



Snowball Earth:

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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

A climate instability caused by ice-albedo feedback

Snowball Earth

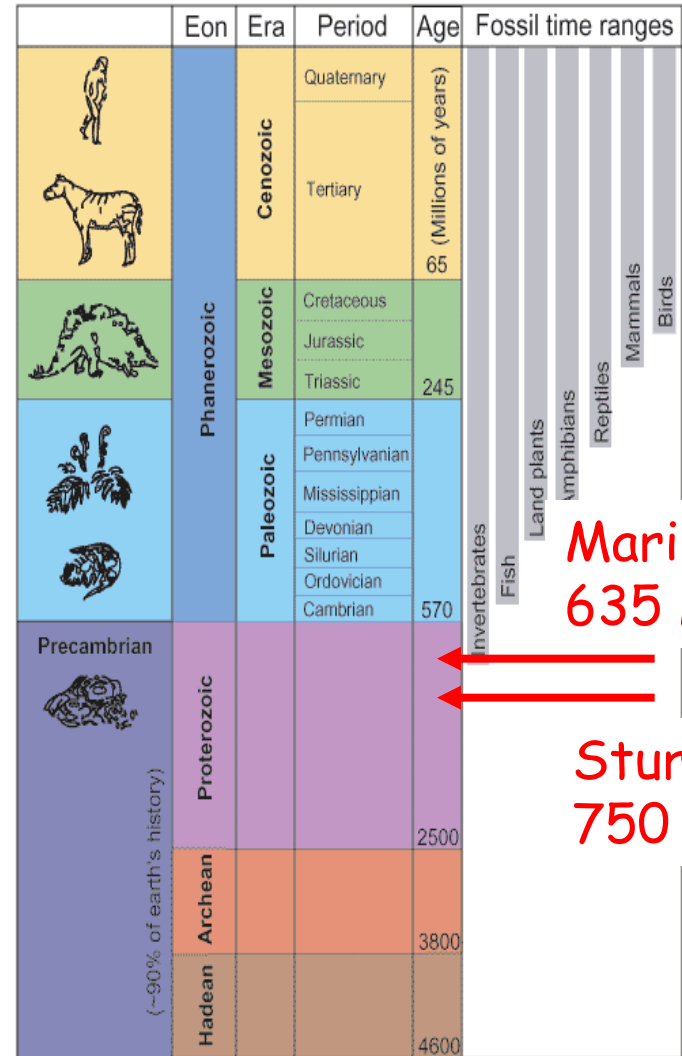
Radiative balance:
 $E_s(1-\alpha) = 4(f \sigma T_s^4)$

UofT

Joe Kirschvink

PFH 99

Geologic Time Scale



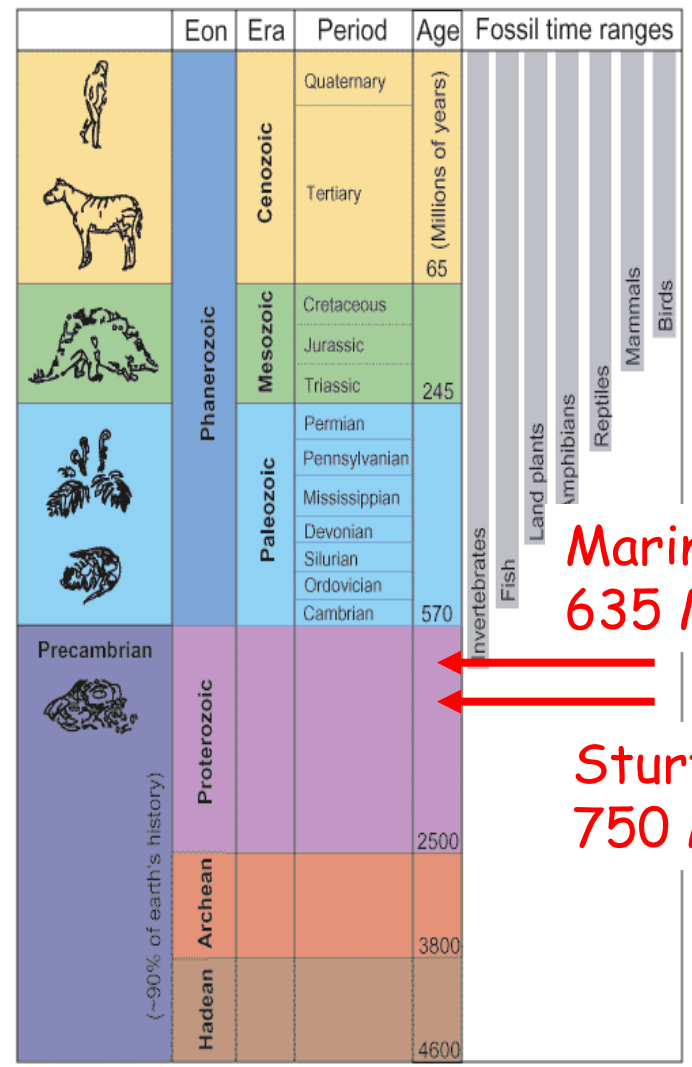
What is the Snowball Earth Theory?

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



(Hoffman and Schrag 2000)

Geologic Time Scale



Marinoan
635 Ma

Sturtian
750 Ma

What is the geological evidence?

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



CARBONATES

GLACIAL DEPOSITS
CRYSTAL FANS

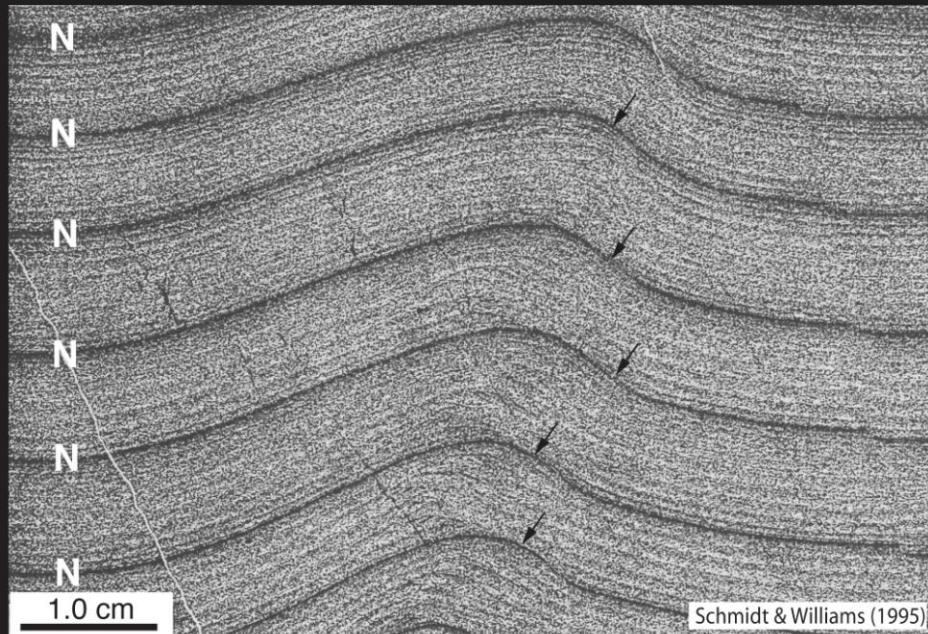


Geologic Time Scale

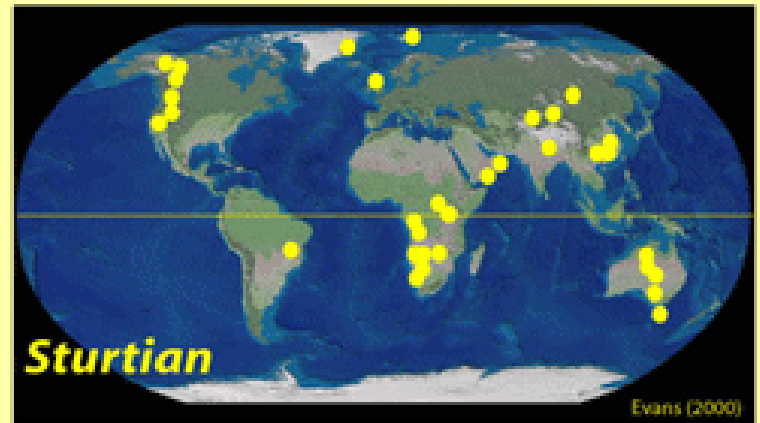
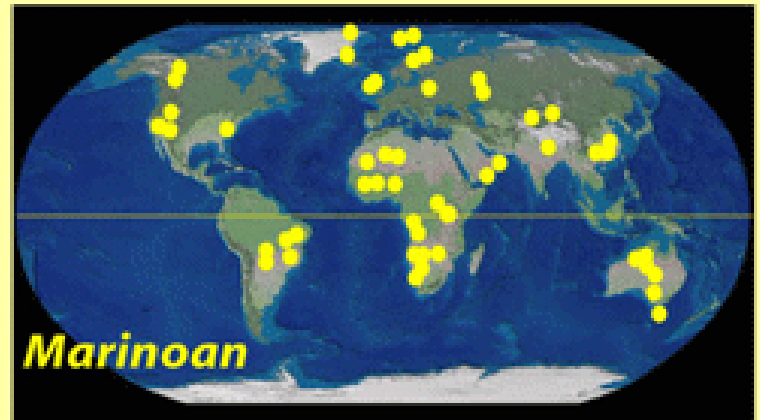
	Eon	Era	Period	Age	Fossil time ranges
 	Phanerozoic	Cenozoic	Quaternary	65 (Millions of years)	Invertebrates Fish Land plants Amphibians Reptiles Mammals Birds
			Tertiary		
		Mesozoic	Cretaceous	245	
			Jurassic		
			Triassic		
		Paleozoic	Permian	570	
			Pennsylvanian		
			Mississippian		
			Devonian		
			Shinarump Ordovician Cambrian		
Precambrian (~90% of earth's history)	Proterozoic		2500		
		Archean	3800		
		Hadean	4600		

