Archaean tides and the origin of life

Carlo Denis

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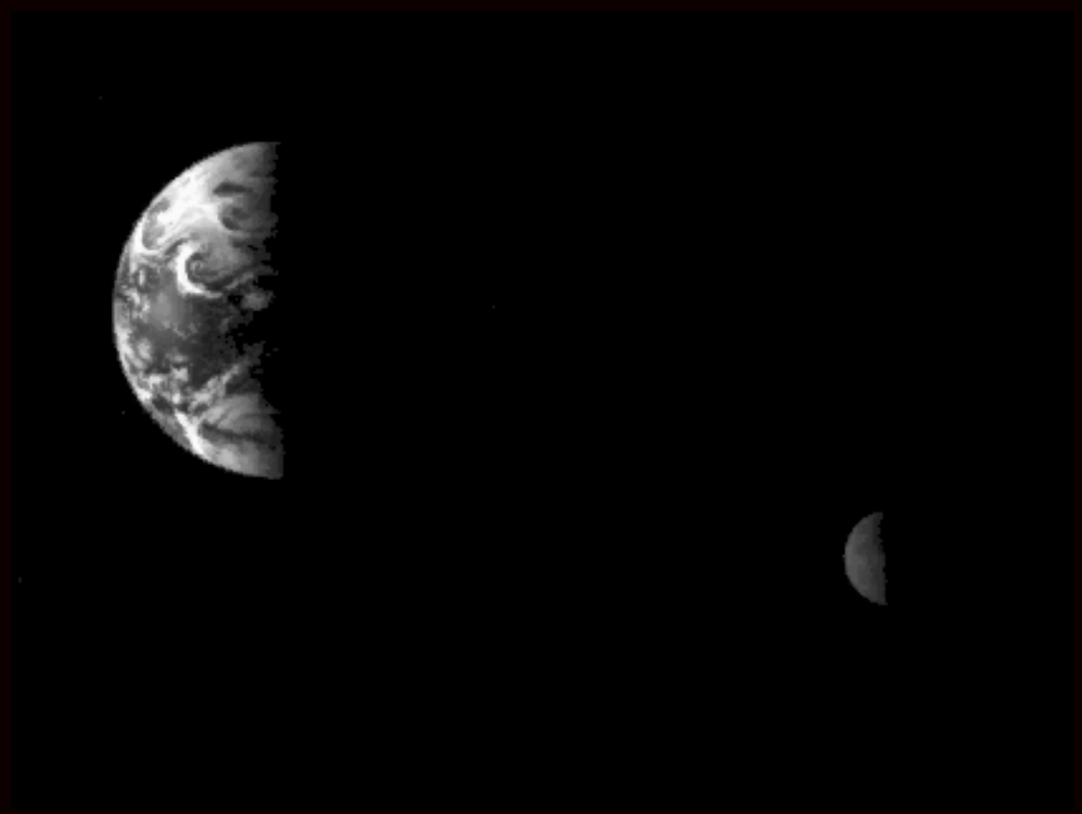
Section of Astrophysics and Geophysics

European Centre of Geodynamics and Seismology



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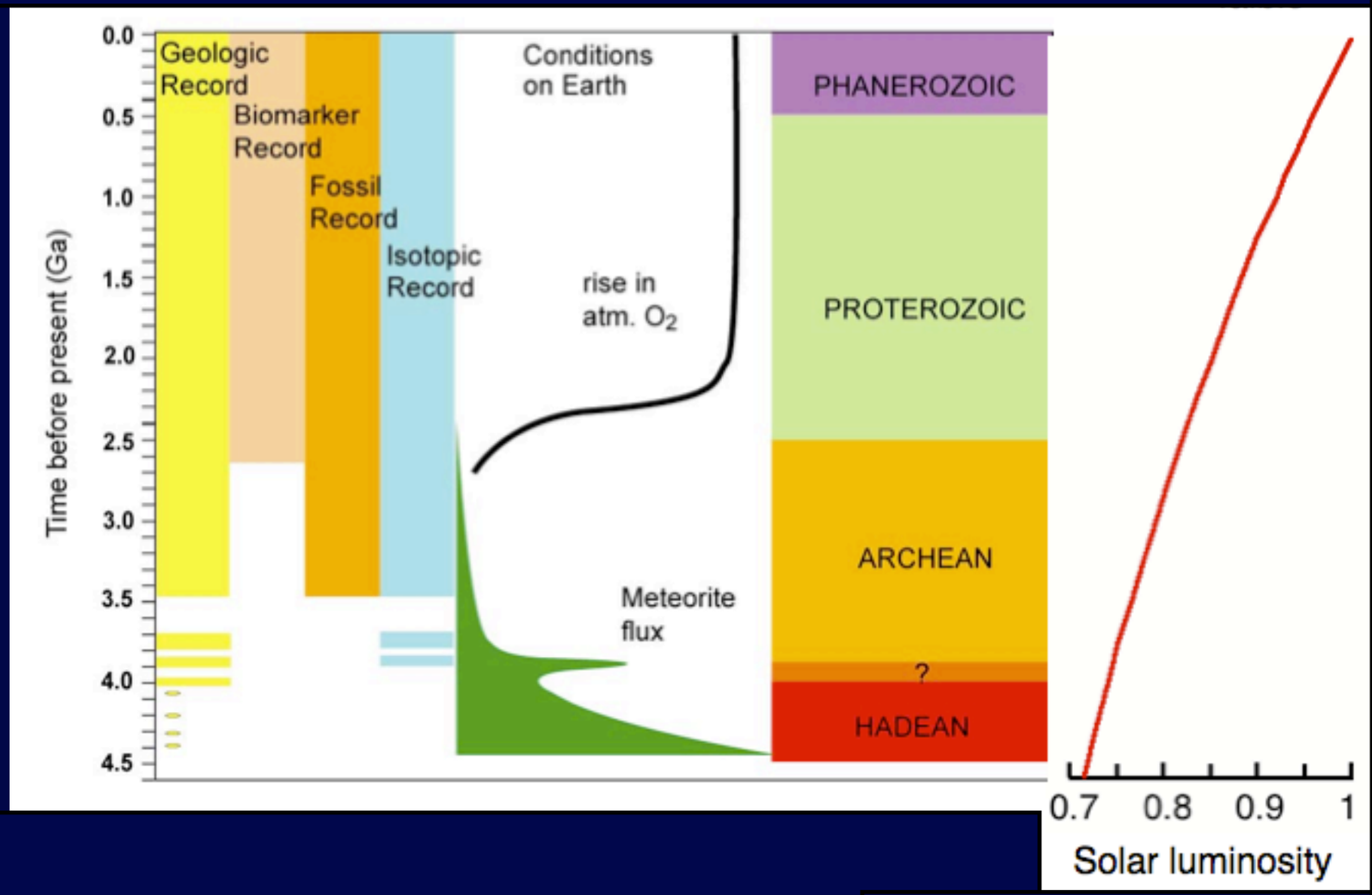
Archaean Environment



Solar luminosity paradox : if the atmosphere had been the same in the Archaean than now, the whole Earth surface should have been frozen throughout geological time and life would not have come into existence

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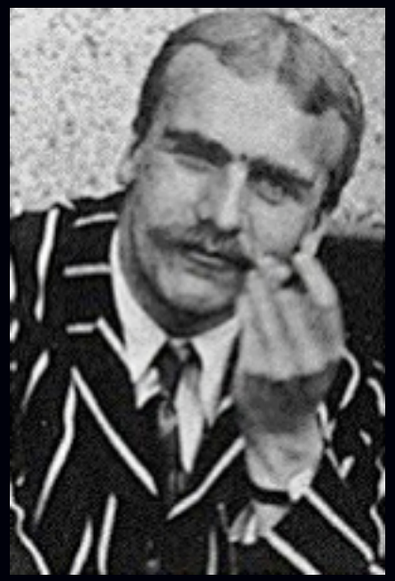
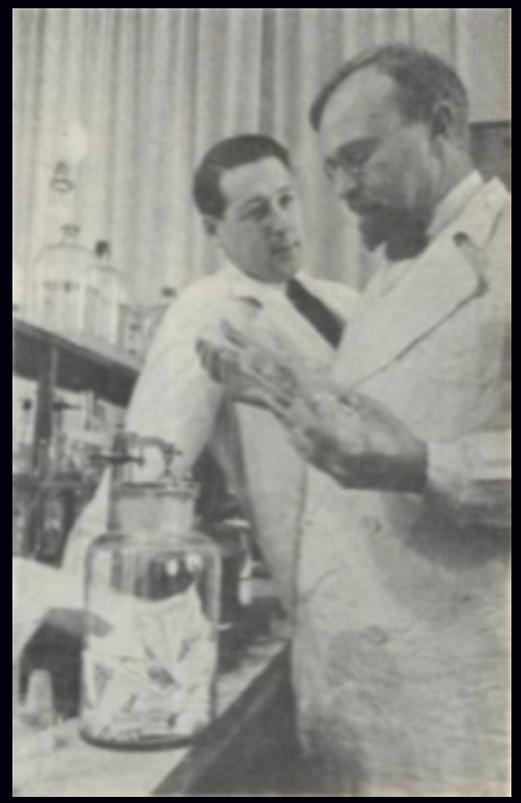


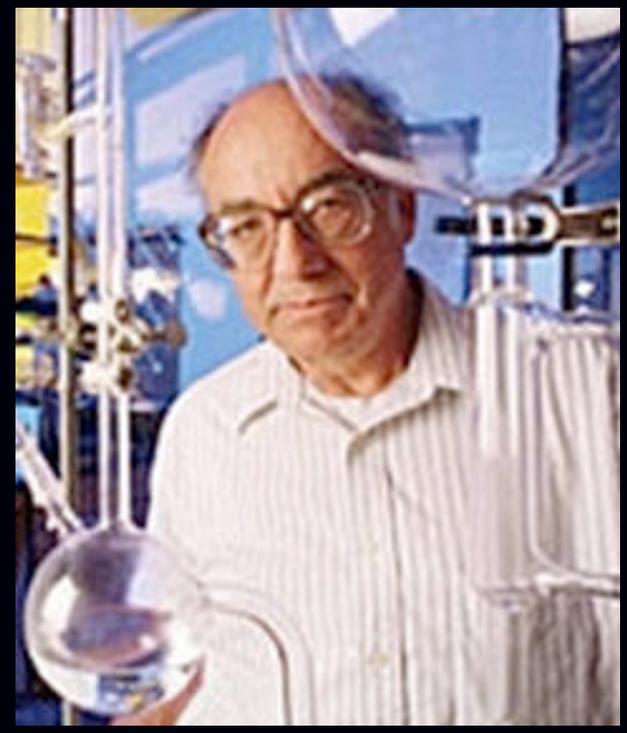
J. Haldane
(1894-1980)

A.I. Oparin
(1894-1980)



A.I. Oparin & A. Kursanov
(1938)

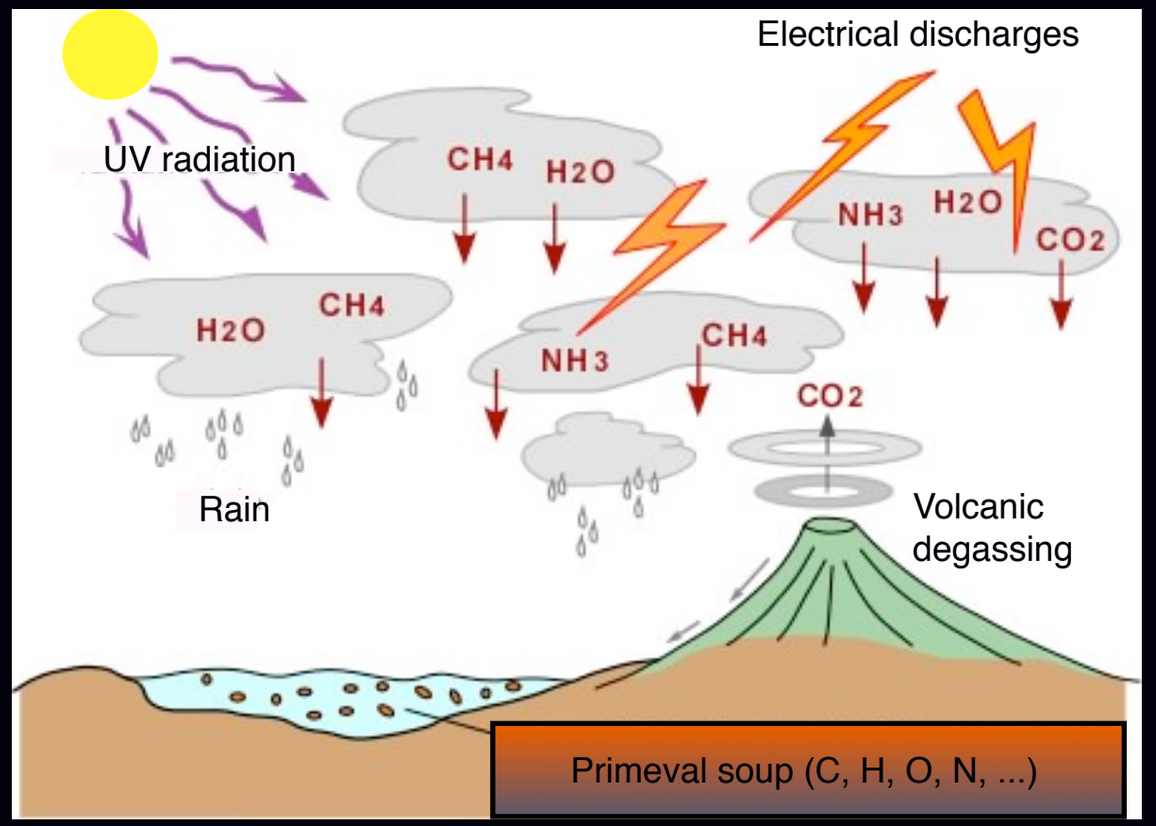
H. Urey
(1893-1981)

