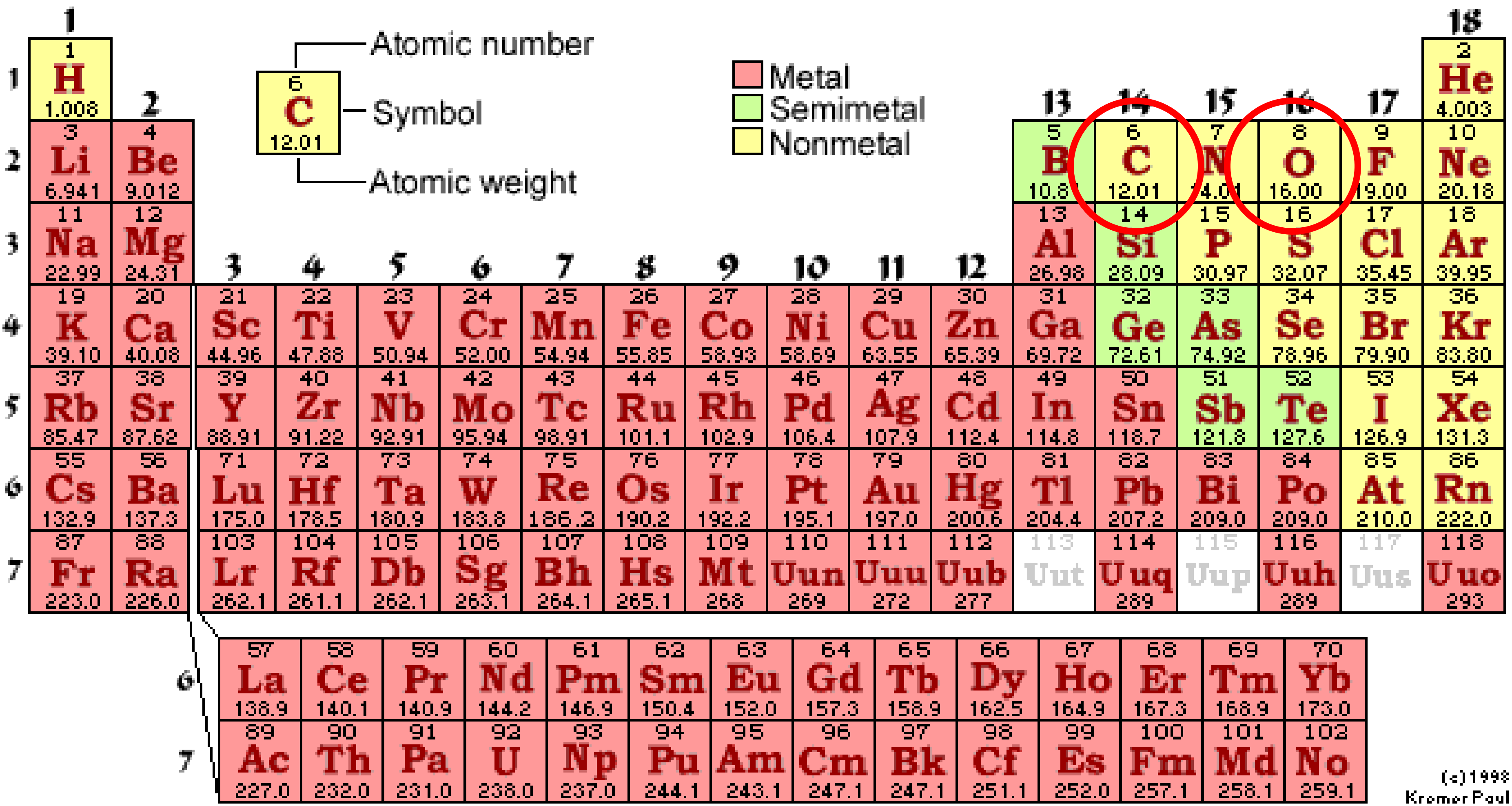
How do we know how long the Snowball Earth events lasted?