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

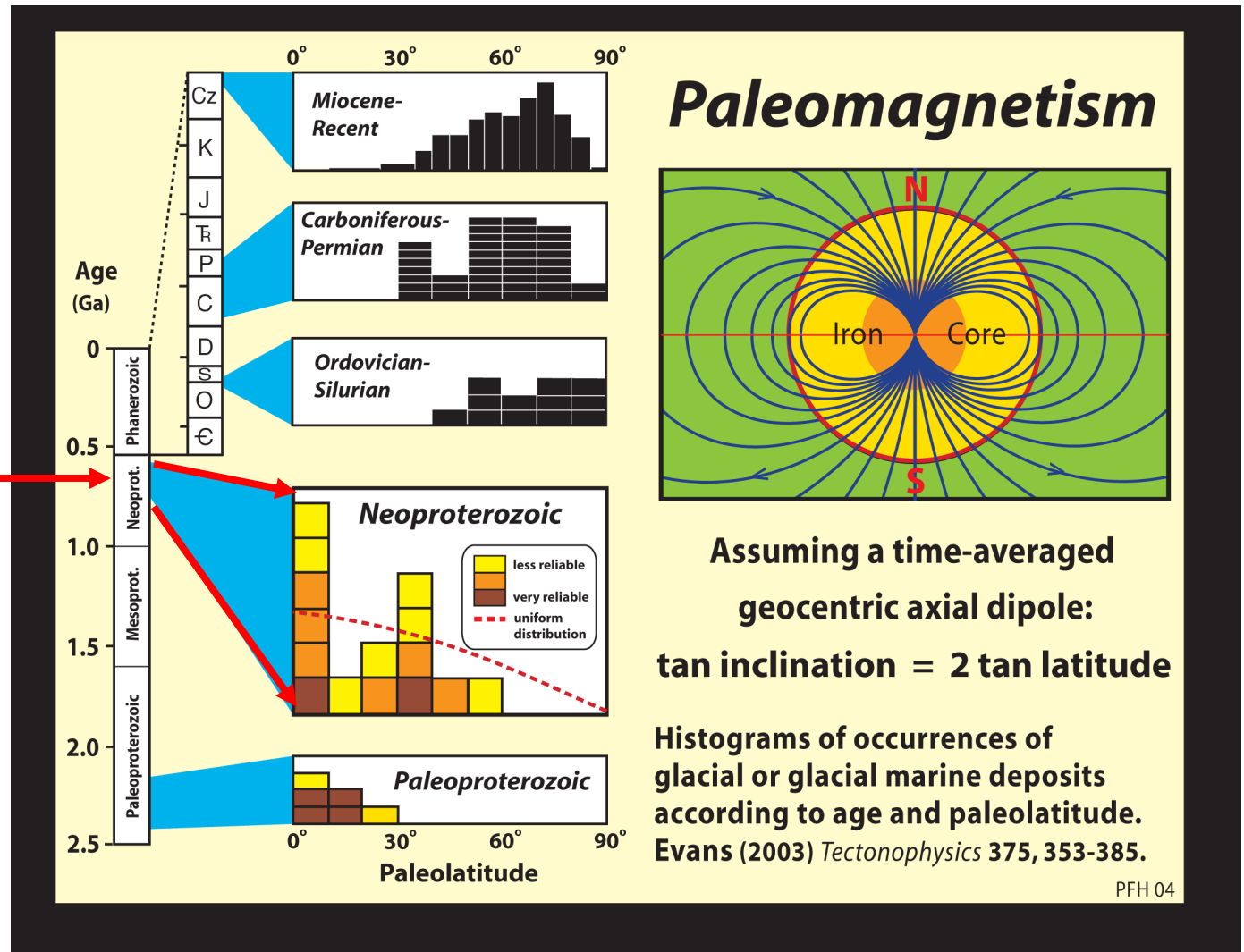


(Hoffman and Schrag 2000)

1. Glacial deposits

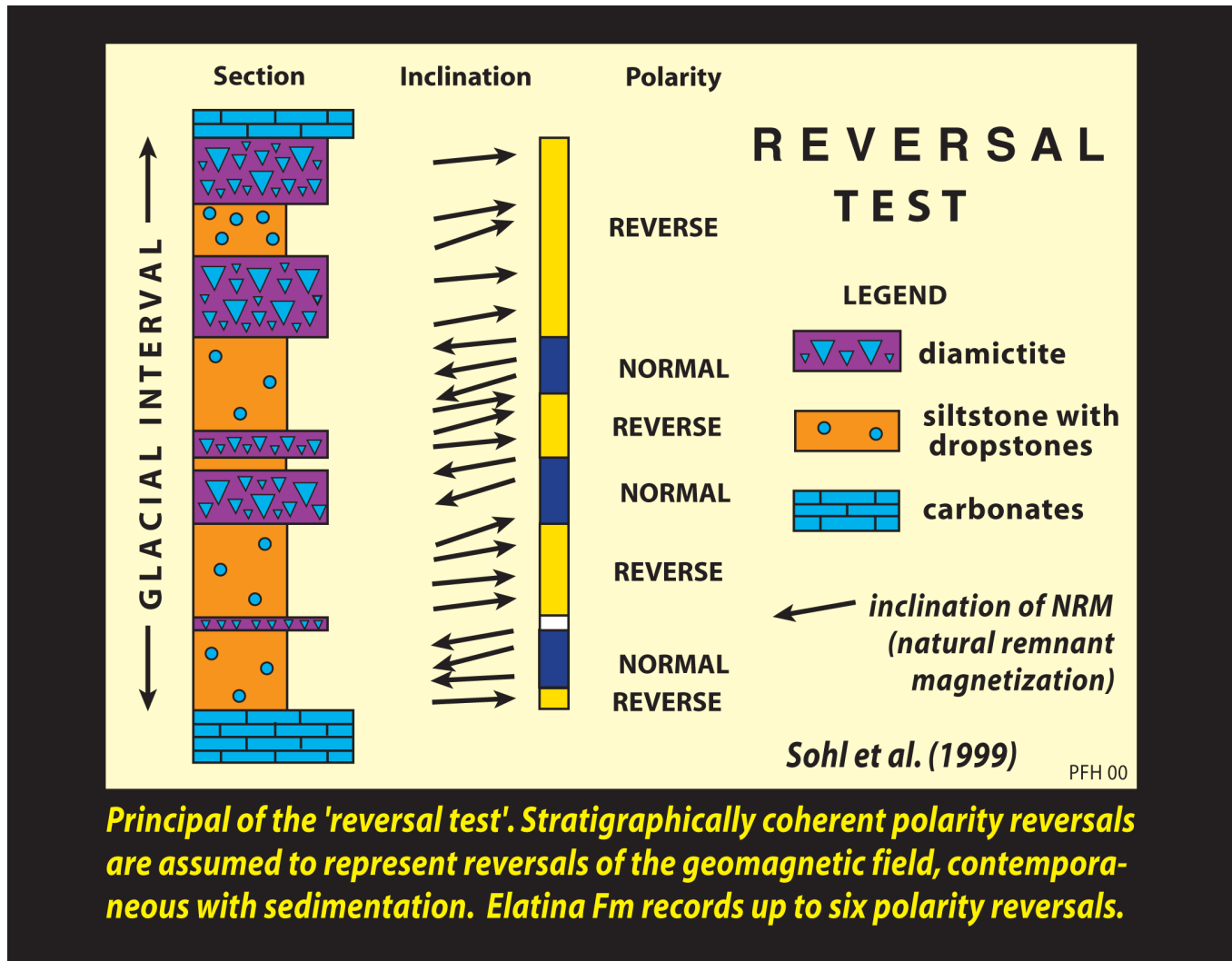
- Paleomagnetic data suggest they formed near the equator, none poleward of 60 degrees

Snowball Earth

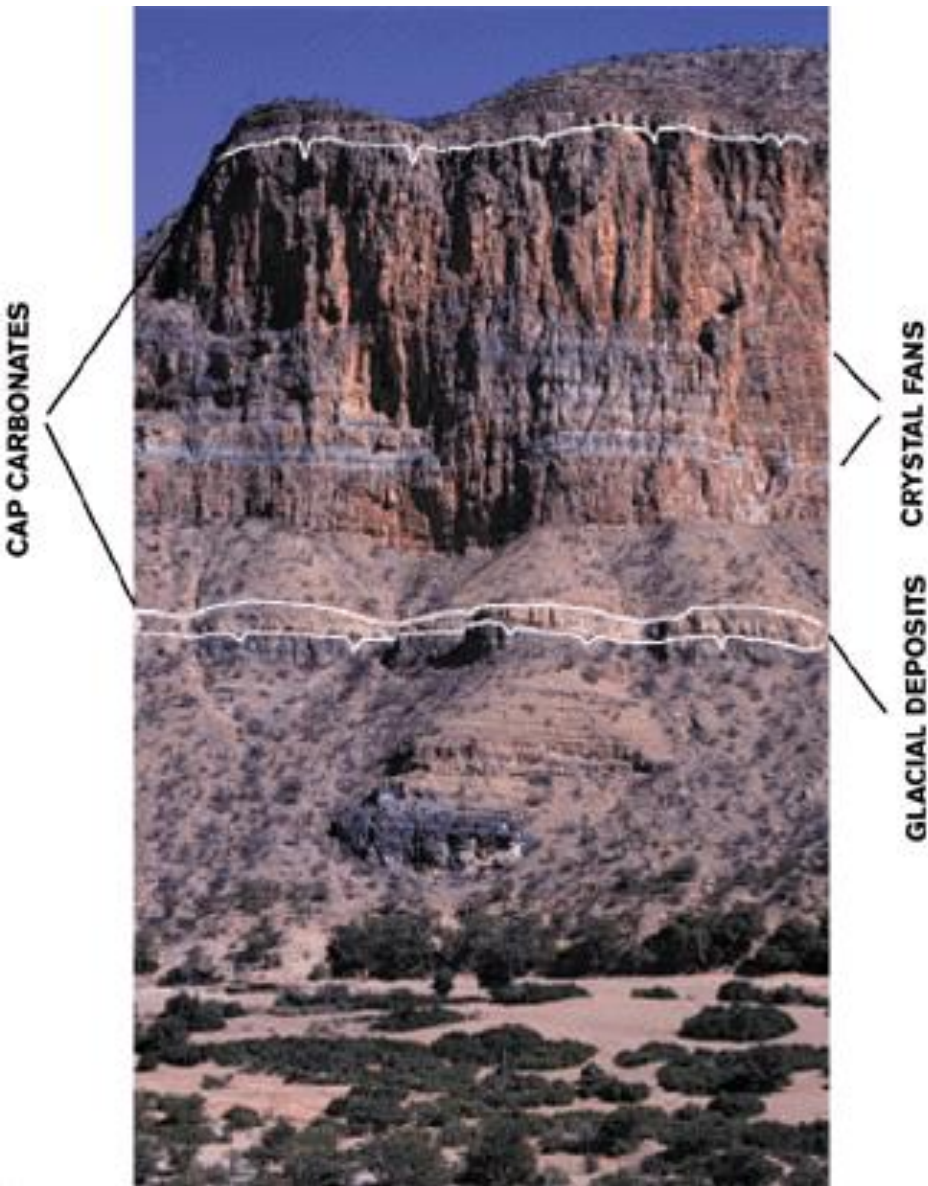


1. Glacial deposits

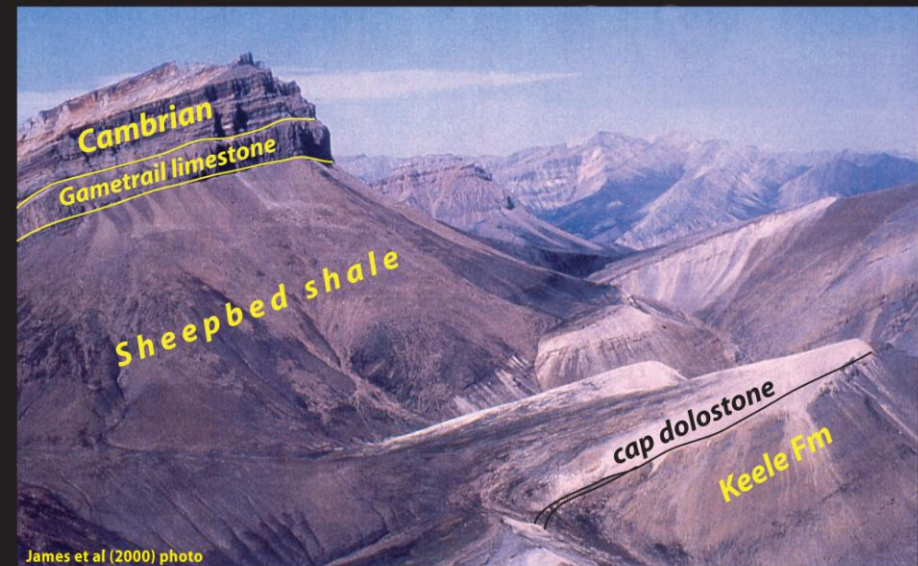
- Multiple magnetic reversals indicate that glaciation lasted several hundreds of thousands, to a few million years