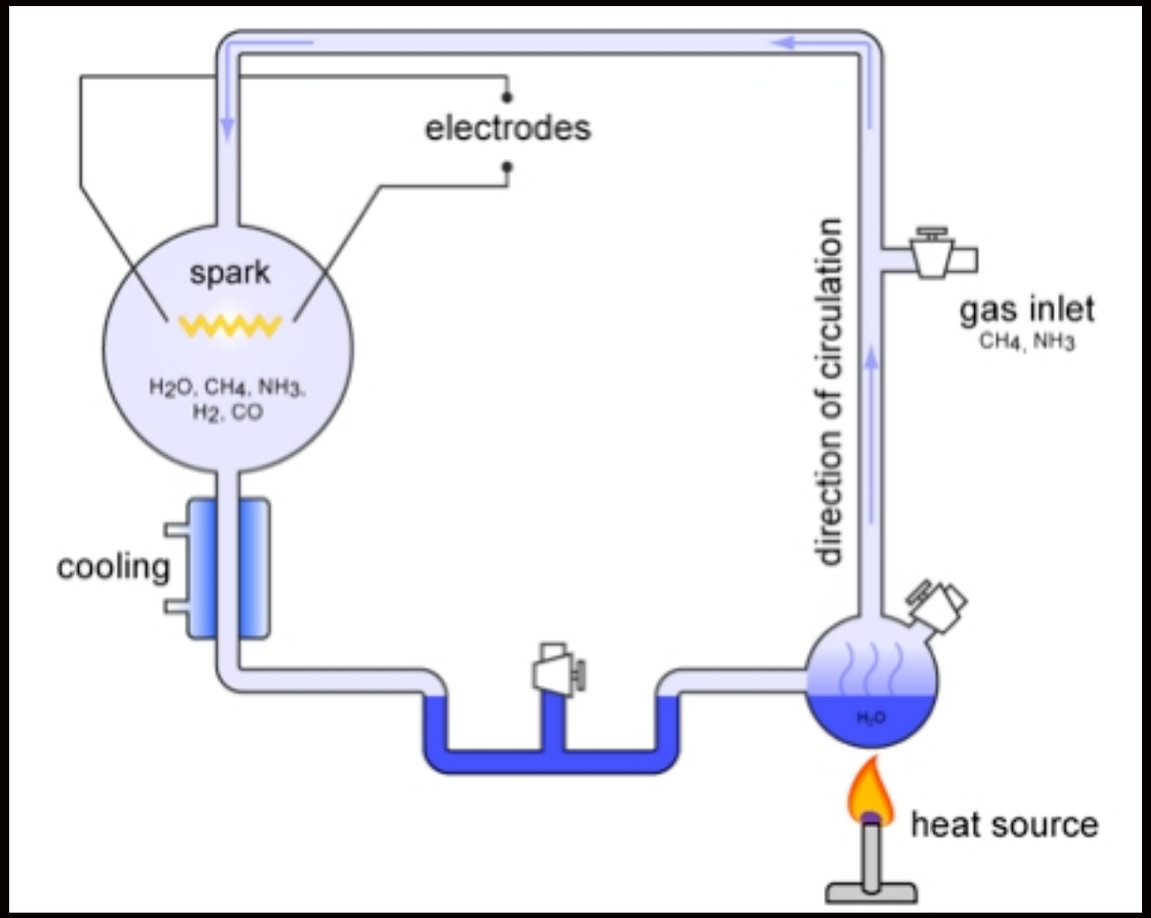


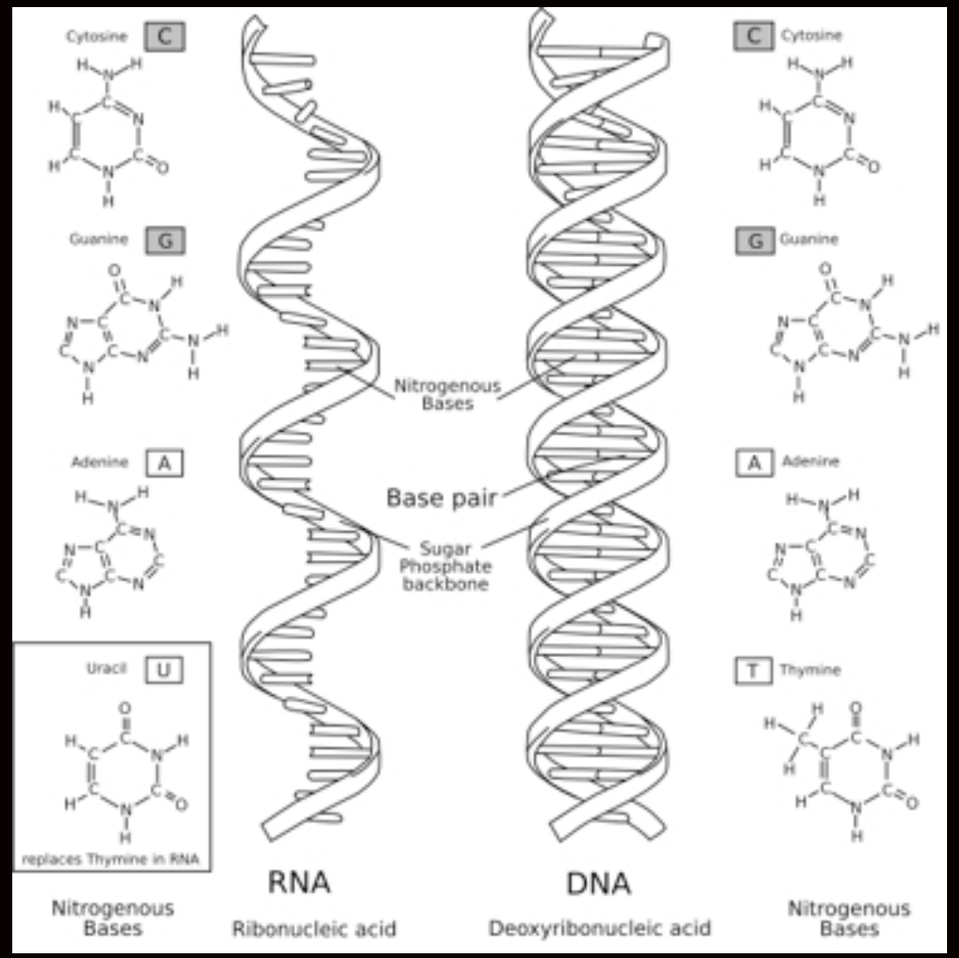
S. Miller
(1930-2007)

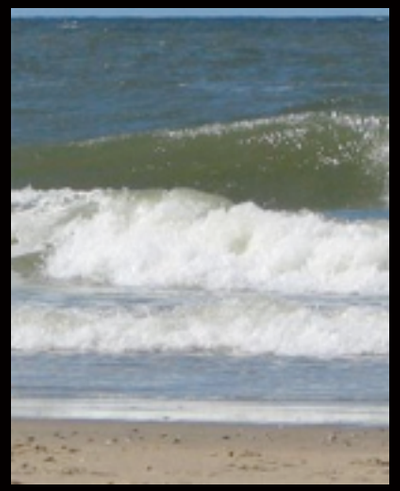
Oparin (1922): There is no fundamental difference between a living organism and lifeless matter. The complex combination of manifestations and properties so characteristic of life must have arisen in the process of the evolution of matter.

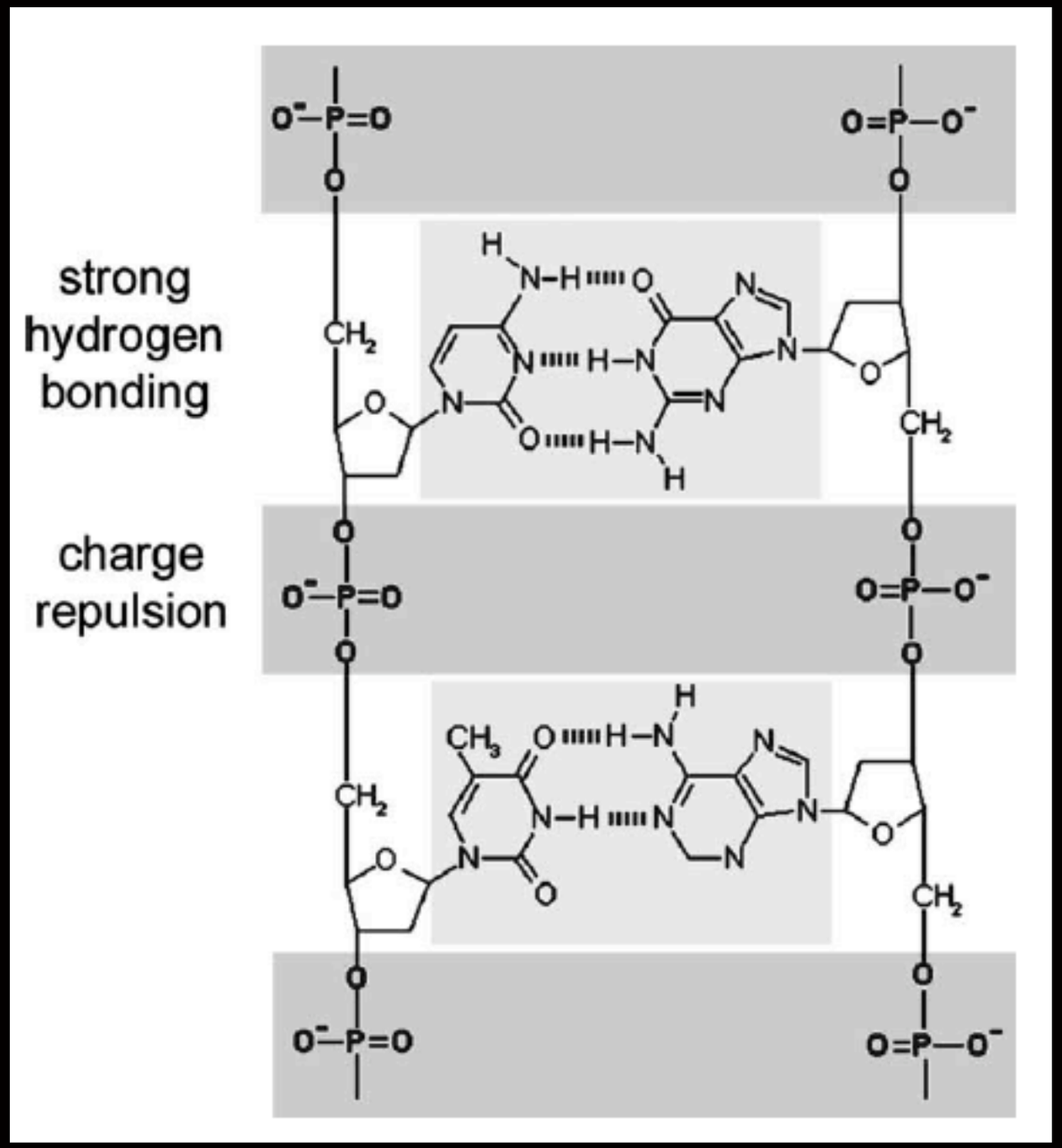
Miller-Urey experiment (1953)

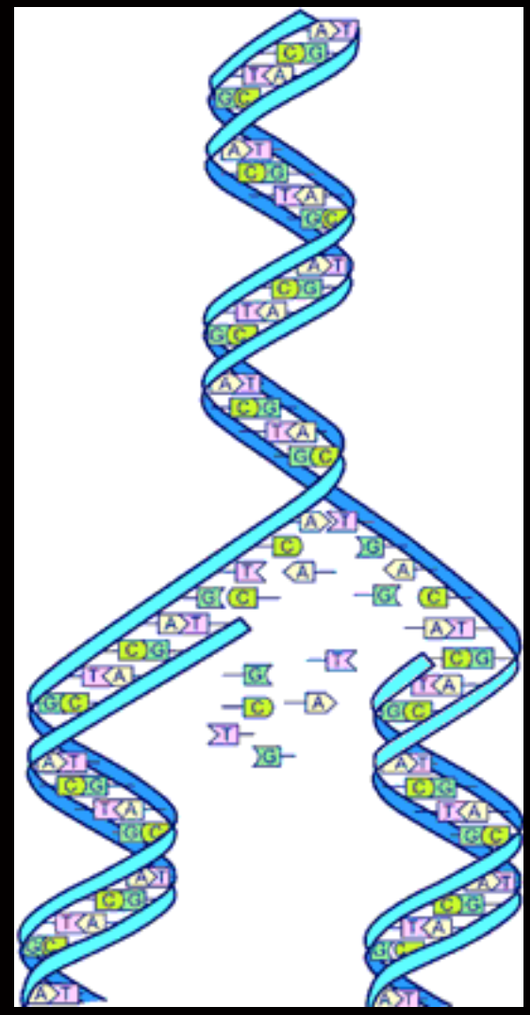



electrodes
spark
H_2O, CH_4, NH_3, H_2, CO
cooling
direction of circulation
gas inlet
CH_4, NH_3
H_2O
heat source


Cytosine C
Guanine G
Adenine A
Uracil U
replaces Thymine in RNA
Nitrogenous Bases
RNA
Ribonucleic acid
Nitrogenous Bases
Base pair
Sugar Phosphate backbone
DNA
Deoxyribonucleic acid
C Cytosine
G Guanine
A Adenine
T Thymine
Nitrogenous Bases







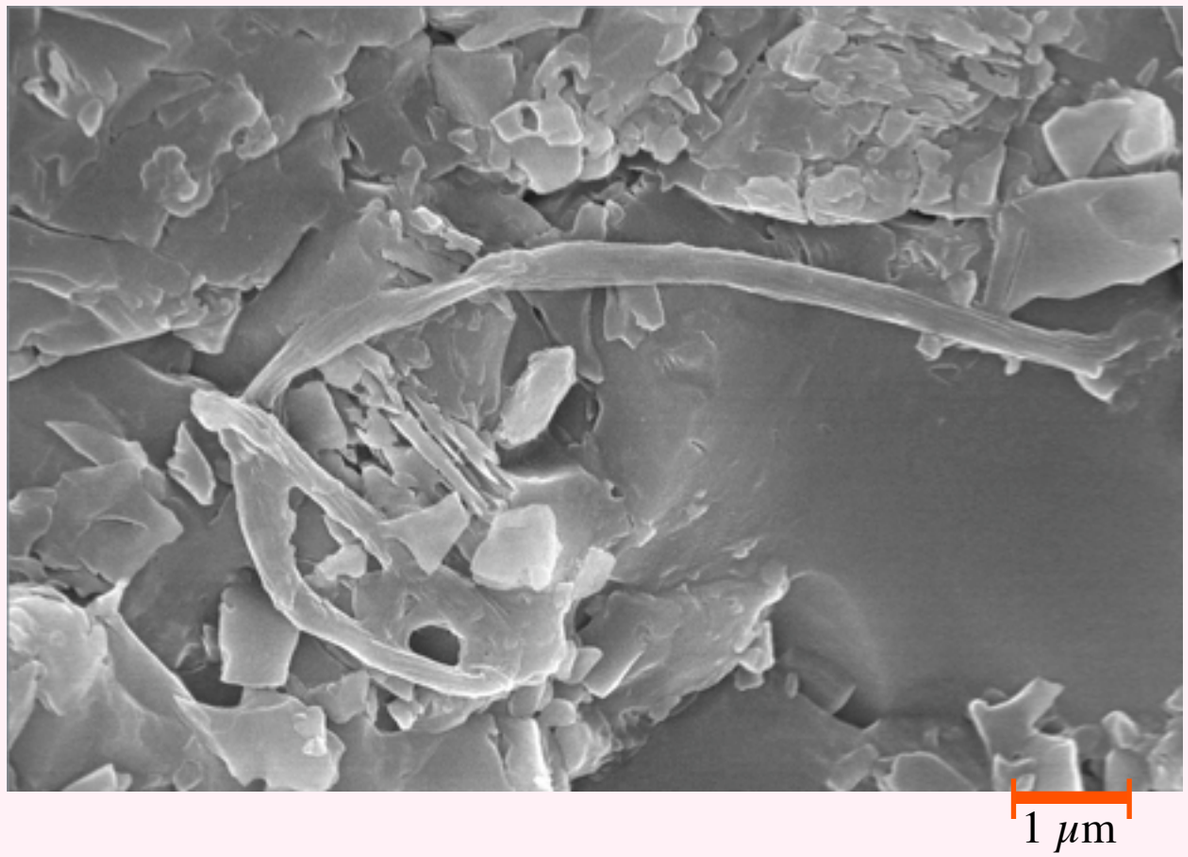
DNA split

flooding ⇒ dilution [NaCl]↓ ⇒ dissociation
drying ⇒ concentration [NaCl]↑
⇒ neutralisation of repulsion between opposing phosphate groups ⇒ association

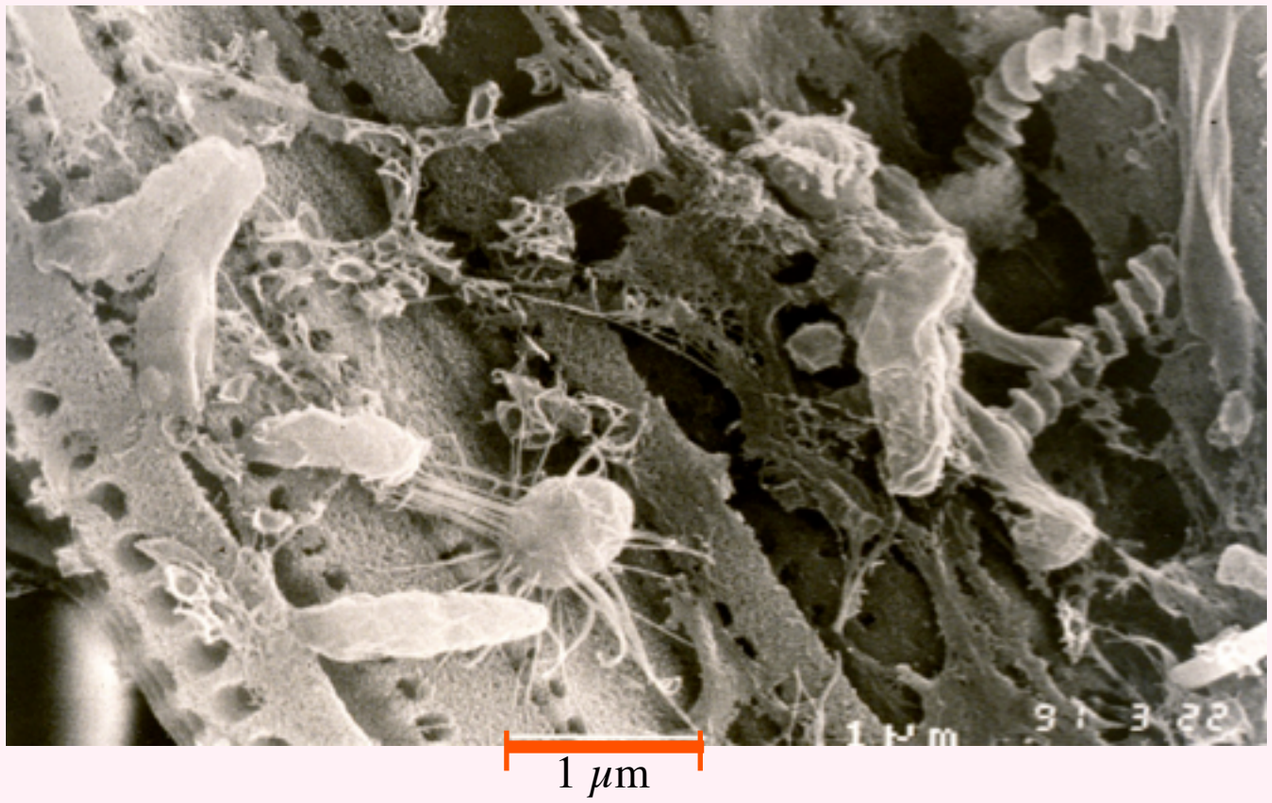
When and how did life begin on Earth?