From simple models, it was calculated that 0.12 Bar (or 120,000 ppm) of CO_2 would be required to melt a completely ice covered Earth.

The present rate of volcanic outgassing of CO_2 ranges between:
2.7×10^{12} mol/y to 5.4×10^{12} mol/y

How do we change mol/y into something more useful?

CO_2 = 1 C atom (12 g/mol) and 2 O atoms (2x16 g/mol) = 44 g/mol



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So 2.7×10^{12} mol/y times 44 g/mol = 1.19×10^{14} g/y

This is also the equivalent of 1.19×10^{11} kg/y or 0.119 Gt/y

Lets consider the current level of CO_2 in the atmosphere

(10^6 kg) Megatonne Mt = (10^{12} kg) Teragram Tg
(10^9 kg) Gigatonne Gt = (10^{15} kg) Petagram Pg

How do we convert Gigatonnes of CO_2 into ppm or visa versa?

First, what does ppm mean?
ppm is parts per million (and usually per volume)

Consider today's atmospheric concentration of CO_2=385 ppm (and rising)

We can convert this volume mixing ratio to the total mass of CO_2 in the atmosphere by multiplying this number by the mass of the atmosphere weighted by the relative mass of CO_2 atoms compared to air molecules (to simplify we assume that air is composed of 80% N_2 and 20% O_2):

We next need to calculate the mass of the atmosphere.

How do we calculate the mass of the atmosphere?

Pressure is Force per Area: $P = F / A$
and Force is Mass times acceleration: $F = m \times g$

So… we can rearrange the equations to solve for mass:

$m = (P \times A)/g$ Area of a sphere (A) = $4 \times \pi \times r^2$

Where: global average surface pressure (P) = 100000 Pa (1000 hPa or mb)
the radius of the Earth (r) = 6370 km (6.37×10^6 m)
the force of gravity (g) = 9.8 m/s^2

So the mass of the atmosphere is:

$m = (100000\ Pa)(4)(3.14)(6370000\ m)^2/9.8\ m/s^2$
$= 5.2\times10^{18}$ kg

How do we convert ppm to Gt?

Now we can convert this volume mixing ratio to the total mass of CO_2 in the atmosphere by multiplying this number by the mass of the atmosphere weighted by the relative mass of CO_2 atoms compared to air molecules (for simplification we assume that air is composed of 80% N_2 (28 g/mol) and 20% 32 g/mol) O_2):

$(385\times10^{-6}) \times 44/(0.8\times28 + 0.2\times32) \times 5.2\times10^{18}$ kg= 3059×10^{12} kgCO_2
= 3059 Gt CO_2

Where:
44 g/mol is the mass of a unit of carbon
28 g/mol is the mass of N_2
32 g/mol is the mass of O_2

(To get the mass of Carbon, divide by 44 and multiply by 12 = 834 Gt C)

So to simplify everything, to convert 385 ppm to Gt CO_2, multiply by 7.8
to convert Gt CO_2 to ppm, divide by 7.8

Getting back to the Snowball Earth

We need 0.12 bar of CO_2 (120,000 ppm) = 9.36×10^5 $GtCO_2$ to melt the snowball Earth.