2. Cap carbonates

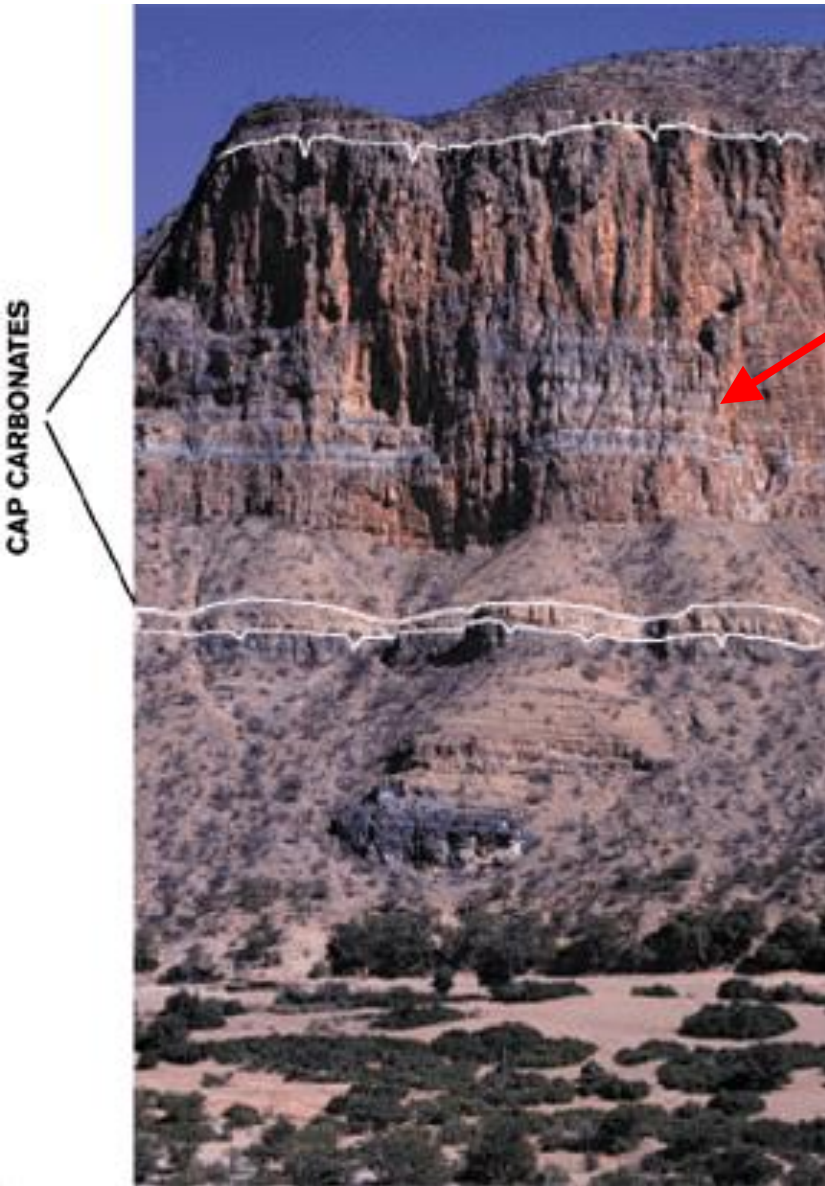


- Warm water deposit
- Associated with most Neoproterozoic glacial deposits
- Can be hundreds of meters thick



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

2. Cap carbonates



CRYSTAL FANS
GLACIAL DEPOSITS



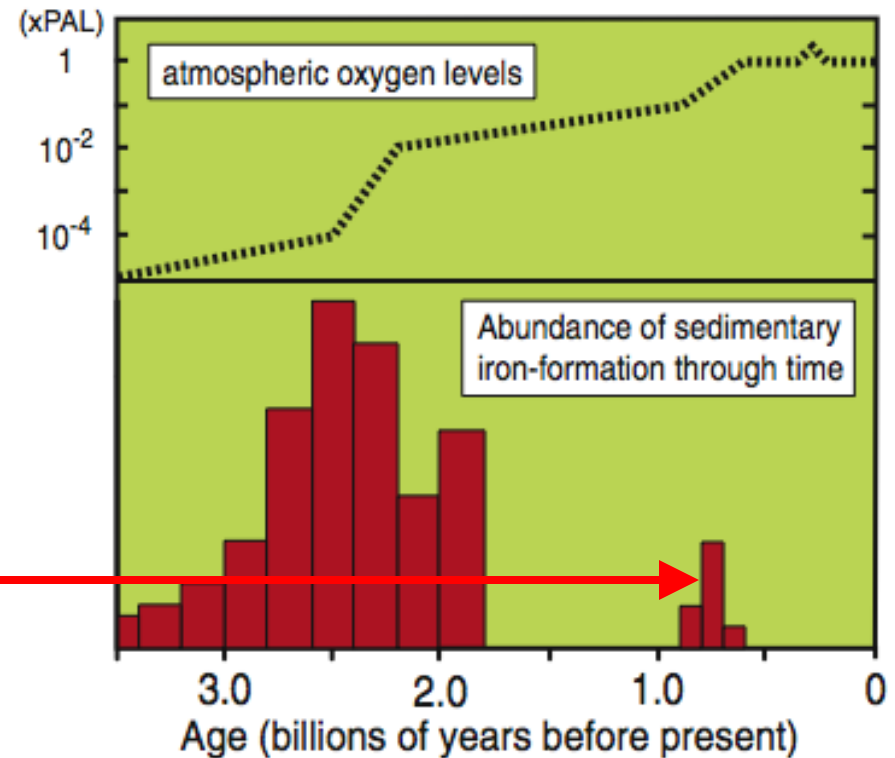
- Aragonite fans indicate rapid deposition under hot temperatures

3. Banded Iron Formation (BIF)

- Absent from the geologic record for a billion years

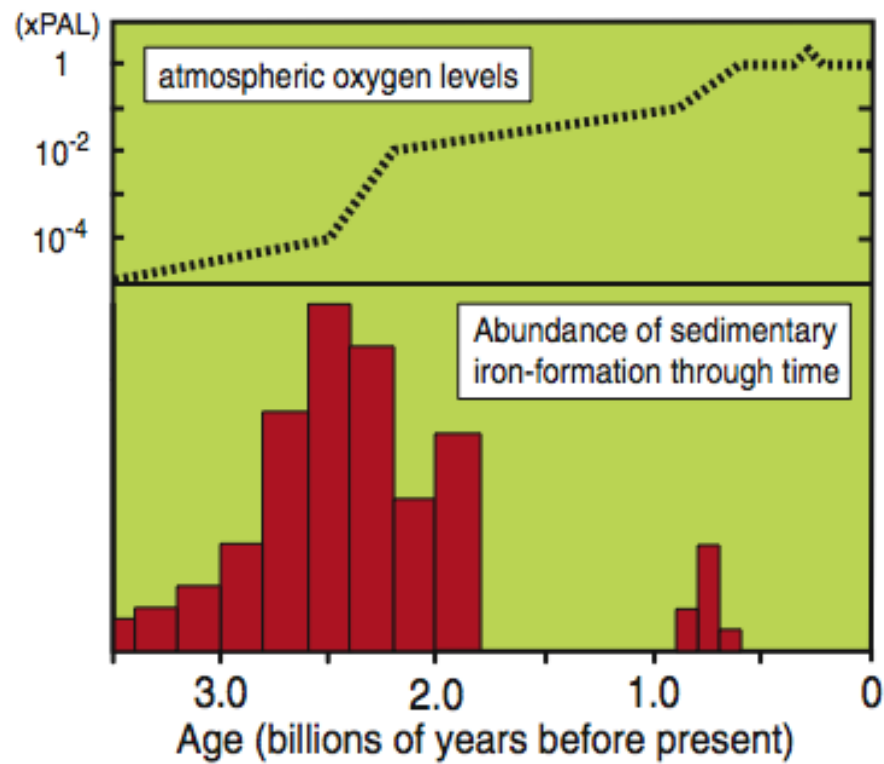
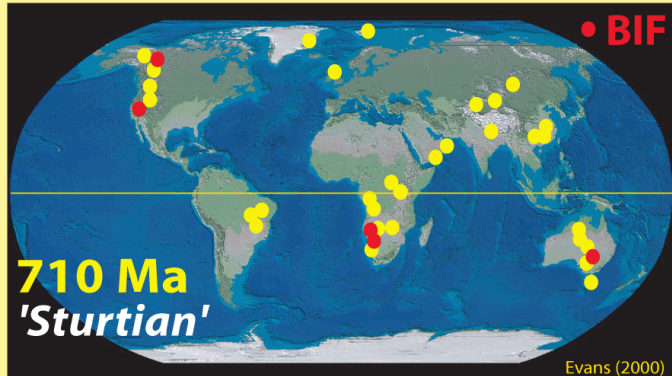
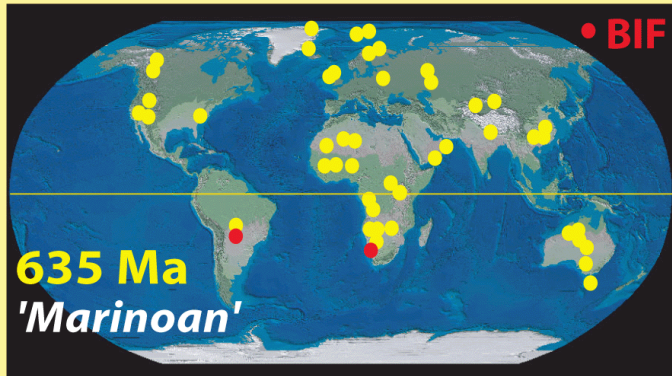
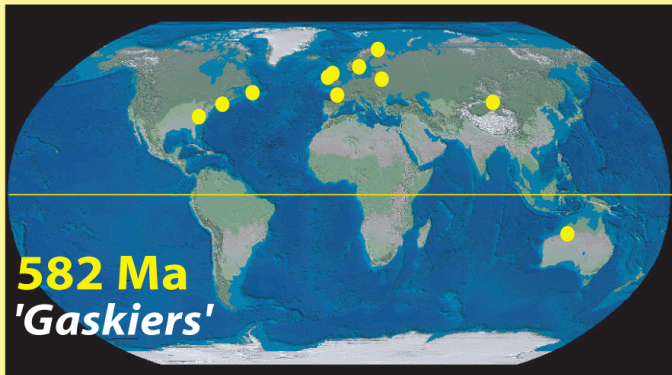


If O_2 is absent, iron is soluble as ferrous (Fe^{2+}) ion.
If O_2 is present, iron is insoluble as ferric (Fe^{3+}) ion.