How ?

- panspermia — bacteria were brought to Earth from space
- endogeneous origin — bacteria formed in the Archaean ocean



Archaean fossil bacteria

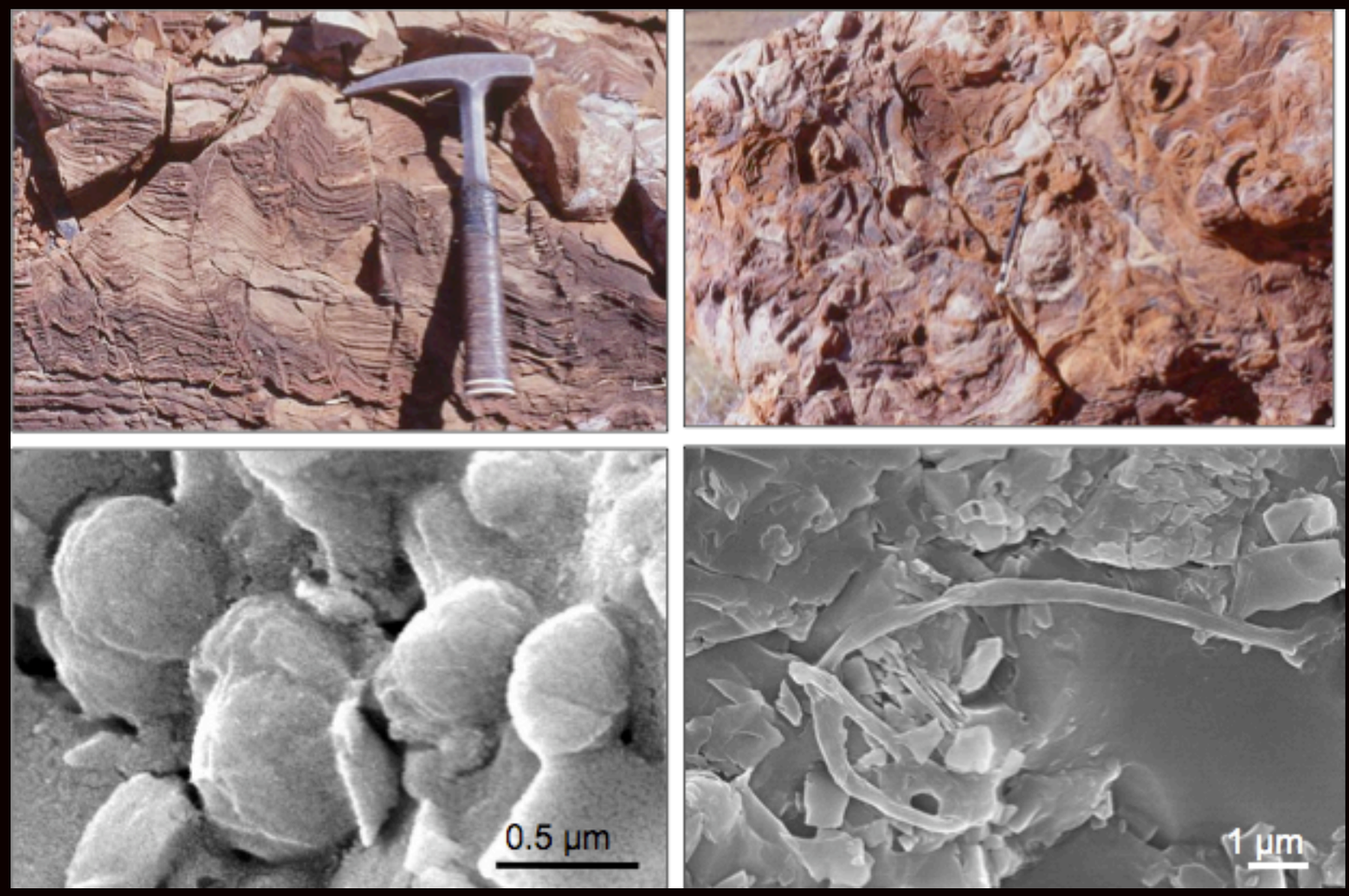


Contemporary bacteria

When and how did life begin on Earth?

WHEN ?

Chert (IPA: /ˈtʃəː(r)t/) is a fine-grained silica-rich cryptocrystalline sedimentary rock that may contain small fossils



Traces of primitive life (ca. 3.5 Ga old)

When and how did life begin on Earth?

WHEN ?

Oldest evidence of photosynthesis

By Paul Rincon
BBC News Online science staff

Scientists claim to have found the oldest evidence of photosynthesis - the most important chemical reaction on Earth - in 3.7-billion-year-old rocks.

The rocks from Isua are amongst the oldest on Earth

Photosynthesis is the process by which plants, algae and certain bacteria convert sunlight to chemical energy.

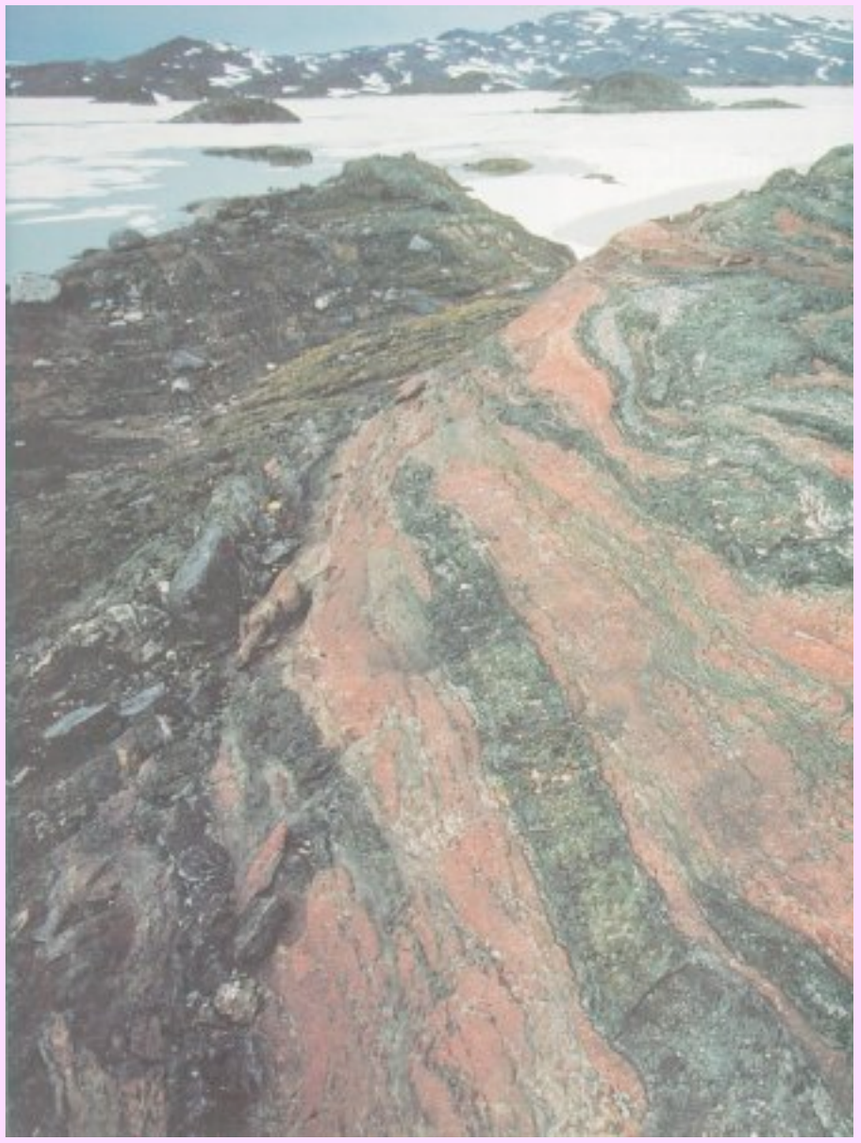
Danish researchers say rocks from Greenland show life-forms were using the process about one billion years earlier than has previously been shown.

Details of the research are published in Earth and Planetary Science Letters.

> **"Life may be older and more robust than we thought"**
>
> Dr Roger Buick, University of Washington, Seattle

Professor Minik Rosing and Professor Robert Frei, both of the University of Copenhagen, Denmark, analysed ancient seafloor sediments in Isua, Greenland, where they had previously found the earliest evidence of life on Earth.

"What this demonstrates is that the Earth had a functioning biosphere before 3.7 billion years ago," Professor Rosing told BBC News Online.



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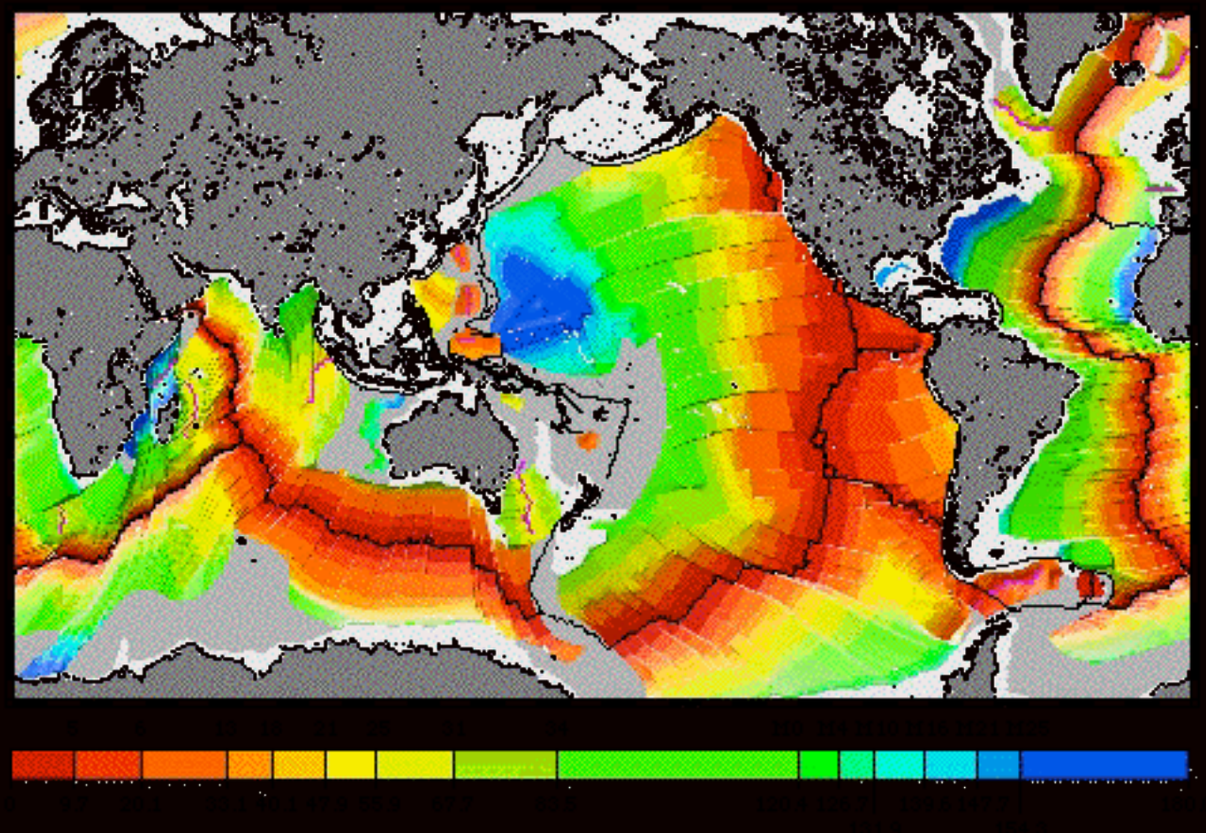
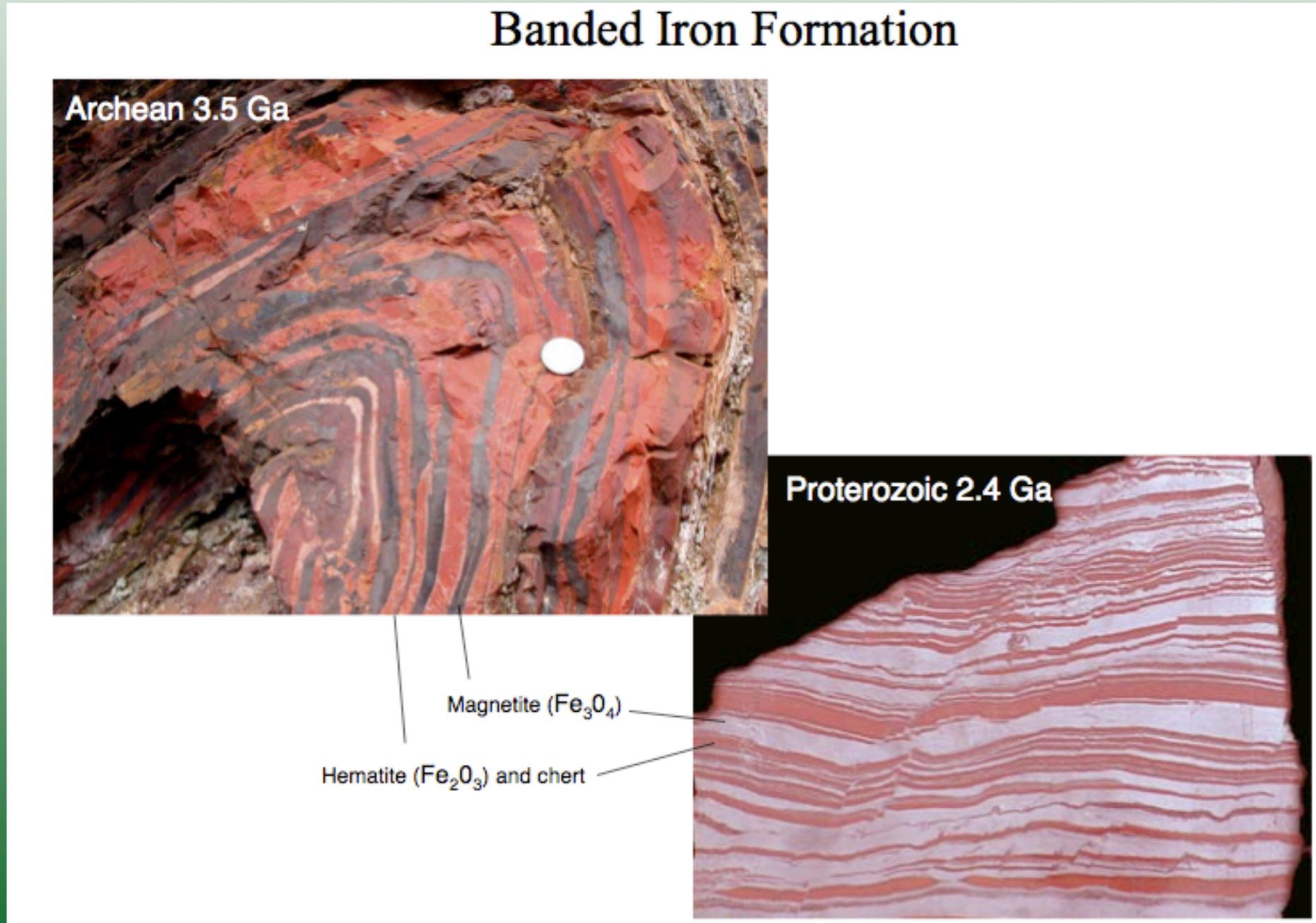
Were there salty seas already 3.9 Ga ago?