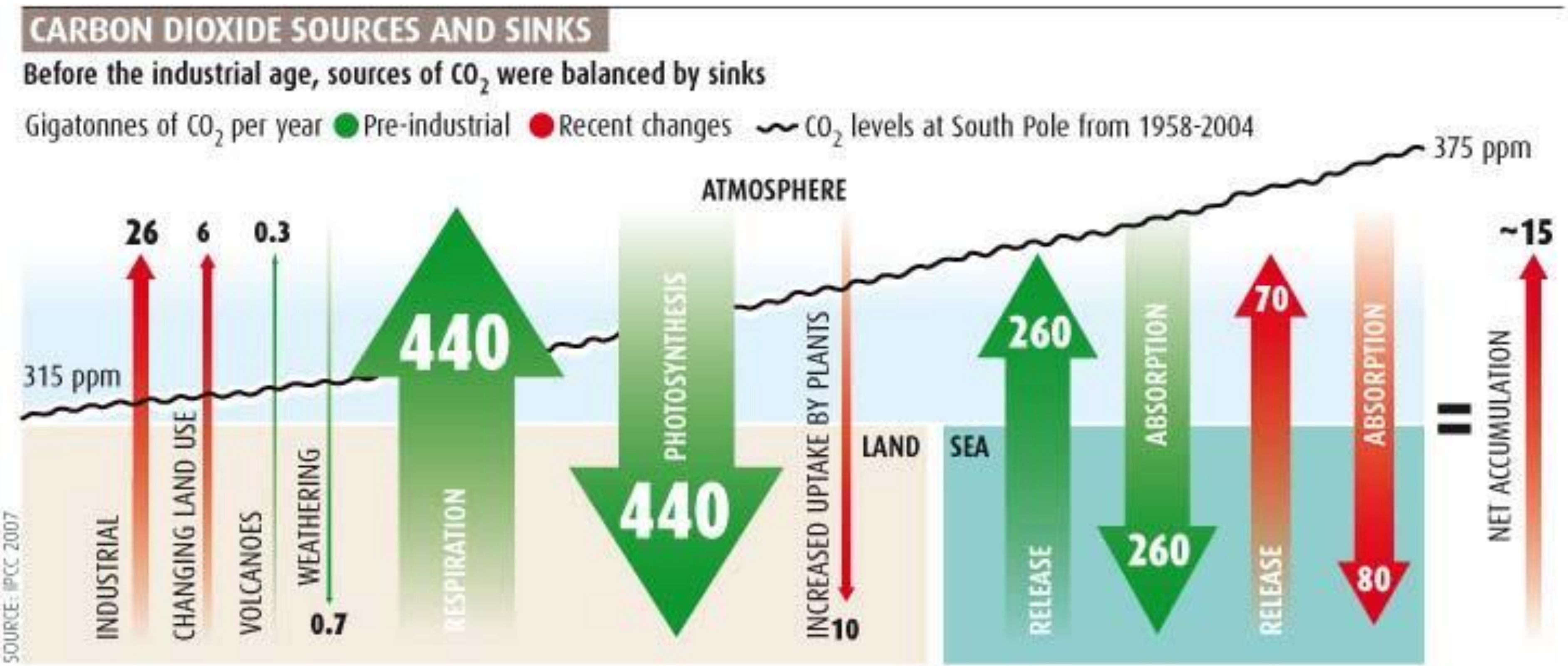
If the rate of volcanic outgassing was 2.7×10^{12} mol/y
we multiply by 44 g/mol = 1.19×10^{14} g/y or 0.119 $GtCO_2$/y