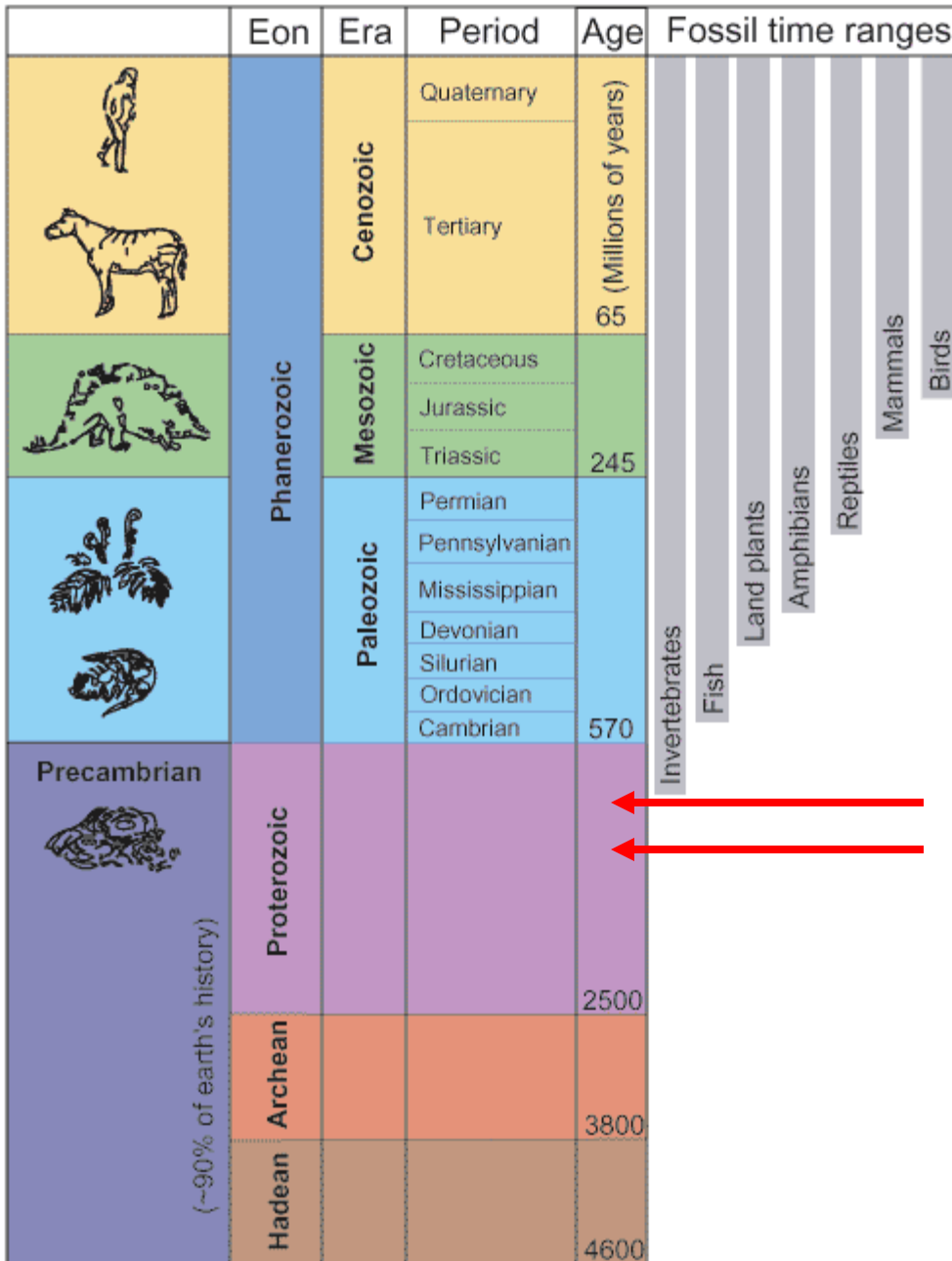


3. Banded Iron Formation (BIF)

If O₂ is absent, iron is soluble as ferrous (Fe²⁺) ion.
If O₂ is present, iron is insoluble as ferric (Fe³⁺) ion.



Geologic Time Scale



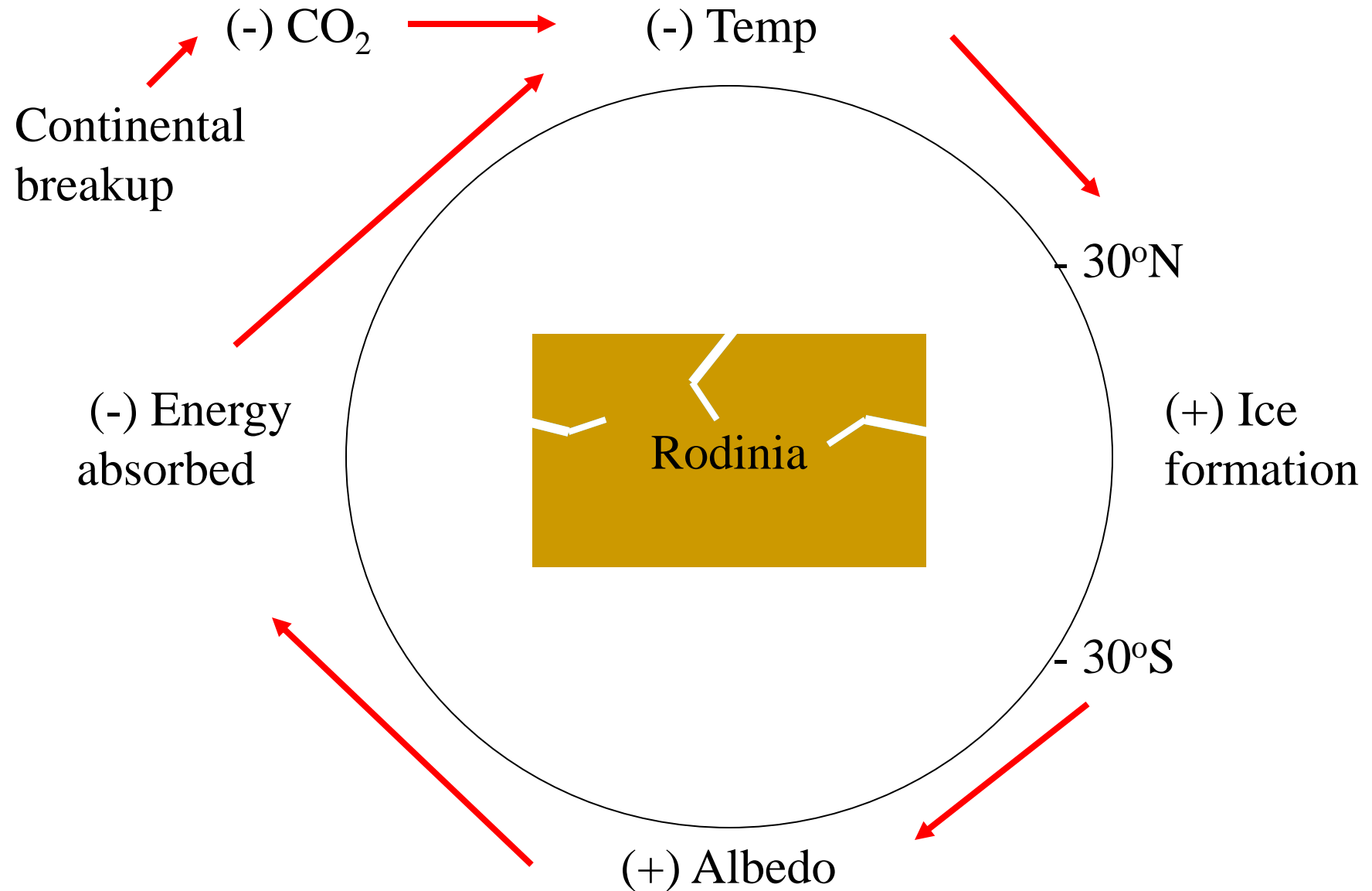
4. Timing of early life

- 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

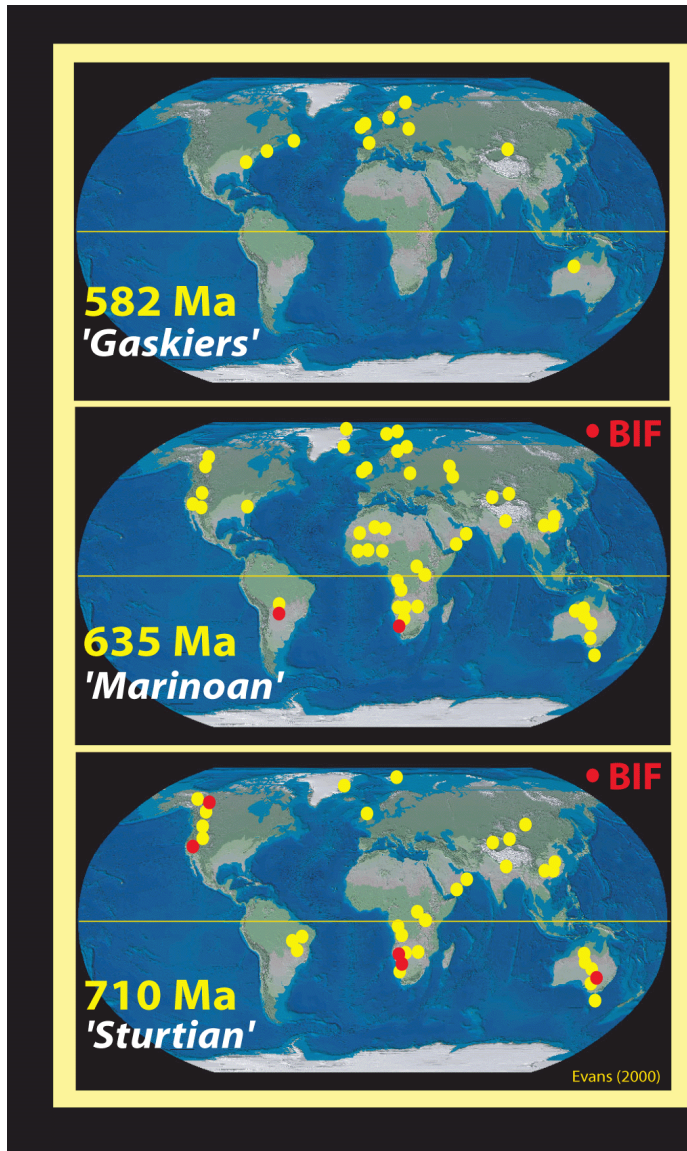
- Glaciation on all continents
- Glaciation at sea level
- Glaciation near the equator
- The glaciations could have lasted for up to 10 million years



(Hoffman and Schrag 2000)