The oldest ocean floors found today are not older than 180 Ma.

Were there salty seas already 3.9 Ga ago?



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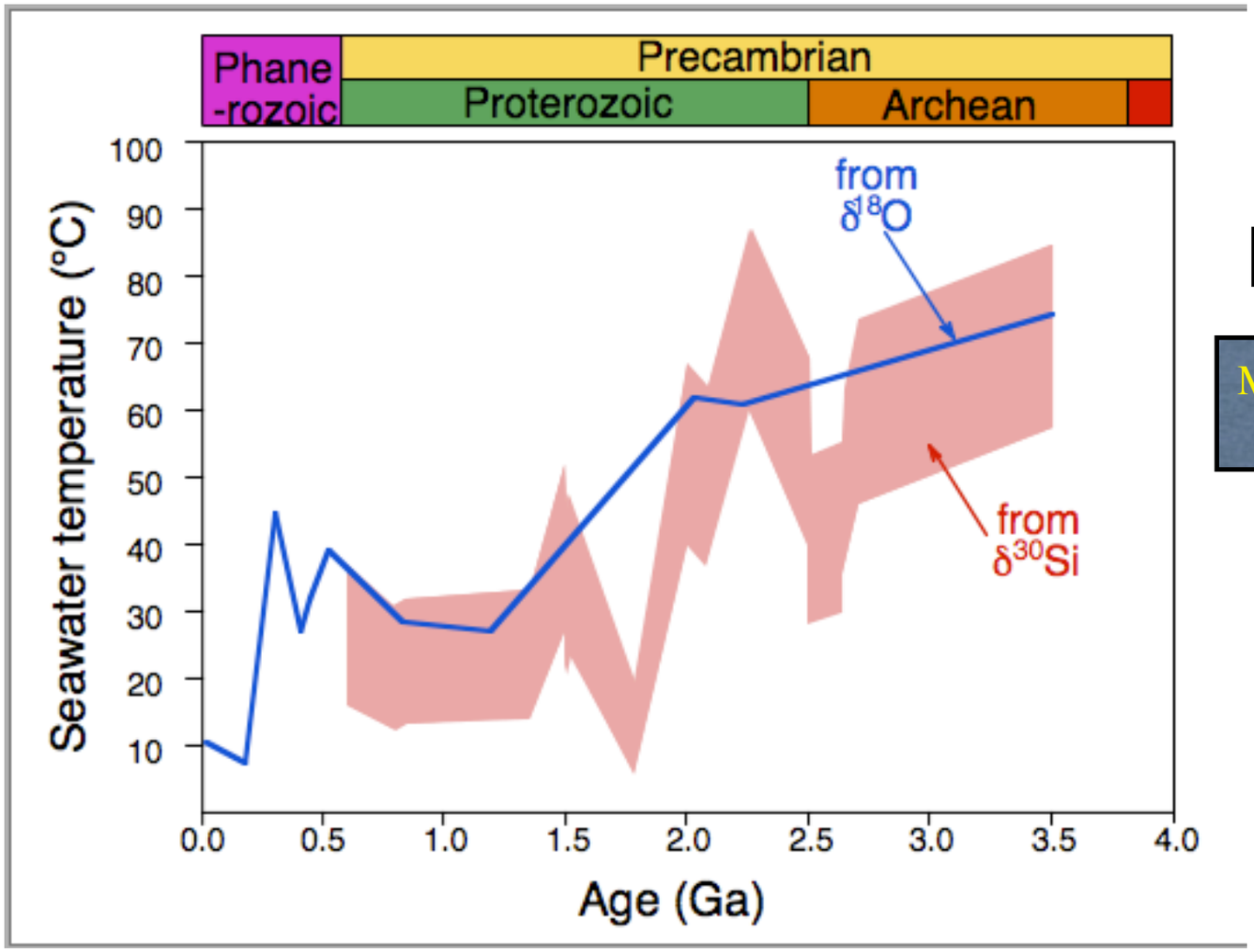
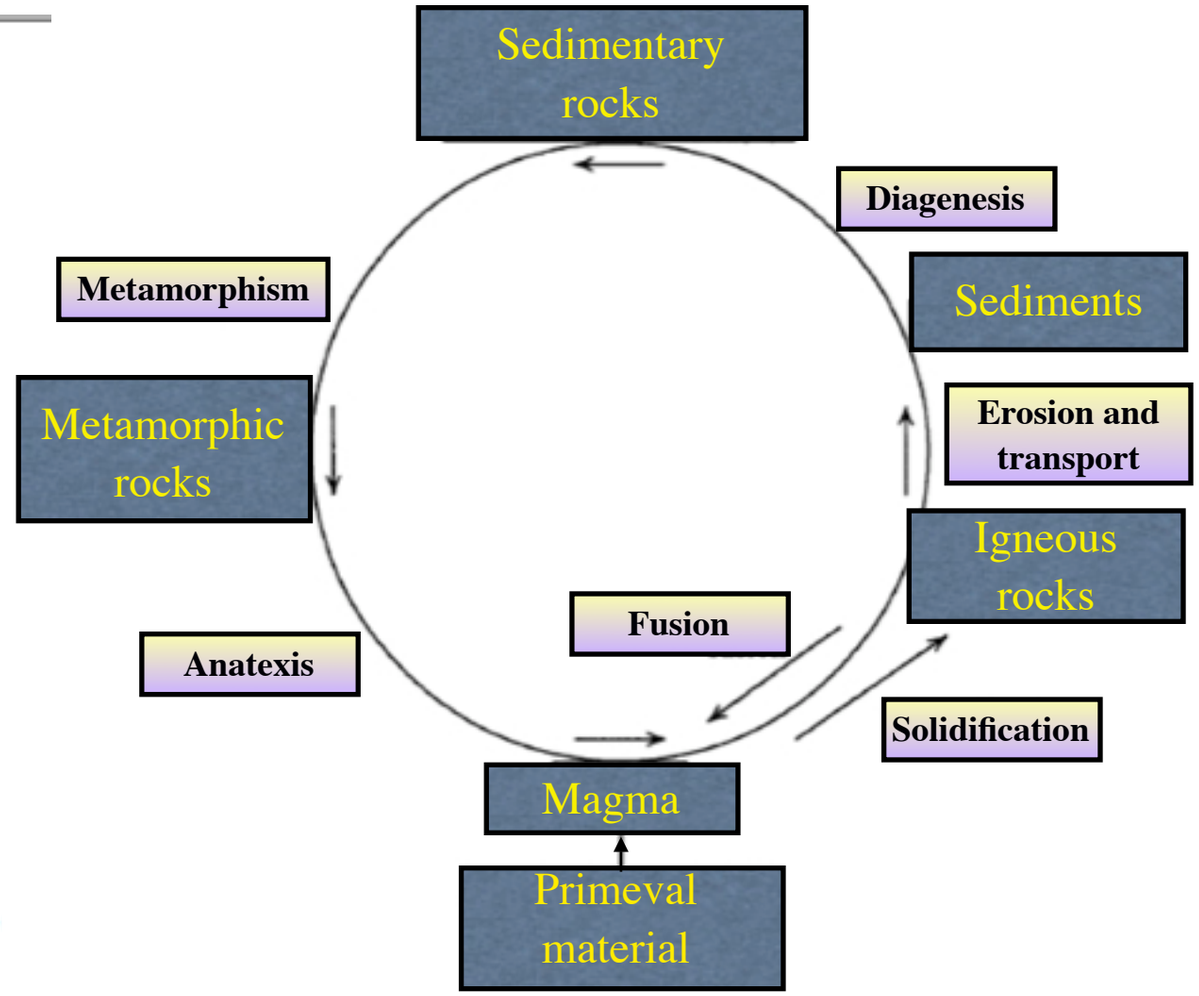
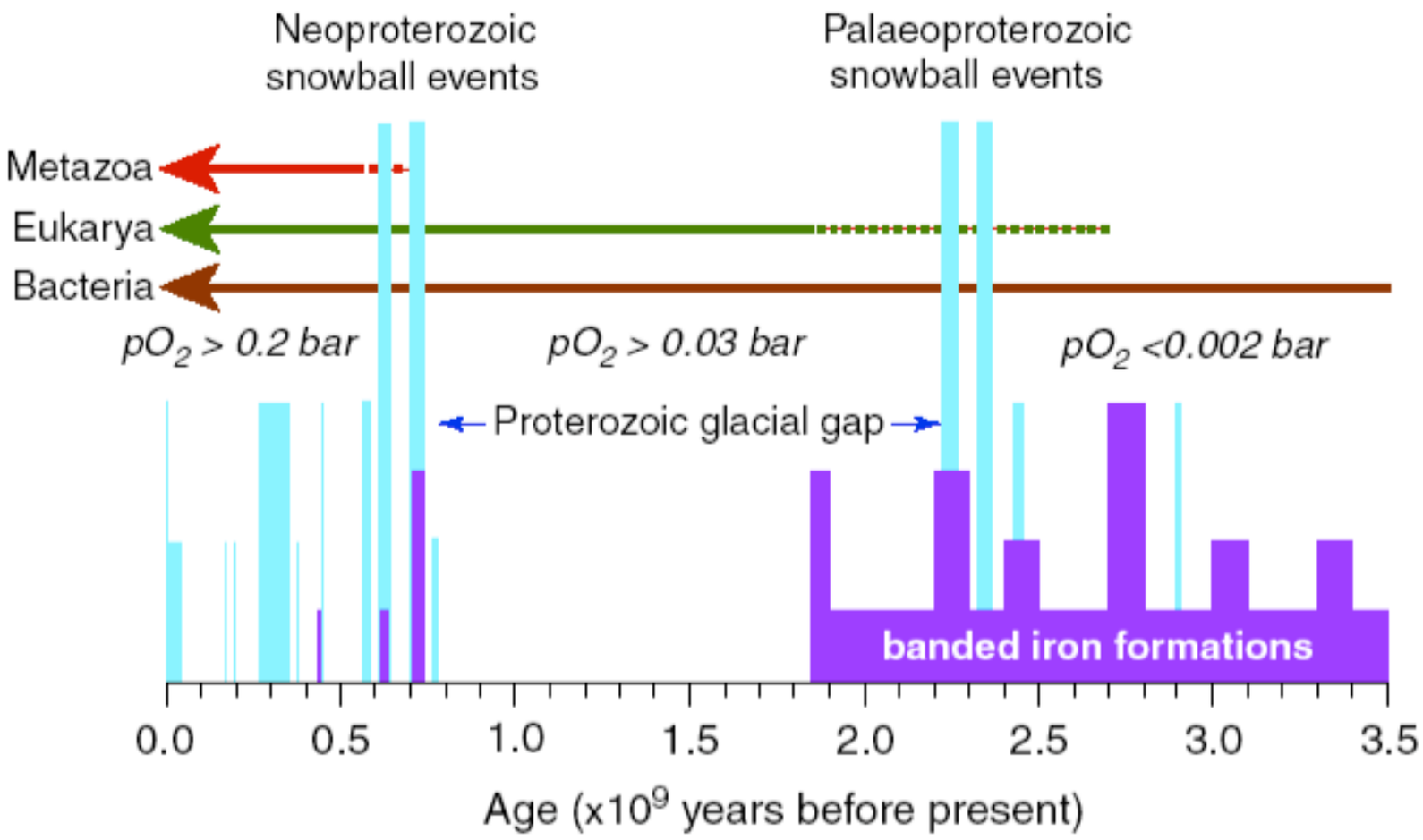




Geological cycle

We can be sure that oceans existed at least 3.8 Ga ago (oldest known marine sediments) and were quite warmer than now, but there were oceans probably as early as 4.4 Ga ago. However, we cannot be sure that there were dissolved salts in the oceans earlier than 1 Ga ago, though this seems more than plausible. Indeed, marine evaporites older than 1 Ga have been destroyed in the geological cycle.