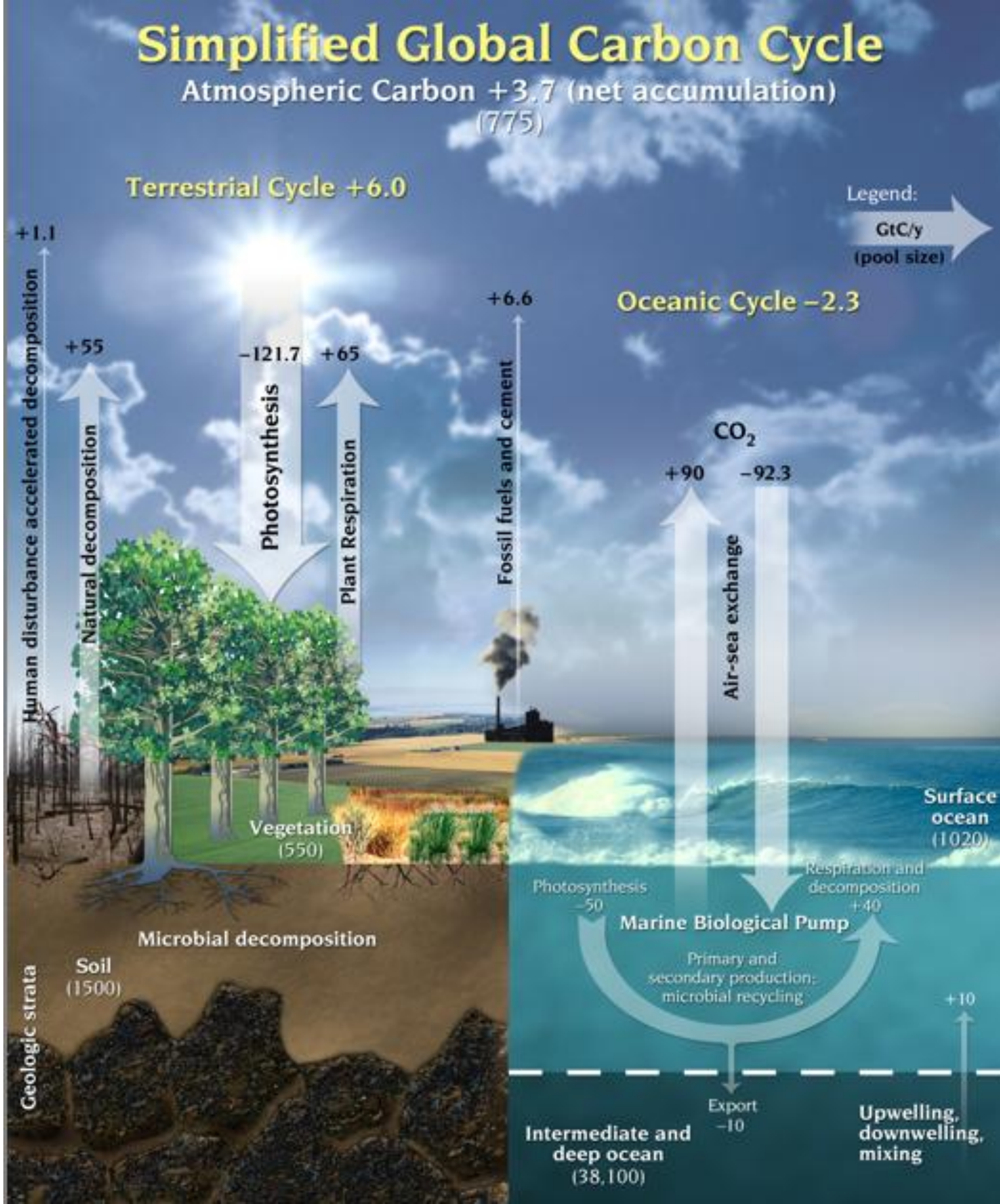
Then…

9.36×10^5 $GtCO_2$ divided by 0.119 $GtCO_2$/y = **8 million years**

For a rate of 5.4×10^{12} mol/y it would take: **4 million years**

Present Day CO_2 emissions




Simplified Global Carbon Cycle
Atmospheric Carbon +3.7 (net accumulation)
(775)
Terrestrial Cycle +6.0
Legend:
GtC/y
(pool size)
+1.1
Human disturbance accelerated decomposition
+55
Natural decomposition
−121.7
Photosynthesis
+65
Plant Respiration
+6.6
Fossil fuels and cement
Oceanic Cycle −2.3
CO2
+90
−92.3
Air-sea exchange
Vegetation
(550)
Surface ocean
(1020)
Respiration and decomposition
+40
Photosynthesis
−50
Marine Biological Pump
Microbial decomposition
Soil
(1500)
Geologic strata
Primary and secondary production; microbial recycling
+10
Export
−10
Intermediate and deep ocean
(38,100)
Upwelling, downwelling, mixing


The End

1. Glacial deposits

- Distributed on all continents
- Tidal rhythmites indicate that they formed at sea level