1. Glacial deposits

Weaknesses



Gaskiers

- Glaciation is not global

Marinoan

- Glaciation is global and synchronous

Sturtian

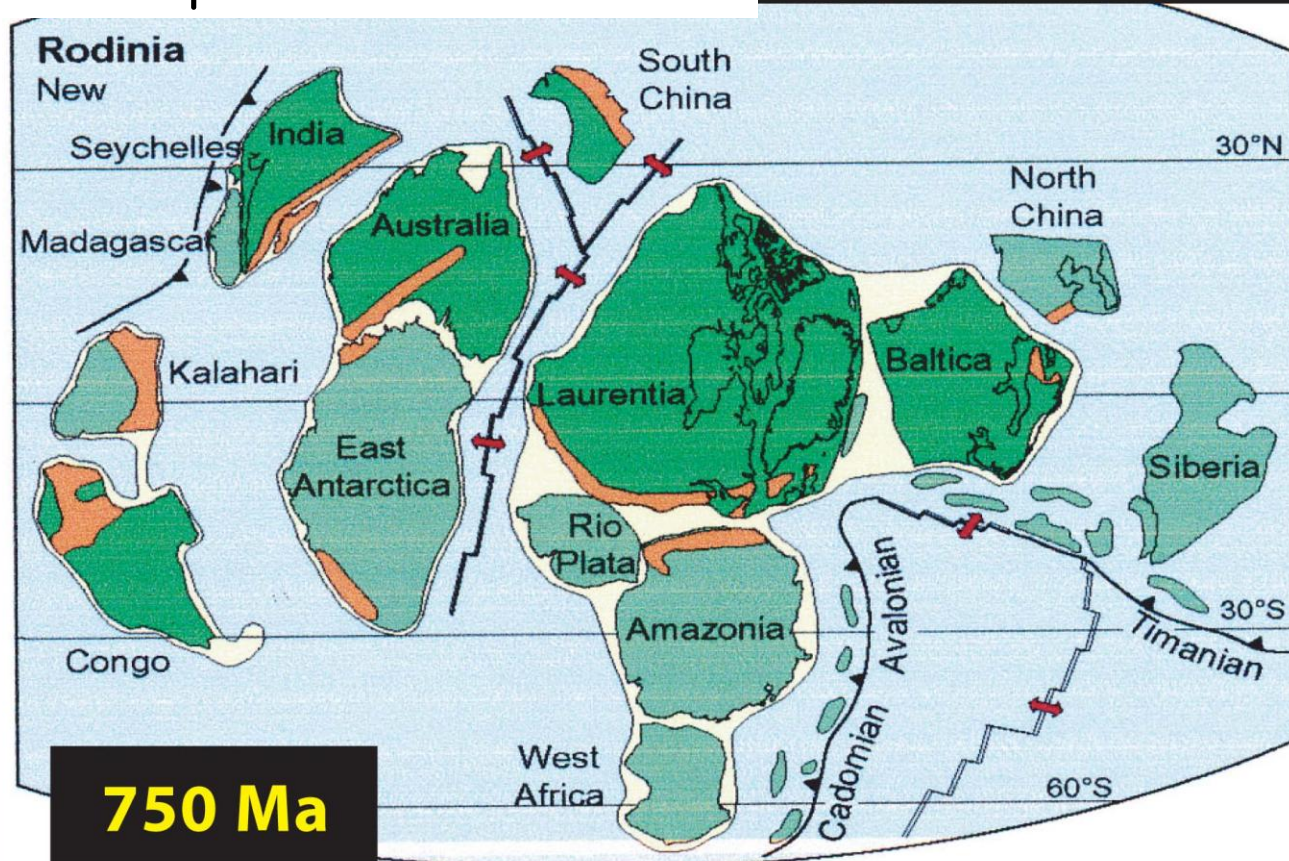
- Glaciation is global but not synchronous

1. Glacial deposits

Weaknesses

Sturtian:
dispersed continents

Rodinia breakup

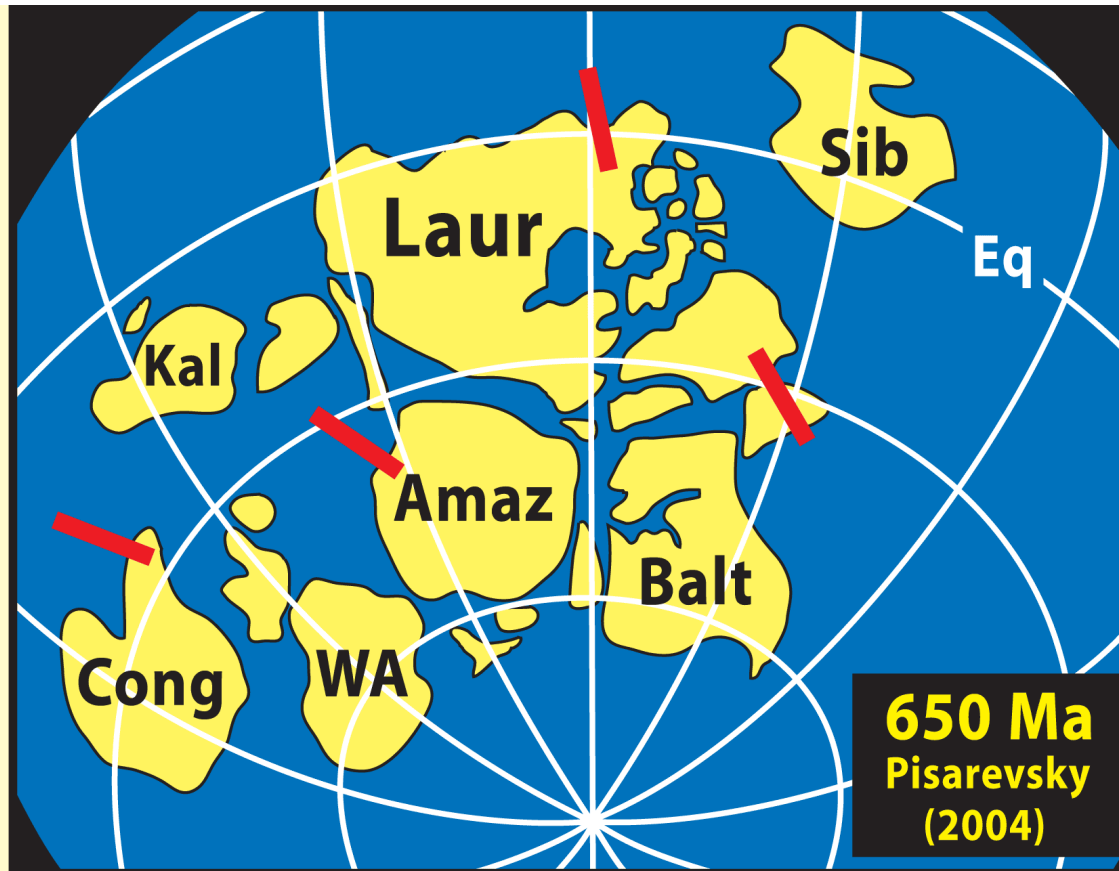


Continents with paleomagnetic data (~750 million years ago)