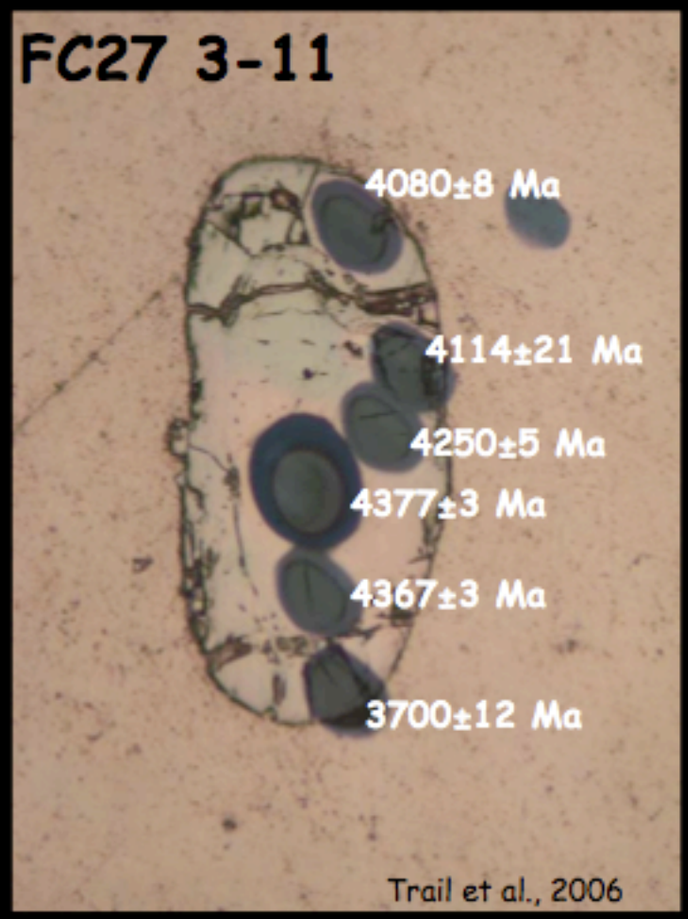


Evidence for marine sediments and global glaciations in the Precambrian

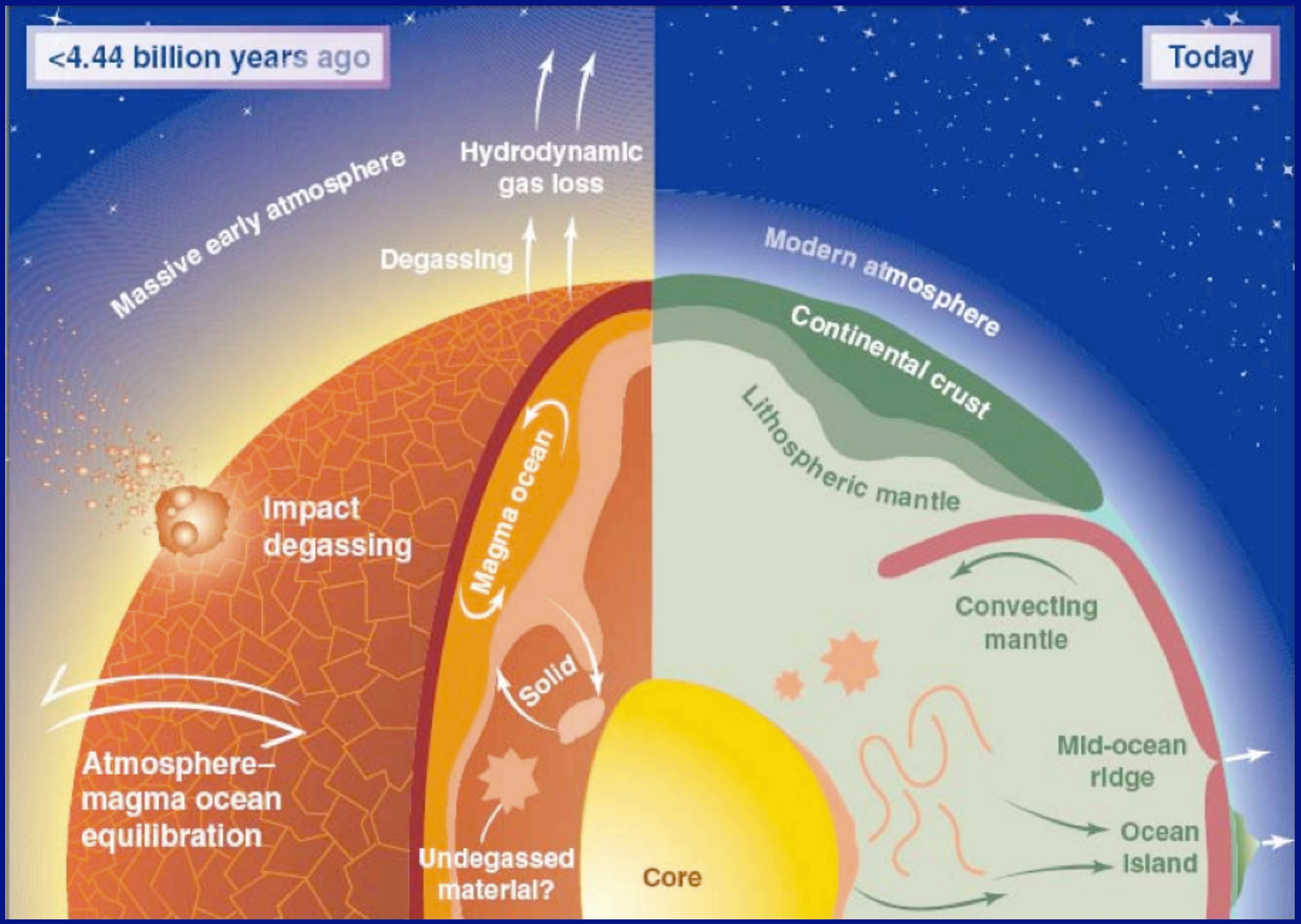
Zircons

Jack Hills, NW Australia – The Archaean sediments contain detrital zircons aged up tu 4.4 Ga.

Geological samples

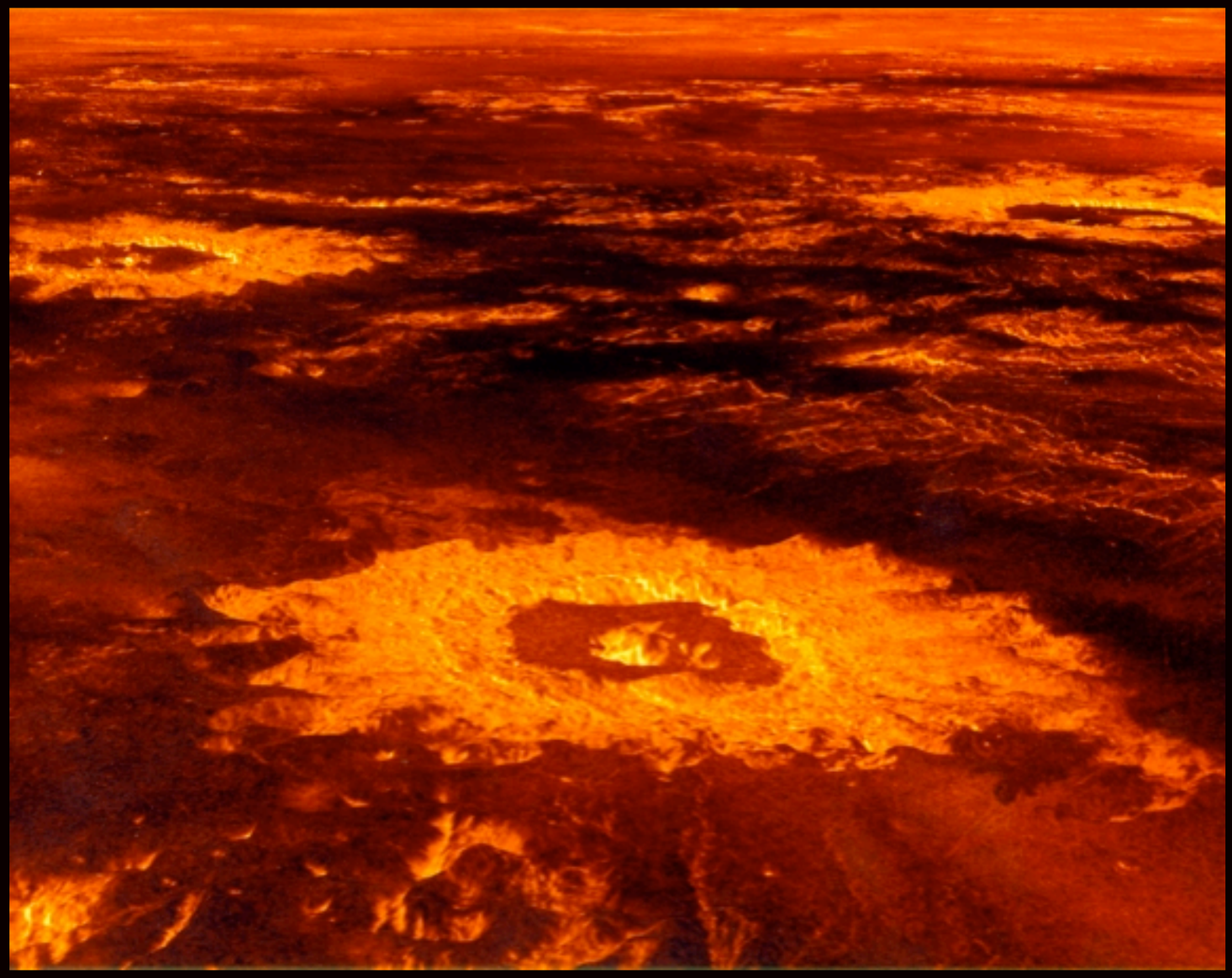


What did the Earth's surface look like 3.9 Ga ago?



What did the Earth's surface look like 3.9 Ga ago?

← Surface of Titan

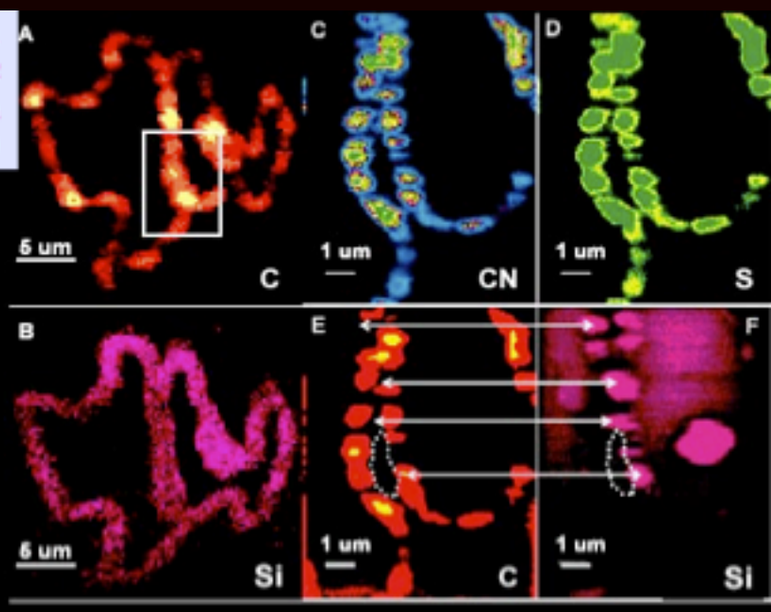


Impact craters on Venus ↑


Image: N.A.S.A.

Stromatolites, ancient and modern

Images chimiques de microfossiles de 0.8 Ga faites avec la Nanosims du Muséum (Robert et al., 2006)



Stromatolite moderne, Shark Bay, Australie

Stromatolites de 3,4 milliards d'années : Dresser formation, North Pole, Australie

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How and when did the Moon form?

Most important constraint :

Conservation of the total angular momentum of the Earth-Moon system

$$L_{\mathrm{EMS}} = C\omega + m\,c^2 n$$

$$C(t)\omega(t) + m(t)c^2(t)n(t) = C_0\omega_0 + m_0 c_0^2 n_0$$

$$L_{\mathrm{EMS}} = 3.476 \times 10^{34}\,\mathrm{kg\,m^2\,s^{-1}}$$

How and when did the Moon form?

(1) Fissure theory (Darwin, 1879)

Initially, Earth and Moon formed a single planet

$\Rightarrow$ rotation period given by

$$L_{\rm EMS} = 3.476 \times 10^{34}\,{\rm kg\,m^2\,s^{-1}}$$

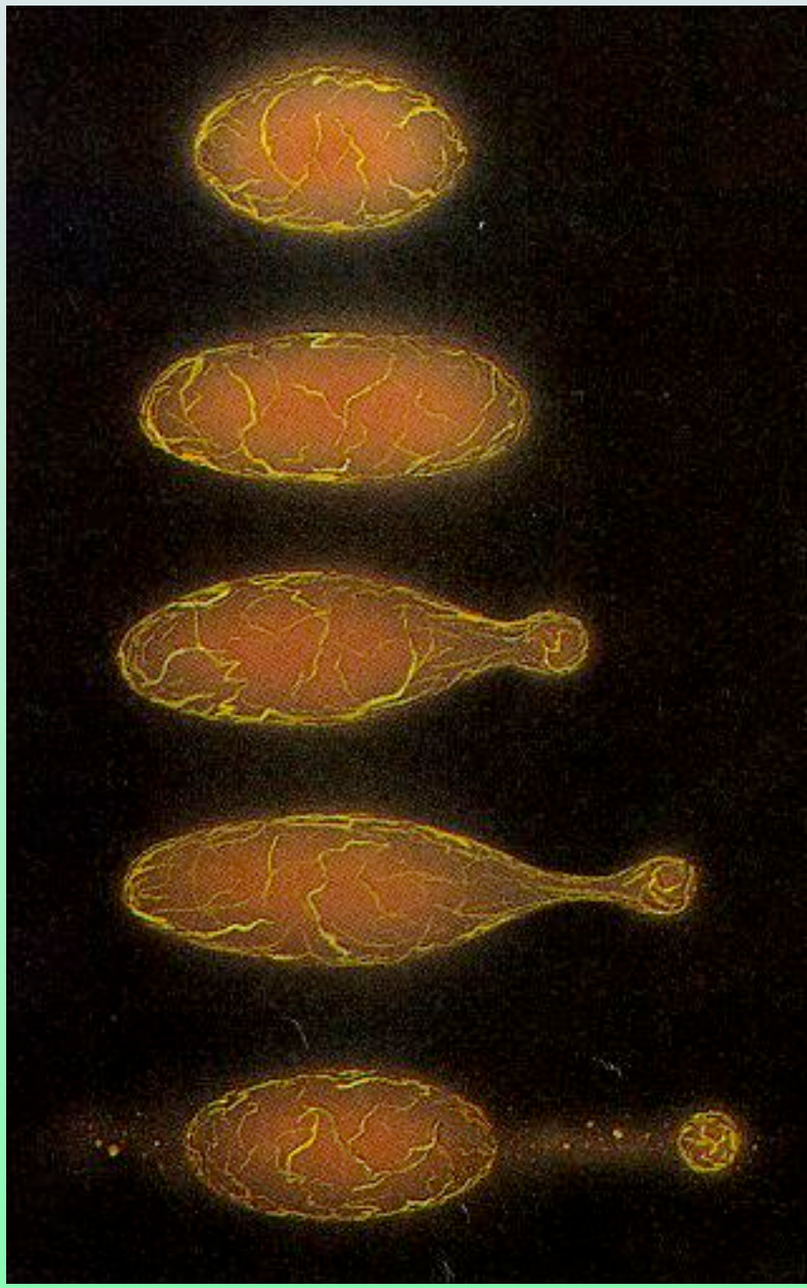
$\Rightarrow$ initial rotation period : $T_o = 4.25$ h

- rotational instability $\omega^2 a \geq {\rm GM}/a^2 \Rightarrow$

$$T_o = 1.4\ {\rm h}$$

- resonance theory

Wise (1963, 1969) and Ringwood (1960, 1970, 1979) tried to revive the fission theory, but it is now considered obsolete.

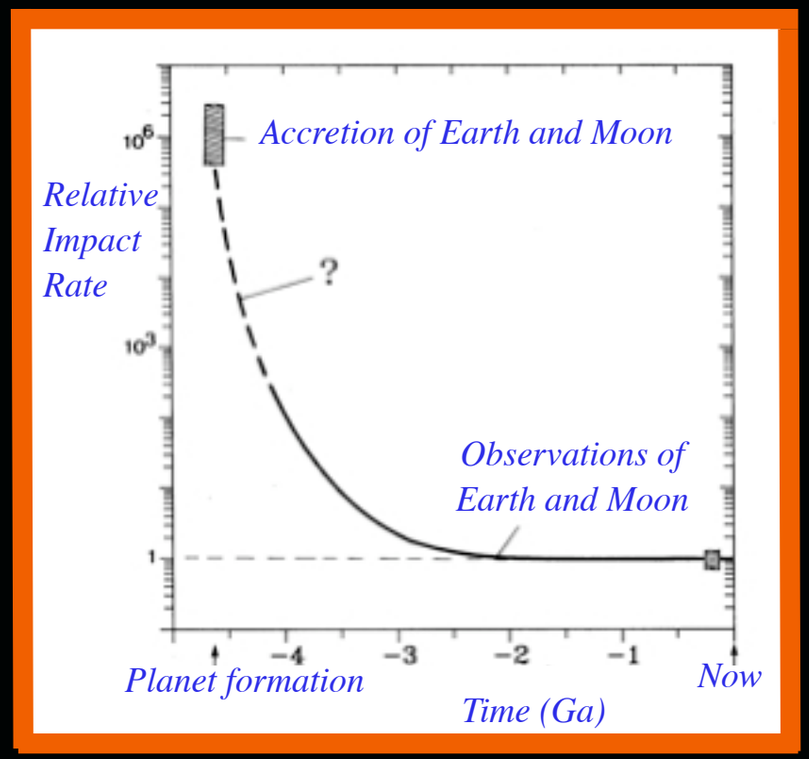


How and when did the Moon form?