1. Glacial deposits

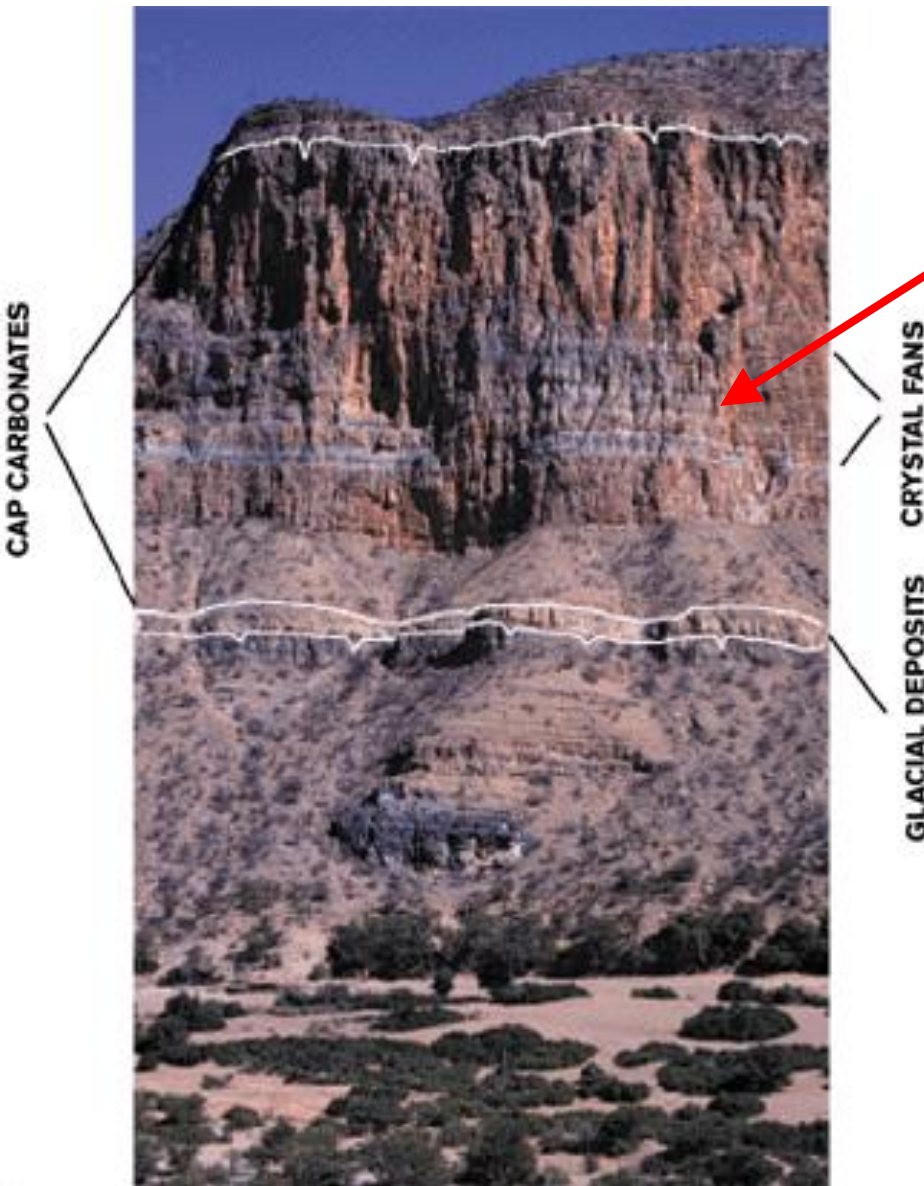
Weaknesses

Marinoan: continents at higher latitudes



2. Cap carbonates

Strengths



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



2. Cap carbonates

Weaknesses

Mackenzie Mtns, NW Canada

Marinoan: Cap carbonate only
1-4 m thick globally

grey

green

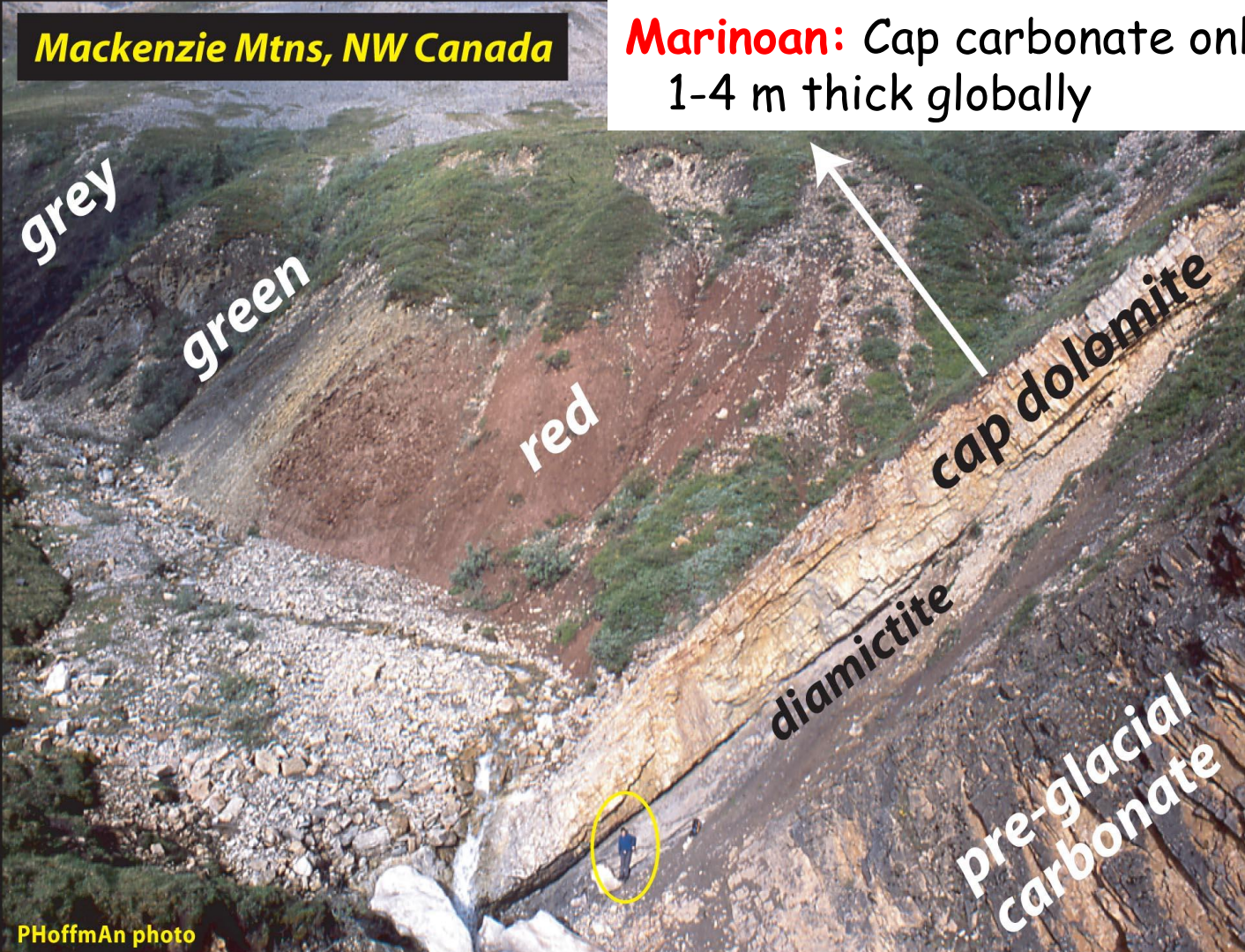
red

cap dolomite

diamictite

pre-glacial
carbonate

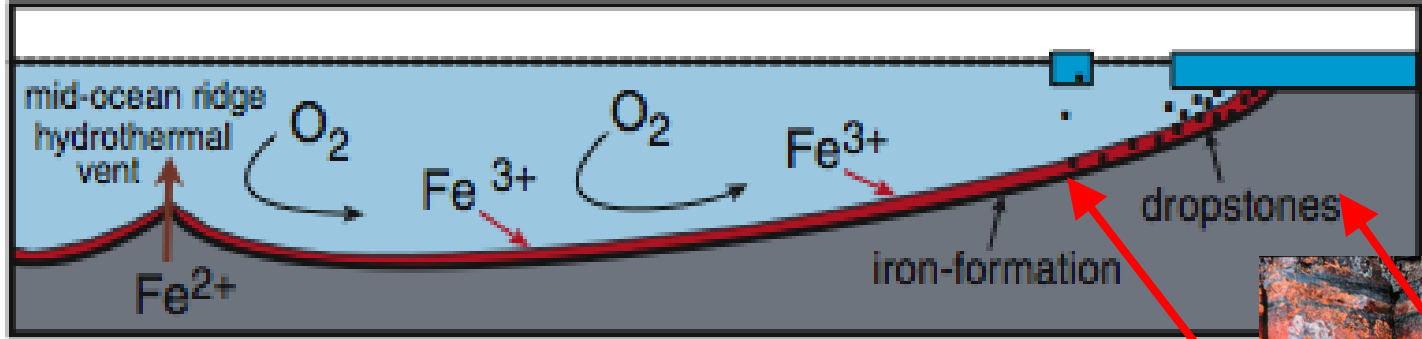
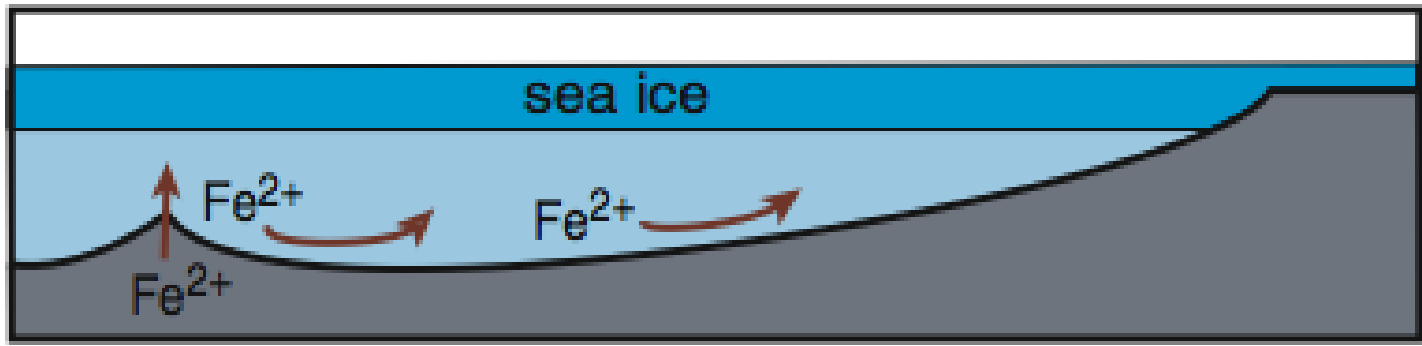
PHoffmAn photo



3. Banded Iron Formation (BIF) Strengths

Strengths

Snowball earth: anoxic ocean



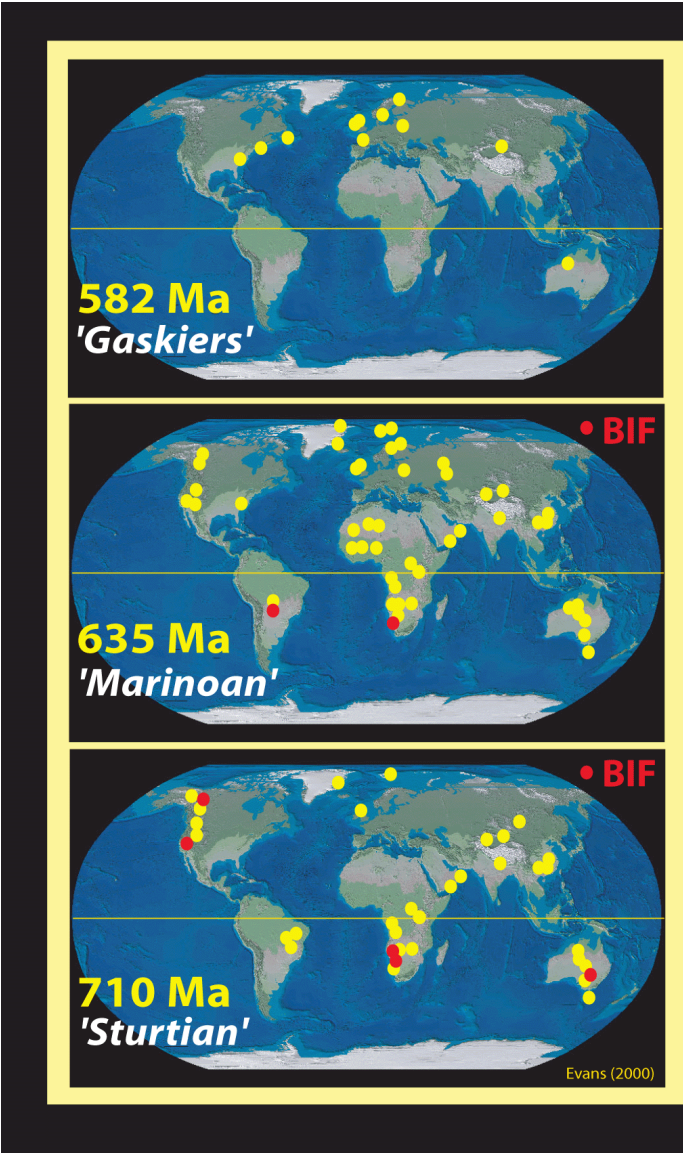
Deglaciation: ocean ventilation

- 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

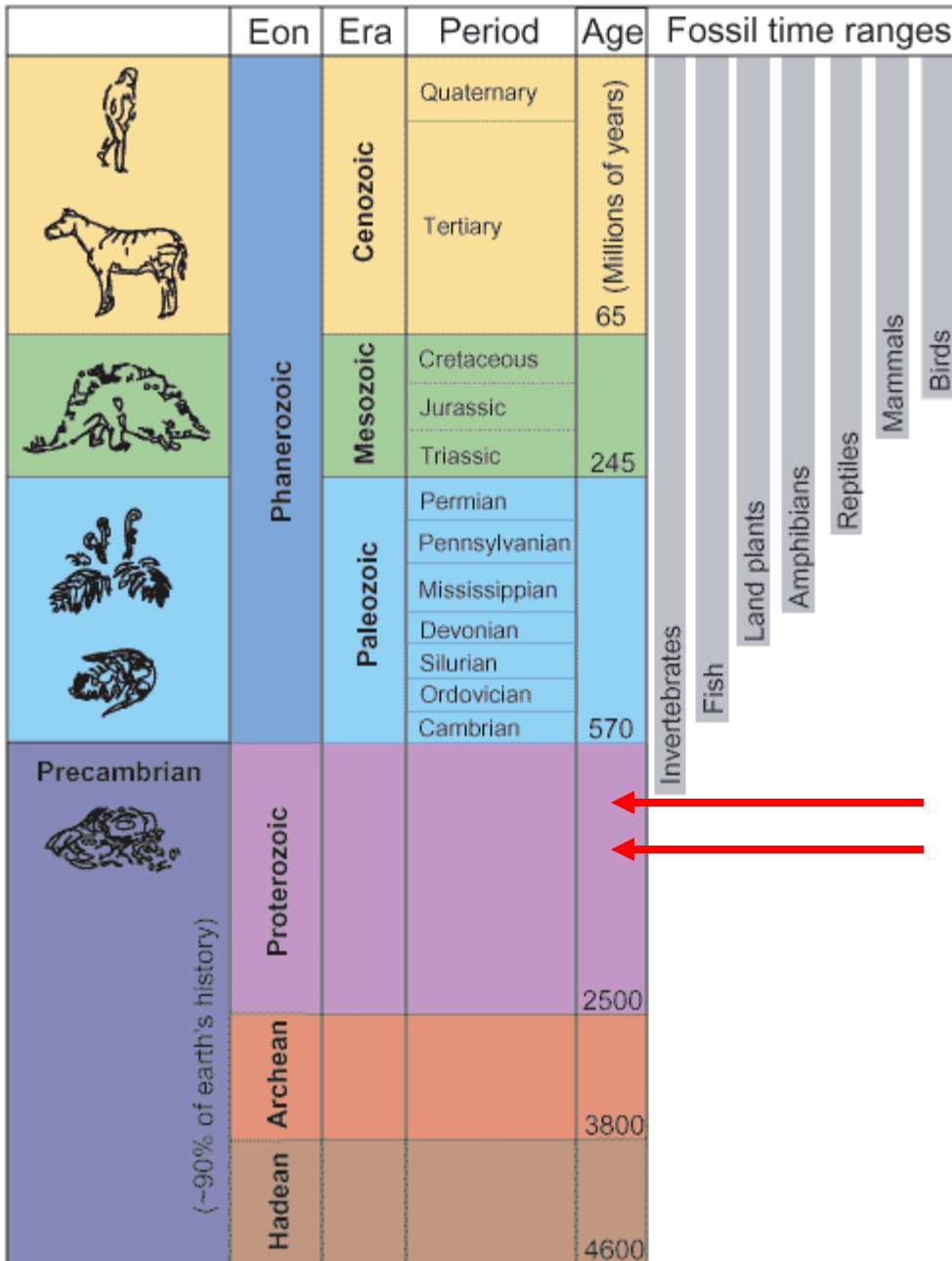
- Very few BIFs

Sturtian

- BIFs



Geologic Time Scale



4. Timing of early life

Strengths

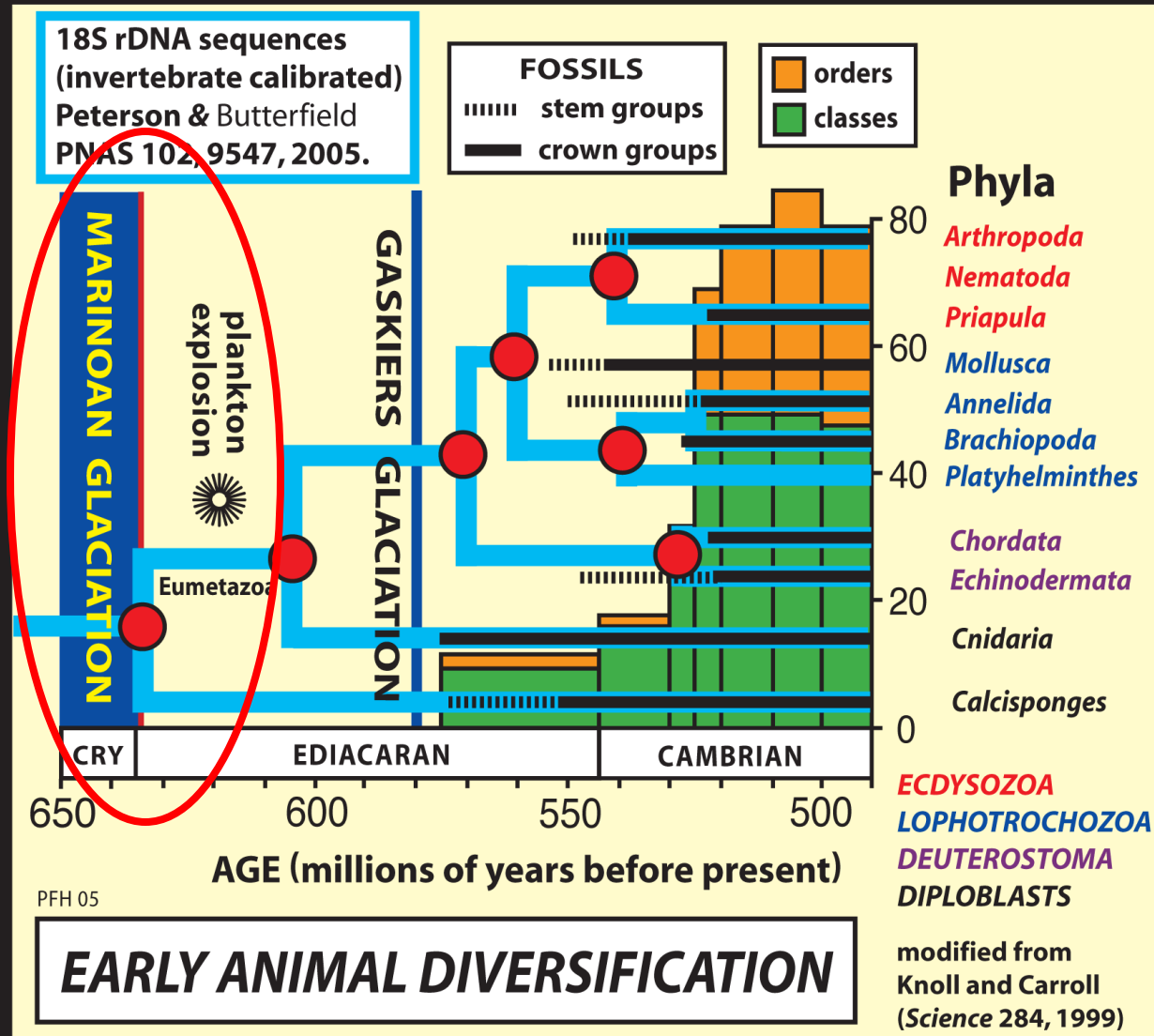
- After Snowball Earth there would be new habitats for life to radiate into

Snowball Earth

~750-635 Ma

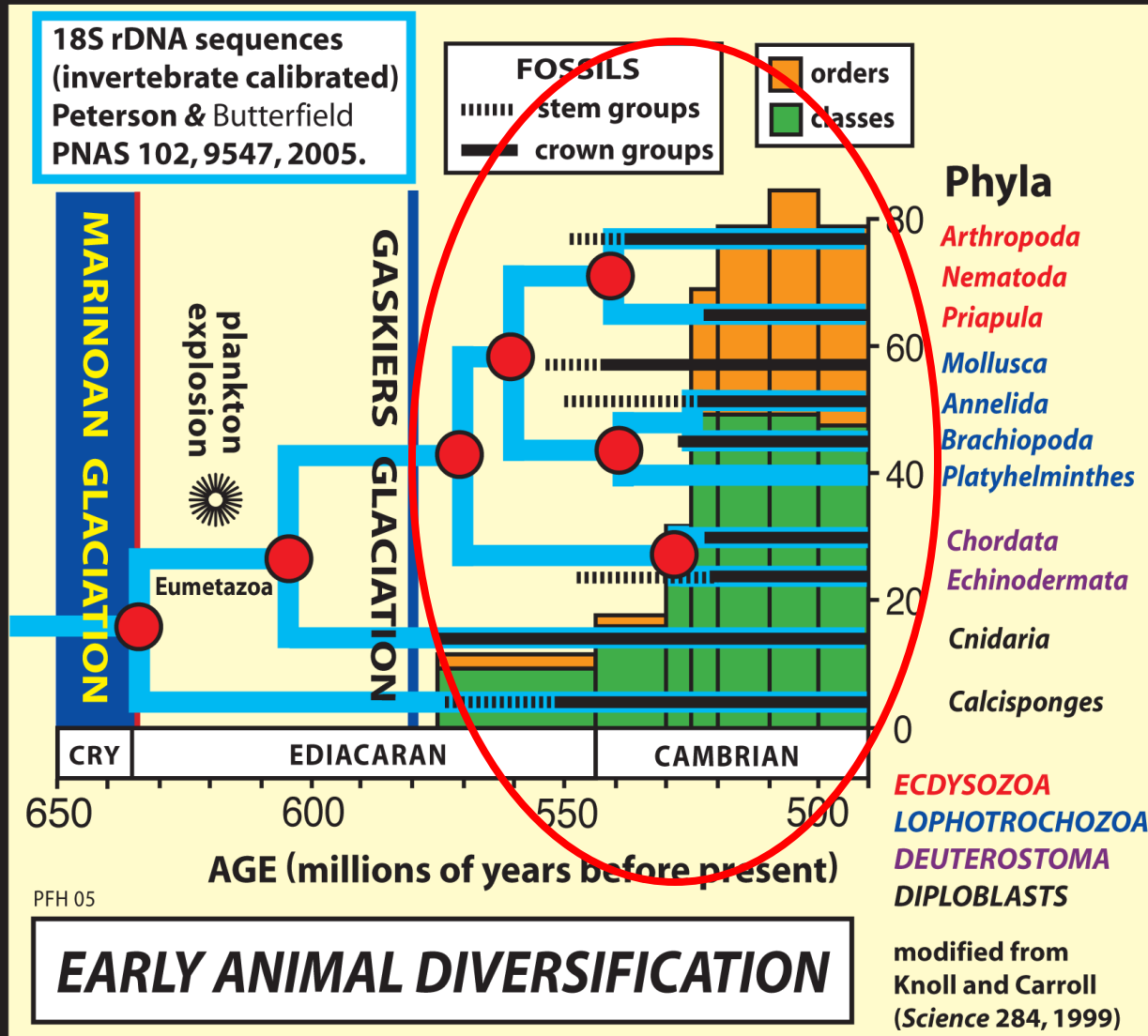
Strengths

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)

Equatorial glacial deposits
Equatorial continents
Thick cap carbonates
Many BIFs
Glaciation not synchronous

Marinoan (635 Ma)

Equatorial glacial deposits
Higher latitude continent
Thin cap carbonates
Very few BIFs
Glaciation is synchronous

Weakness of Snowball Earth: photosynthetic life

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

A wide, flat, icy landscape under a cloudy sky, with snow-covered mountains in the background. The foreground is a vast, flat expanse of ice or snow, possibly a frozen lake or a tundra, with subtle textures and shadows. In the distance, a range of mountains is visible, their peaks and slopes covered in snow. The sky is overcast with soft, grey clouds. The overall color palette is muted, consisting of various shades of blue, grey, and white.

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?

$CO_2 = 1 \text{ C atom (12 g/mol) and 2 O atoms (2 \times 16 g/mol) = 44 g/mol}$

Atomic number

Symbol

Atomic weight

Metal

Semimetal

Nonmetal

1 1 H 1.008	2 3 Li 6.941	4 4 Be 9.012											13 5 B 10.8	14 6 C 12.01	15 7 N 14.01	16 8 O 16.00	17 9 F 19.00	18 10 Ne 20.18
11 3 Na 22.99	12 4 Mg 24.31	3 21 Sc 44.96	4 22 Ti 47.88	5 23 V 50.94	6 24 Cr 52.00	7 25 Mn 54.94	8 26 Fe 55.85	9 27 Co 58.93	10 28 Ni 58.69	11 29 Cu 63.55	12 30 Zn 65.39	13 31 Al 26.98	14 32 Si 28.09	15 33 P 30.97	16 34 S 32.07	17 35 Cl 35.45	18 36 Ar 39.95	
19 4 K 39.10	20 4 Ca 40.08	39 3 Y 88.91	40 4 Zr 91.22	41 5 Nb 92.91	42 6 Mo 95.94	43 7 Tc 98.91	44 8 Ru 101.1	45 9 Rh 102.9	46 10 Pd 106.4	47 11 Ag 107.9	48 12 Cd 112.4	49 13 In 114.8	50 14 Sn 118.7	51 15 Sb 121.8	52 16 Te 127.6	53 17 I 126.9	54 18 Xe 131.3	
55 6 Cs 132.9	56 6 Ba 137.3	71 3 Lu 175.0	72 4 Hf 178.5	73 5 Ta 180.9	74 6 W 183.8	75 7 Re 186.2	76 8 Os 190.2	77 9 Ir 192.2	78 10 Pt 195.1	79 11 Au 197.0	80 12 Hg 200.6	81 13 Tl 204.4	82 14 Pb 207.2	83 15 Bi 209.0	84 16 Po 209.0	85 17 At 210.0	86 18 Rn 222.0	
87 7 Fr 223.0	88 7 Ra 226.0	103 3 Lr 262.1	104 4 Rf 261.1	105 5 Db 262.1	106 6 Sg 263.1	107 7 Bh 264.1	108 8 Hs 265.1	109 9 Mt 268	110 10 Uun 269	111 11 Uuu 272	112 12 Uub 277	113 13 Uut	114 14 Uuq 289	115 15 Uup	116 16 Uuh 289	117 17 Uus	118 18 Uuo 293	
		57 6 La 138.9	58 6 Ce 140.1	59 6 Pr 140.9	60 6 Nd 144.2	61 6 Pm 146.9	62 6 Sm 150.4	63 6 Eu 152.0	64 6 Gd 157.3	65 6 Tb 158.9	66 6 Dy 162.5	67 6 Ho 164.9	68 6 Er 167.3	69 6 Tm 168.9	70 6 Yb 173.0			
		89 7 Ac 227.0	90 7 Th 232.0	91 7 Pa 231.0	92 7 U 238.0	93 7 Np 237.0	94 7 Pu 244.1	95 7 Am 243.1	96 7 Cm 247.1	97 7 Bk 247.1	98 7 Cf 251.1	99 7 Es 252.0	100 7 Fm 257.1	101 7 Md 258.1	102 7 No 259.1			