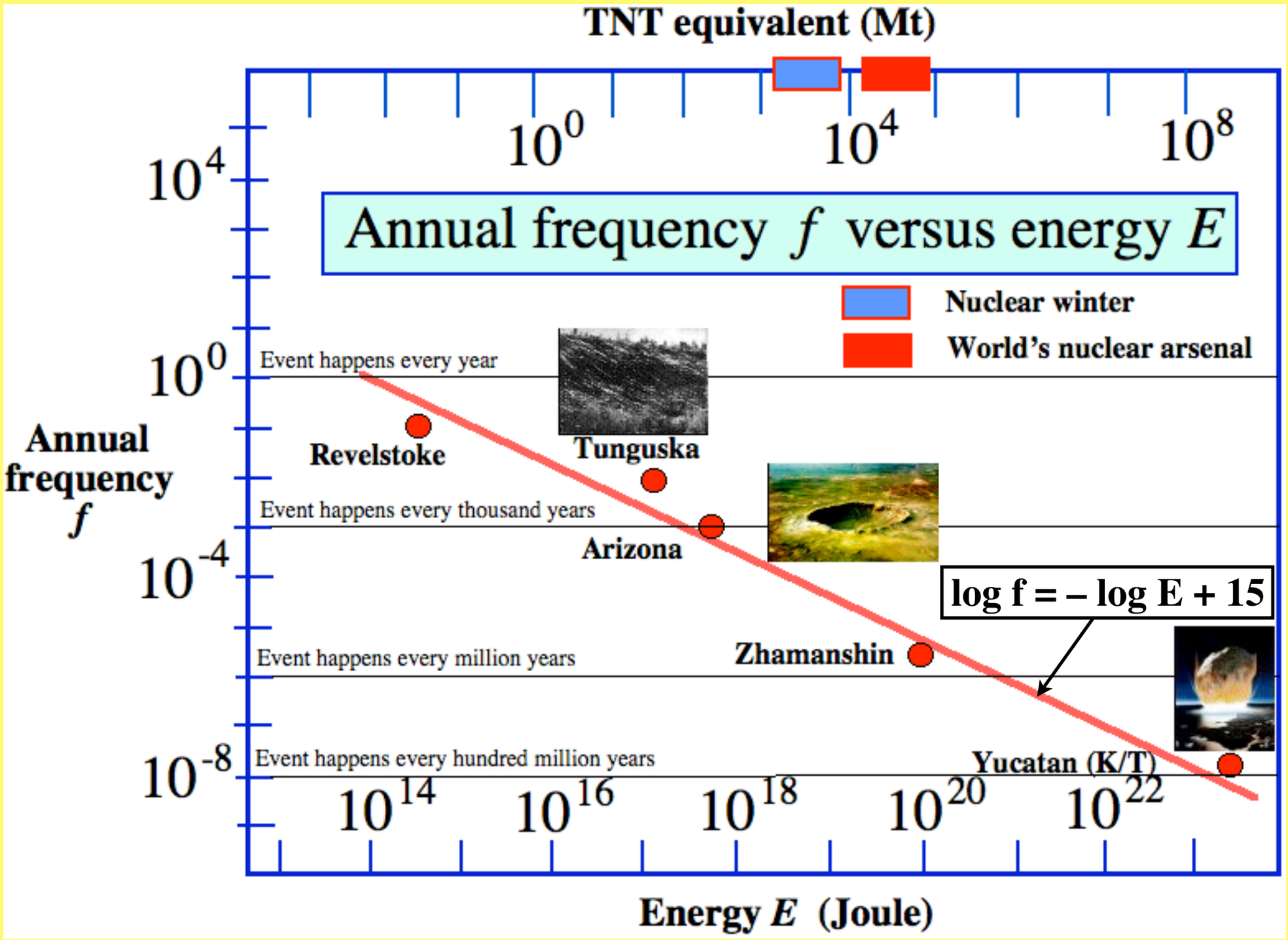
(2) Capture theory (Gerstenkorn, 1955, 1969)

The capture theory it is now considered obsolete.

(3) Impact theory (Hartmann & Davis, 1975; Cameron & Ward, 1976)



Collisions between embryonic planets and planetesimals



Kinetic energy associated with the rotation of the Earth : 2 x 10^29 J

For a Mars-sized asteroid: log E ≅ 31 .. 32 ⇒ log *f* ≅ –16 .. –17

How and when did the Moon form?

(4) Double planet theory

Earth and Moon were born simultaneously during the accretion process that led to the formation of the whole solar system, out of two gravitationally interacting turbulent eddies composed of gas, dust and planetesimals.

Most ‘serious’ objection found in the literature: Why do Mercury and Venus not have any satellite, and why is the Moon such a large satellite compared to the Earth?

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Did the Earth ever rotate very fast?

(that is, at rates as fast as those suggested by Lathe)

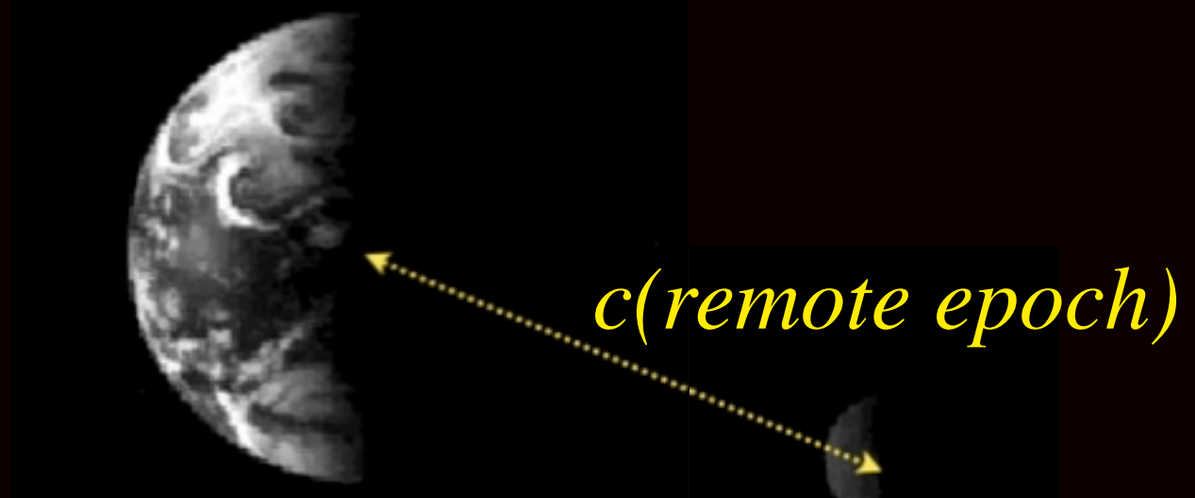
- Theoretical considerations
  - ◊ celestial mechanics (lunar recession rate)
  - ◊ tidal theory
  - ◊ theory of tidal friction

- Empirical data
  - ◊ paleo-LOD values obtained from ‘fossil clocks’
  - ◊ paleogeographic coastlines

Theory

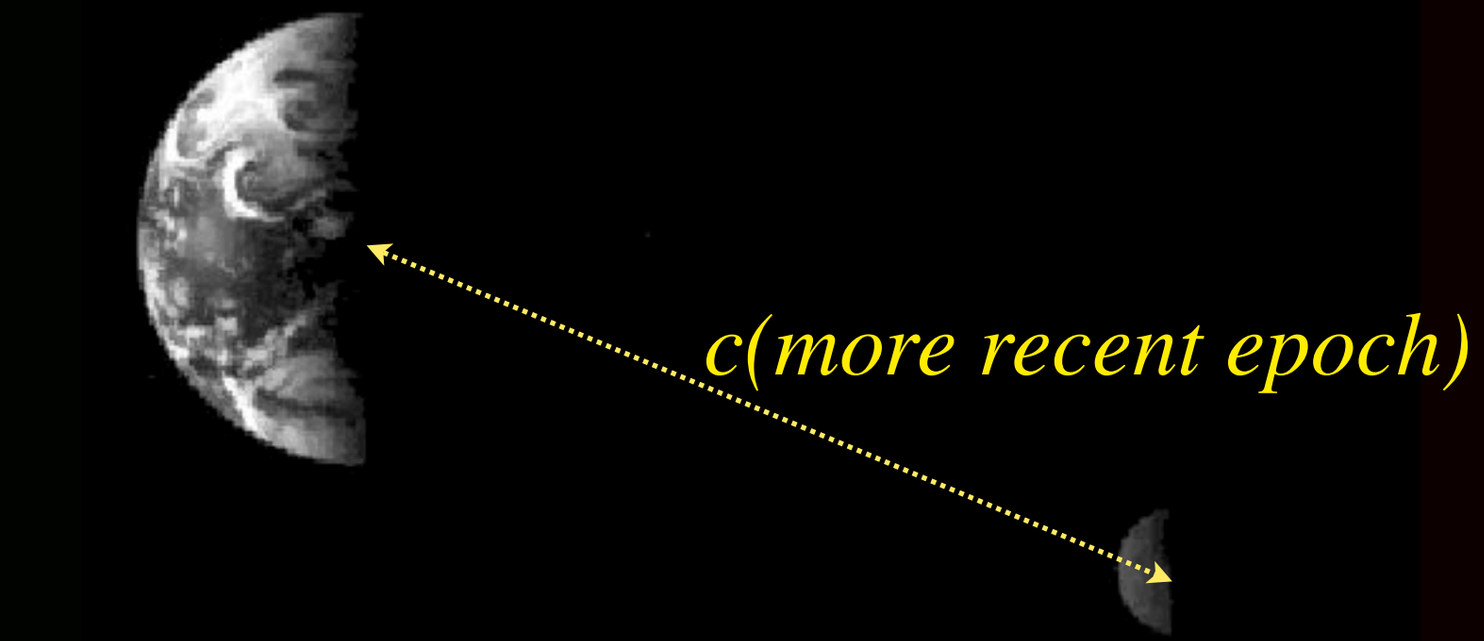
Earth-Moon distance

In the very distant past



At a later epoch

$c = 6371\ \gamma$



The conservation of the total angular momentum of the Earth-Moon system results in lunar recession throughout geological time. At the present epoch, the Moon recedes from the Earth at a rate of about 3.8 cm per year.

$$C\Omega + mc^2 n = C_o\Omega_o + mc_o^2 n_o$$

After core formation was completed:

$$C \approx C_o.$$

Kepler's Third Law: $n \approx (GM)^{1/2} c^{-3/2}$

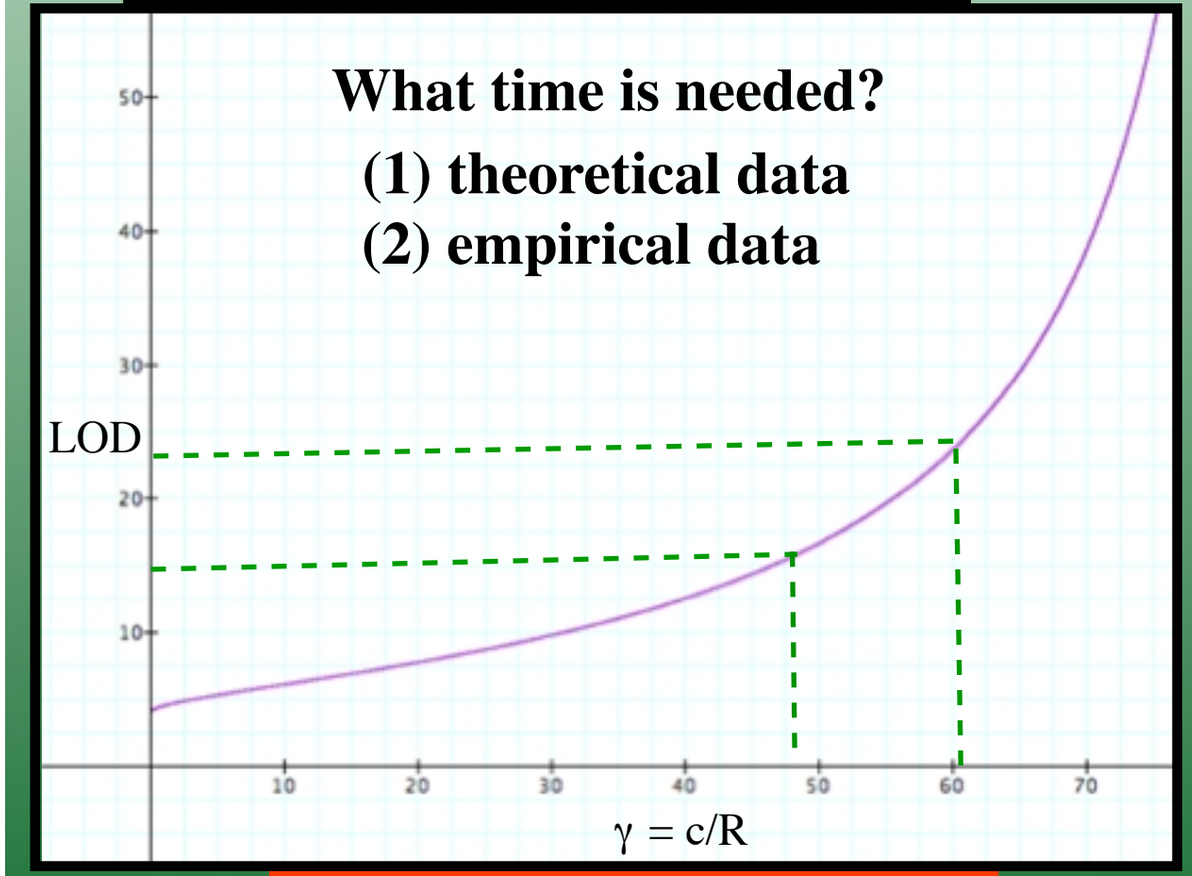
$$\Omega \approx \Omega_o + \frac{(GM)^{1/2} m}{C_o}\left(c_o^{1/2} - c^{1/2}\right)$$

Putting numerical values and expressing the lunar distance γ in terms of the Earth's mean radius $R = 6371\,\mathrm{km}$, $\gamma = c/R$:

$$\Omega \approx 4.306 \times 10^{-4}\left(1 - 0.107\,\gamma^{1/2}\right)$$

$$\mathrm{LOD} \approx \frac{4.053}{1 - 0.107\,\gamma^{1/2}} \text{ hours}$$

LOD	c / R
6.126	10.0
7.772	20.0
9.126	30.0
12.537	40.0
16.652	50.0
23.677	60.0



$$\gamma = \left(9.346 - \frac{37.88}{\mathrm{LOD}}\right)^2$$

Tidal torque

Hypotheses:

- core formation is completed ($C = C_o$)
- Moon's orbit is circular ($a = c$)
- change of Earth's spin $d\Omega/dt$ only caused by the lunar tidal retarding torque $-N$

$$\Omega \approx \Omega_o + \frac{(GM)^{1/2} m}{C_o}\left(c_o^{1/2} - c^{1/2}\right)$$

$$C_o \frac{d\Omega}{dt} \approx -\frac{(GM)^{1/2}\, m\, c^{-1/2}}{2}\frac{dc}{dt}$$

$$C_o \frac{d\Omega}{dt} = -N$$

$$\frac{dc}{dt} \approx \frac{2\, c^{1/2}\, N}{(GM)^{1/2}\, m}$$

for oceanic tides, provided the Moon is a few radii away from the Earth for the deformation equations to become linear, we have for the semi-diurnal tides:

$$N = \frac{8\pi\, G\, m\, R^4\, \rho_s\, H\, \sin 2\epsilon}{5\, c^3}$$

H is the height of the ocean tide raised by the lunar tide-generating potential W_2 of degree 2:

$$H = \frac{R^2\, W_2}{GM} = \frac{3\, m\, R^4}{4\, M\, c^3}$$

ρ_s is the density of sea water; ϵ is the tidal phase lag; if $\sin 2\epsilon \ll 1 \Longrightarrow 2\epsilon = Q^{-1}$

$$N = \frac{6\pi\, G\, m^2\, \rho_s}{5\, M}\frac{R^8}{c^6}\sin 2\epsilon$$

$$\frac{d\gamma}{dt} = \alpha\,\gamma^{-11/2}\,\sin 2\epsilon \approx \frac{\alpha}{Q}\,\gamma^{-11/2}, \quad \gamma = \frac{c}{R}$$

$$\alpha = \frac{12\pi\,G^{1/2}\,m\,\rho_s\,R^{3/2}}{5\,M^{3/2}} \approx 5.084\times10^{-6}\,\mathrm{s}^{-1}$$

Integrate from epoch t_1 to $t_2 = t_1 + \Delta t$:

$$\gamma^{13/2}(t_2) - \gamma^{13/2}(t_1) = \frac{13\,\alpha\,(t_2 - t_1)}{2\langle Q\rangle}$$

Assume $t_1 = 0,\ \gamma(0) = 0 \implies$

$$\Delta t \approx 3.03 \times 10^4\,\langle Q\rangle\,\gamma^{13/2}$$

$$\gamma \approx \left(\frac{\Delta t}{3.03 \times 10^4\,\langle Q\rangle}\right)^{2/13}$$

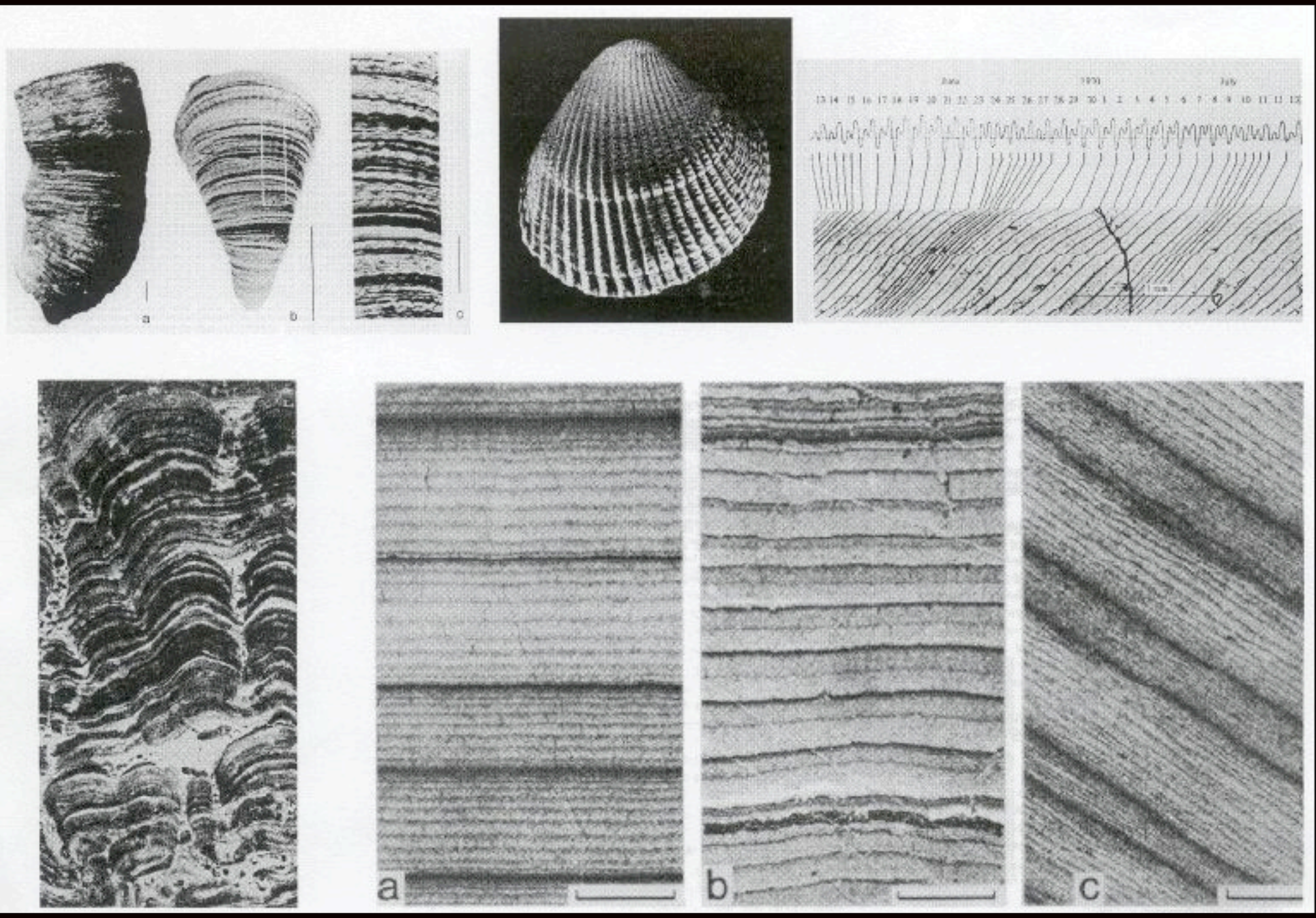
After $\Delta t = 500\,\mathrm{Ma}$

for $\langle Q\rangle = 10 \implies \gamma = 44.54$ LOD = 14.18 hr

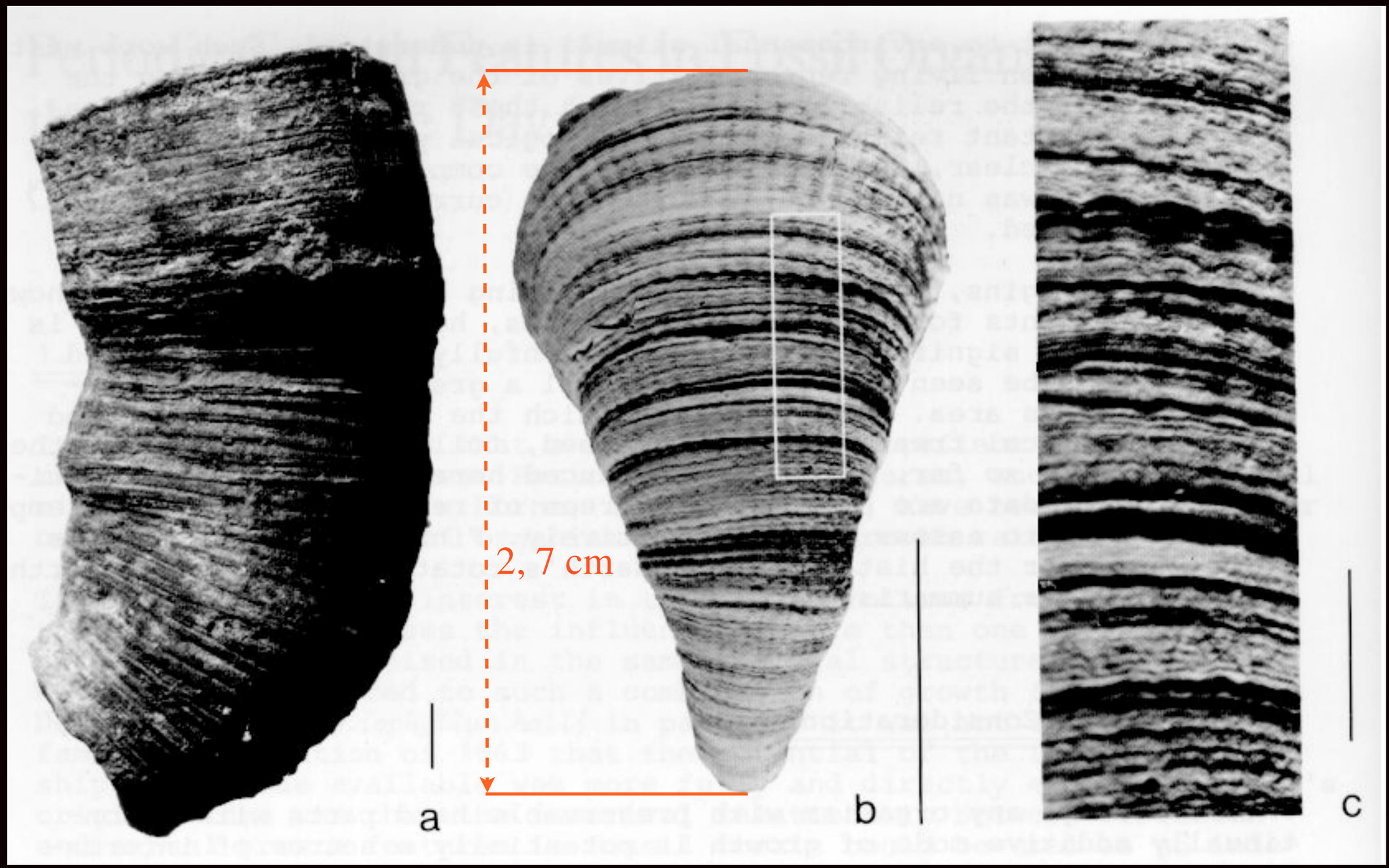
for $\langle Q\rangle = 100 \implies \gamma = 31.26$ LOD = 10.09 hr

Observations

Paleorotation



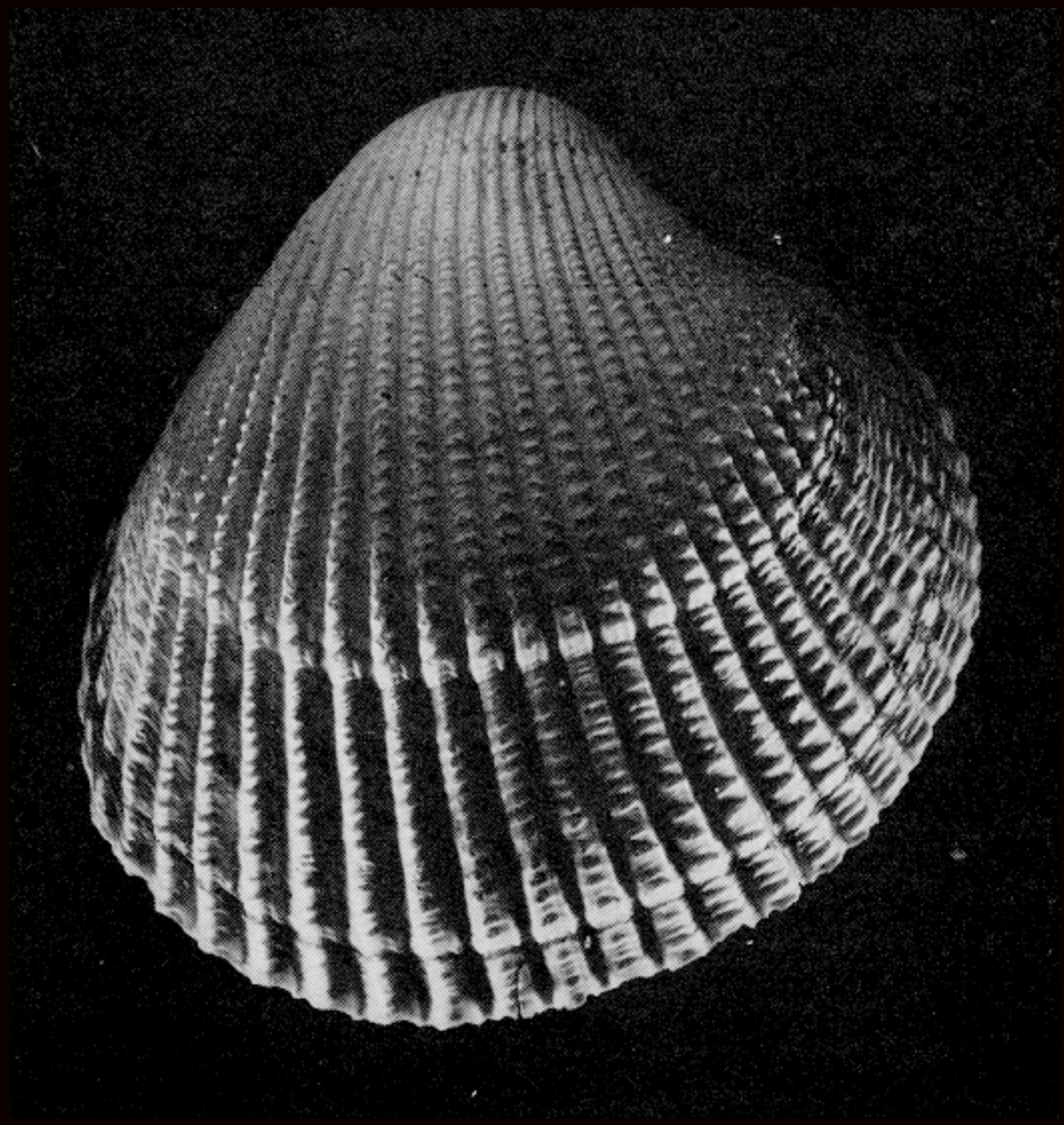
Paleorotation – Phanerozoic



Fossil coral from the Middle Devonian (Michigan, USA)

Specialists count 13 strips, each containing an average of 30.8 ripples.
[J.W. Wells, 1963 ; C.T. Scrutton, 1965]

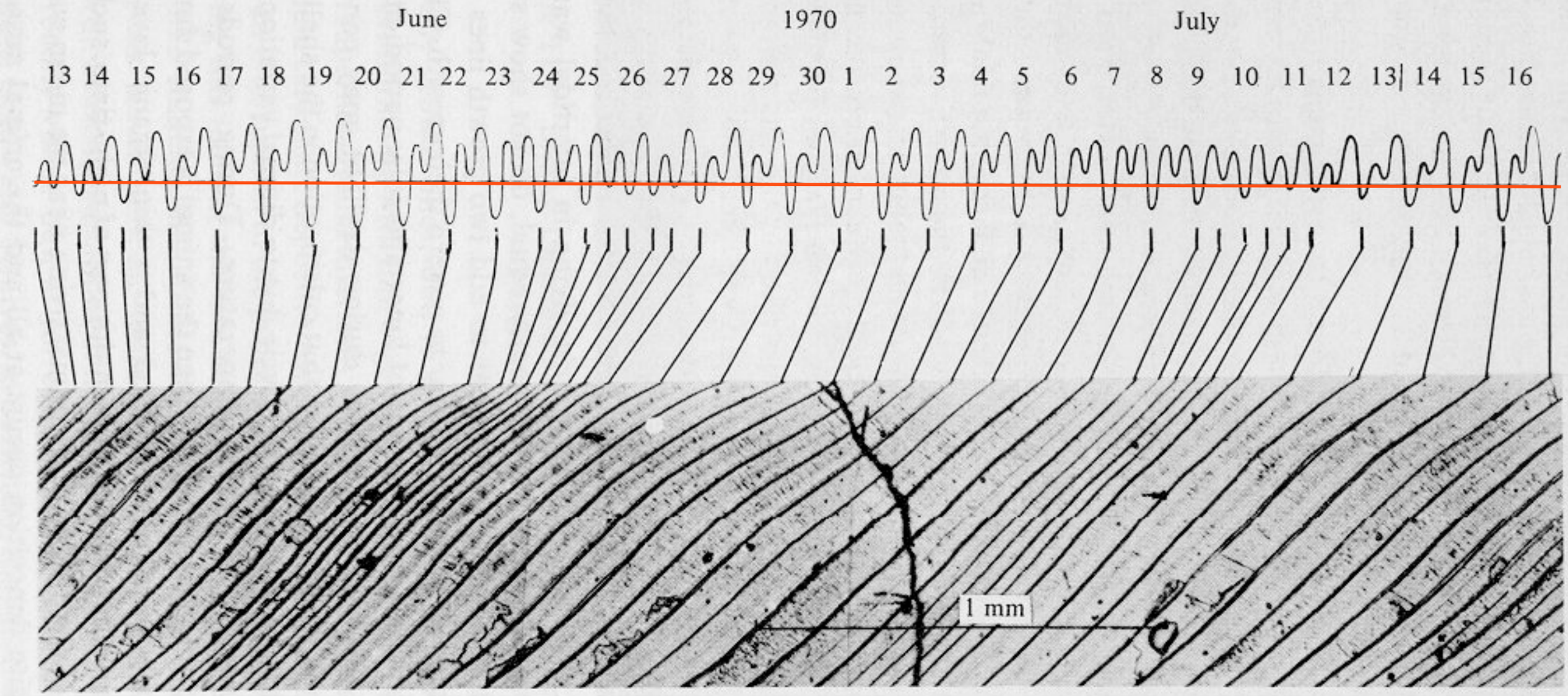
Phanerozoic



Bivalve *Clinocardium nuttalli* showing external growth increments (J.W. Evans, 1975).