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

$\text{CO}_2 = 1 \text{ C atom (12 g/mol) and 2 O atoms (2} \times 16 \text{ g/mol) = 44 g/mol}$

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 $\text{CO}_2=385 \text{ ppm}$ (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:

$$m = (P \times A) / g$$

$$\text{Area of a sphere (A)} = 4 \times \pi \times r^2$$

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/s²

So the mass of the atmosphere is:

$$\begin{aligned} m &= (100000 \text{ Pa})(4)(3.14)(6370000 \text{ m})^2 / 9.8 \text{ m/s}^2 \\ &= 5.2 \times 10^{18} \text{ kg} \end{aligned}$$

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):

$$(385 \times 10^{-6}) \times 44 / (0.8 \times 28 + 0.2 \times 32) \times 5.2 \times 10^{18} \text{ kg} = 3059 \times 10^{12} \text{ kgCO}_2 \\ = 3059 \text{ Gt CO}_2$$

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) = $9.36 \times 10^5 \text{ GtCO}_2$
to melt the snowball Earth.

If the rate of volcanic outgassing was $2.7 \times 10^{12} \text{ mol/y}$
we multiply by $44 \text{ g/mol} = 1.19 \times 10^{14} \text{ g/y}$ or $0.119 \text{ GtCO}_2/\text{y}$

Then...

$9.36 \times 10^5 \text{ GtCO}_2$ divided by $0.119 \text{ GtCO}_2/\text{y} = 8 \text{ million years}$

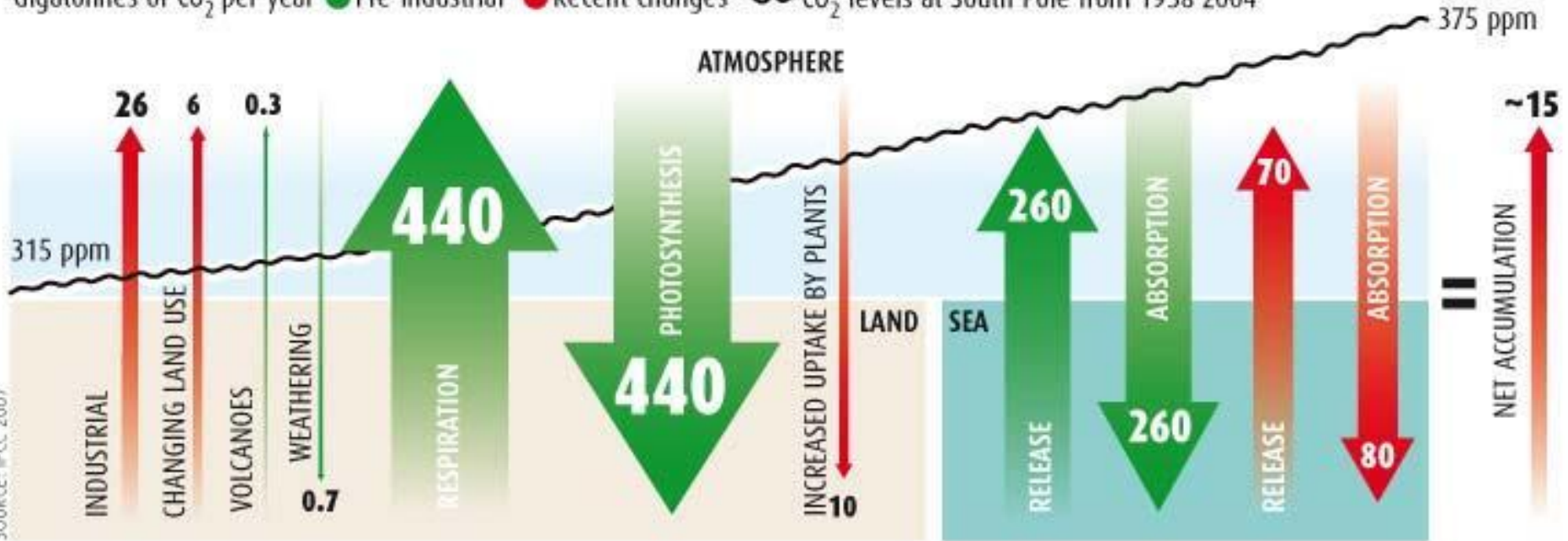
For a rate of $5.4 \times 10^{12} \text{ mol/y}$ it would take: 4 million years

Present Day CO₂ emissions

CARBON DIOXIDE SOURCES AND SINKS

Before the industrial age, sources of CO₂ were balanced by sinks

Gigatonnes of CO₂ per year ● Pre-industrial ● Recent changes ~ CO₂ levels at South Pole from 1958-2004



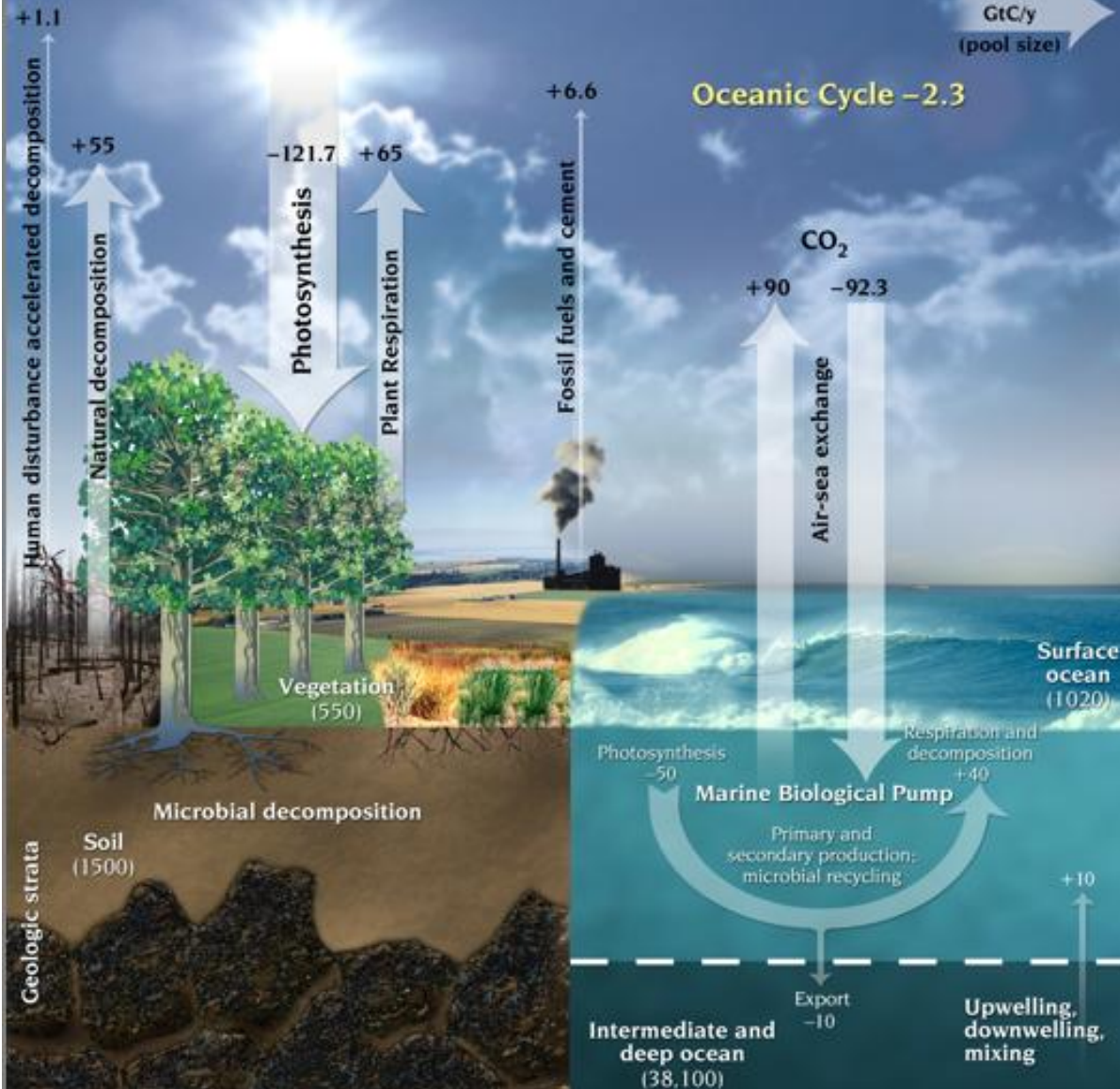
Simplified Global Carbon Cycle

Atmospheric Carbon +3.7 (net accumulation)
(775)

Terrestrial Cycle +6.0

Legend:

GtC/y
(pool size)

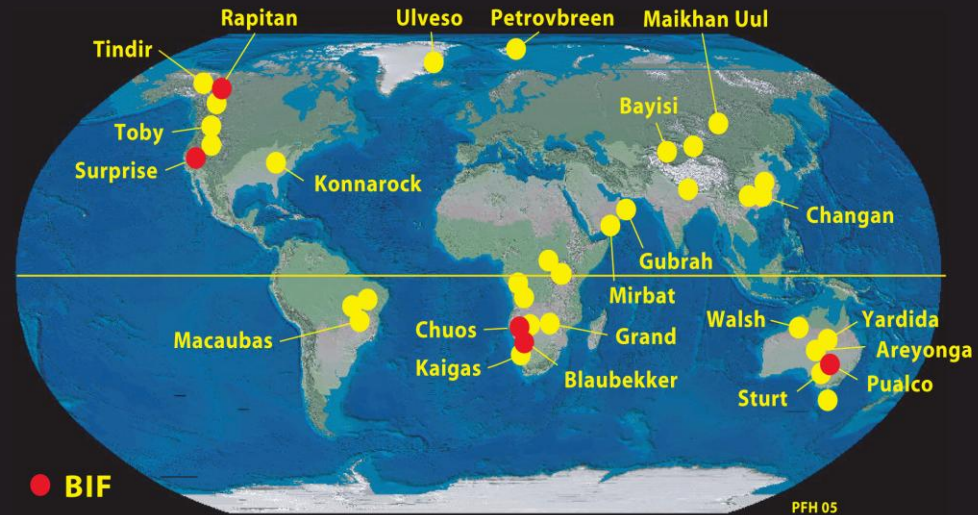




The End

1. Glacial deposits

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



Older Cryogenian ('Sturtian') glacials
730 - 700 Ma