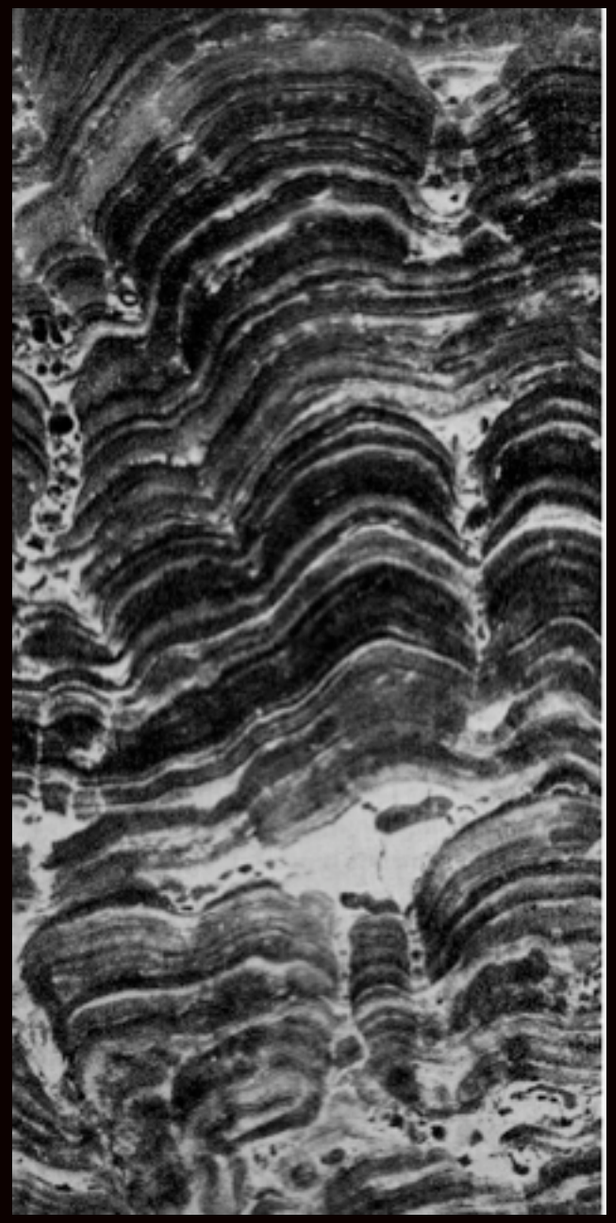
Phanerozoic

Growth rythms are poorly understood.



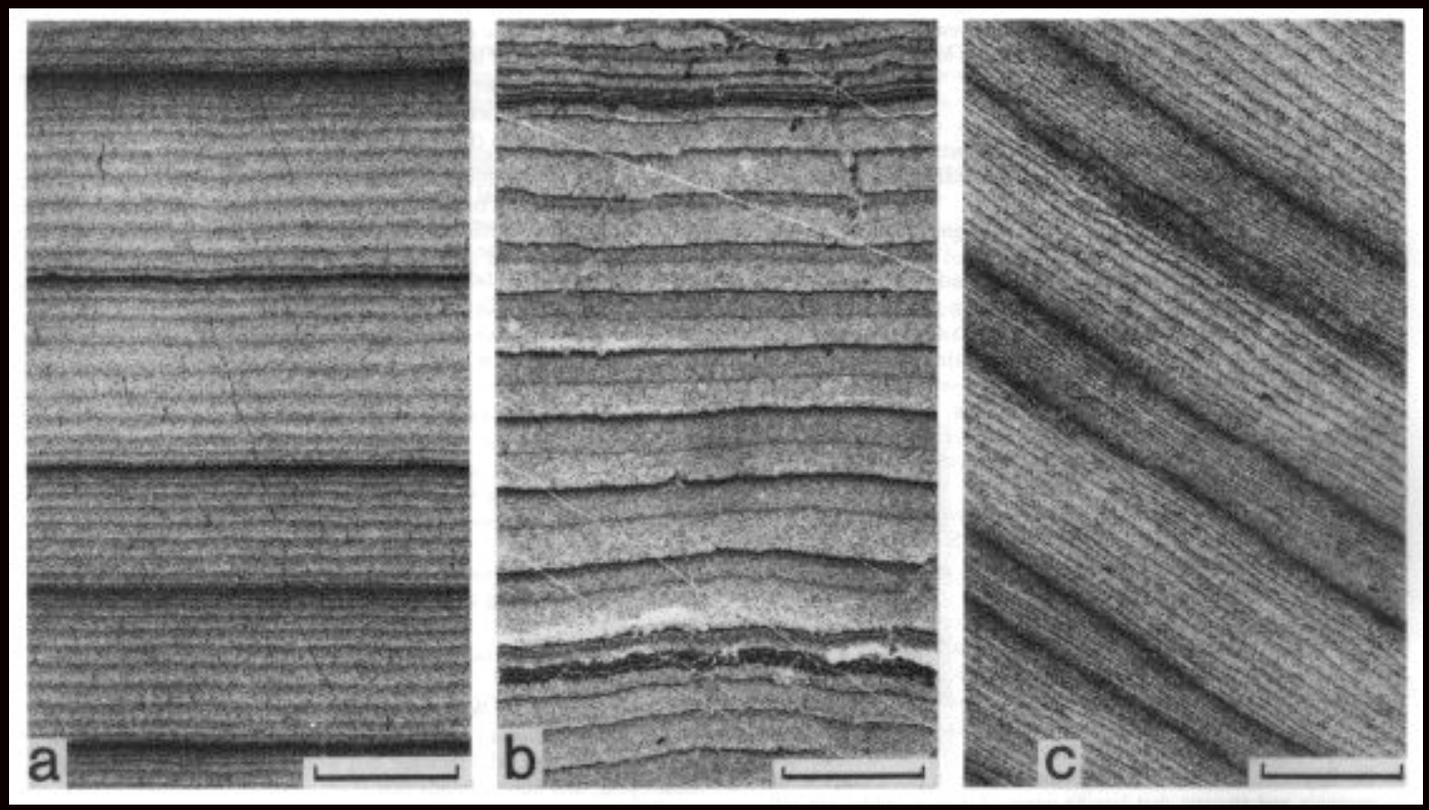
Internal growth lines in Clinocardium nuttalli compared to tidal predictions for the same epoch. Growth lines form when the tide falls below the intertidal line (drawn in red), marking the position where the specimen was found (J.W.Evans, 1972).

Proterozoic

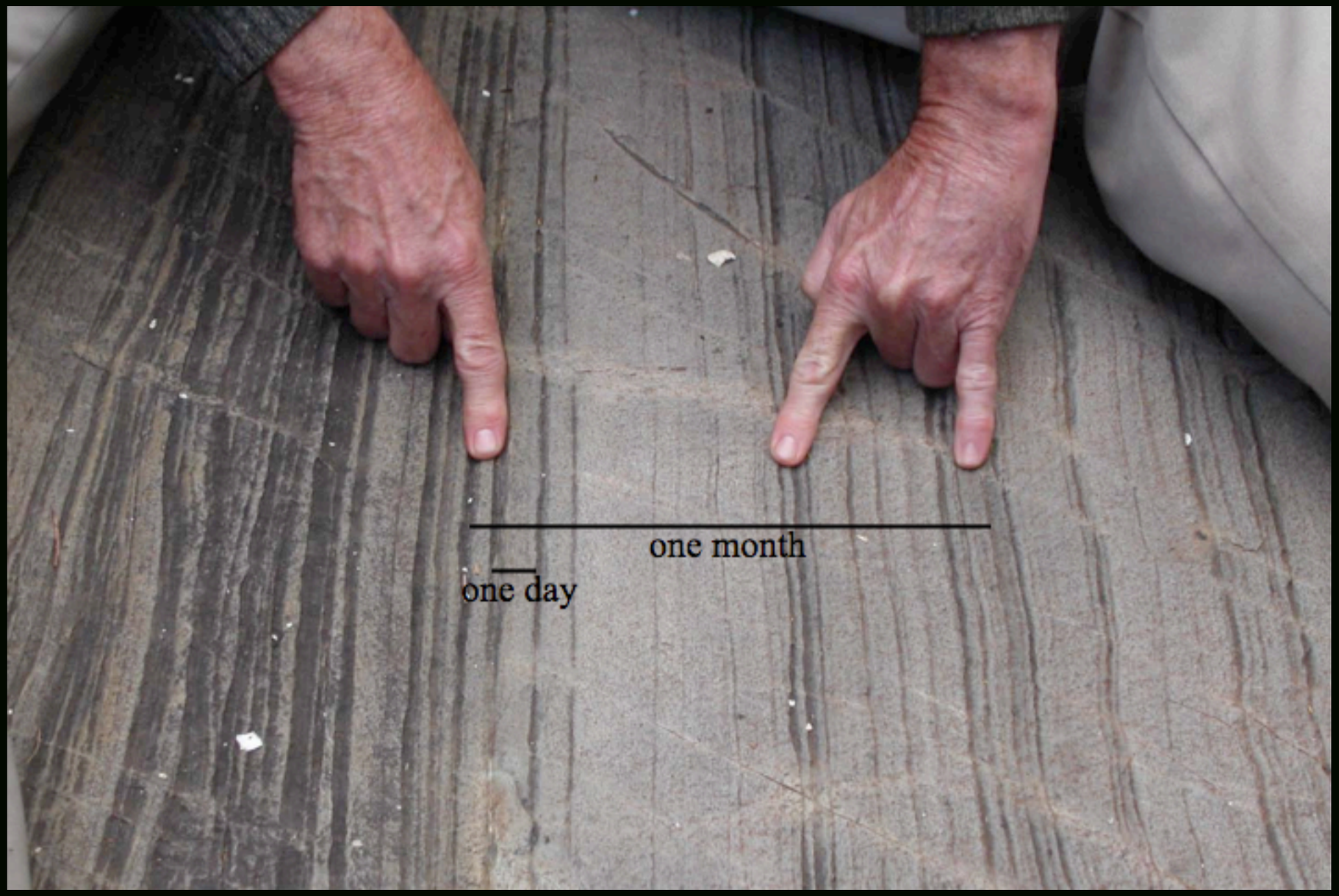


Precambrian stromatolite from Montana, USA

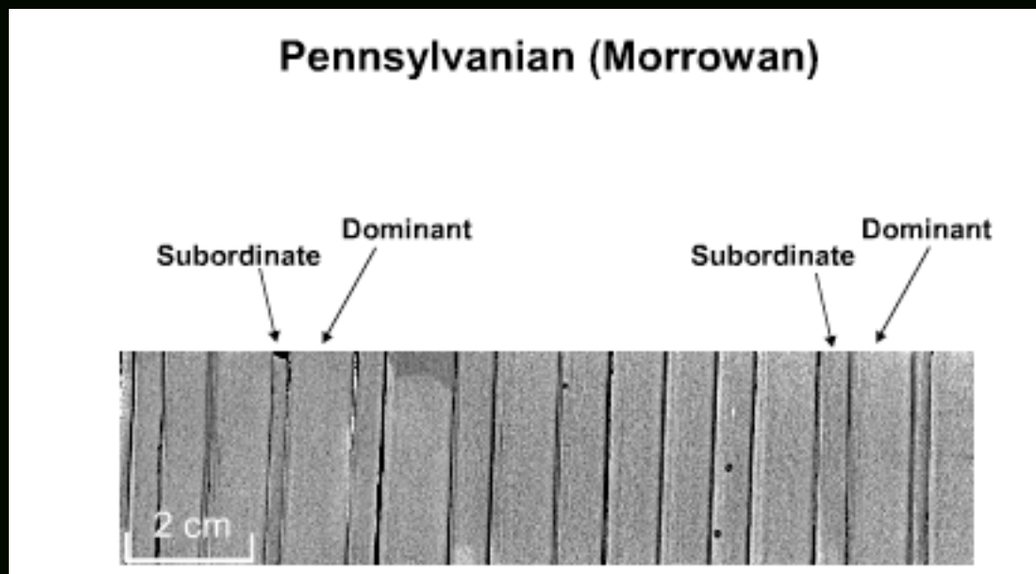
Proterozoic



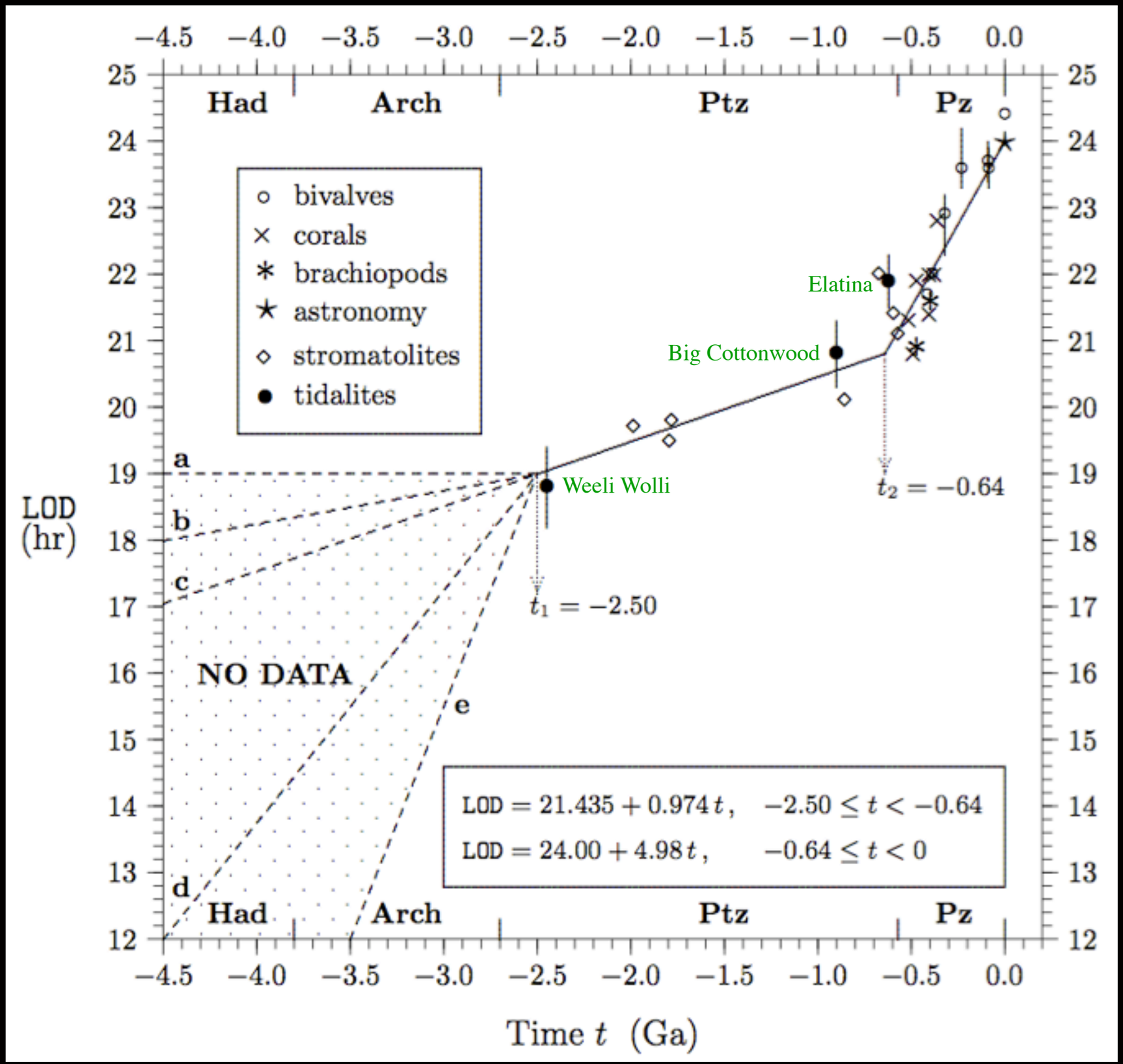
Australian tidal rhythmites (tidalites)



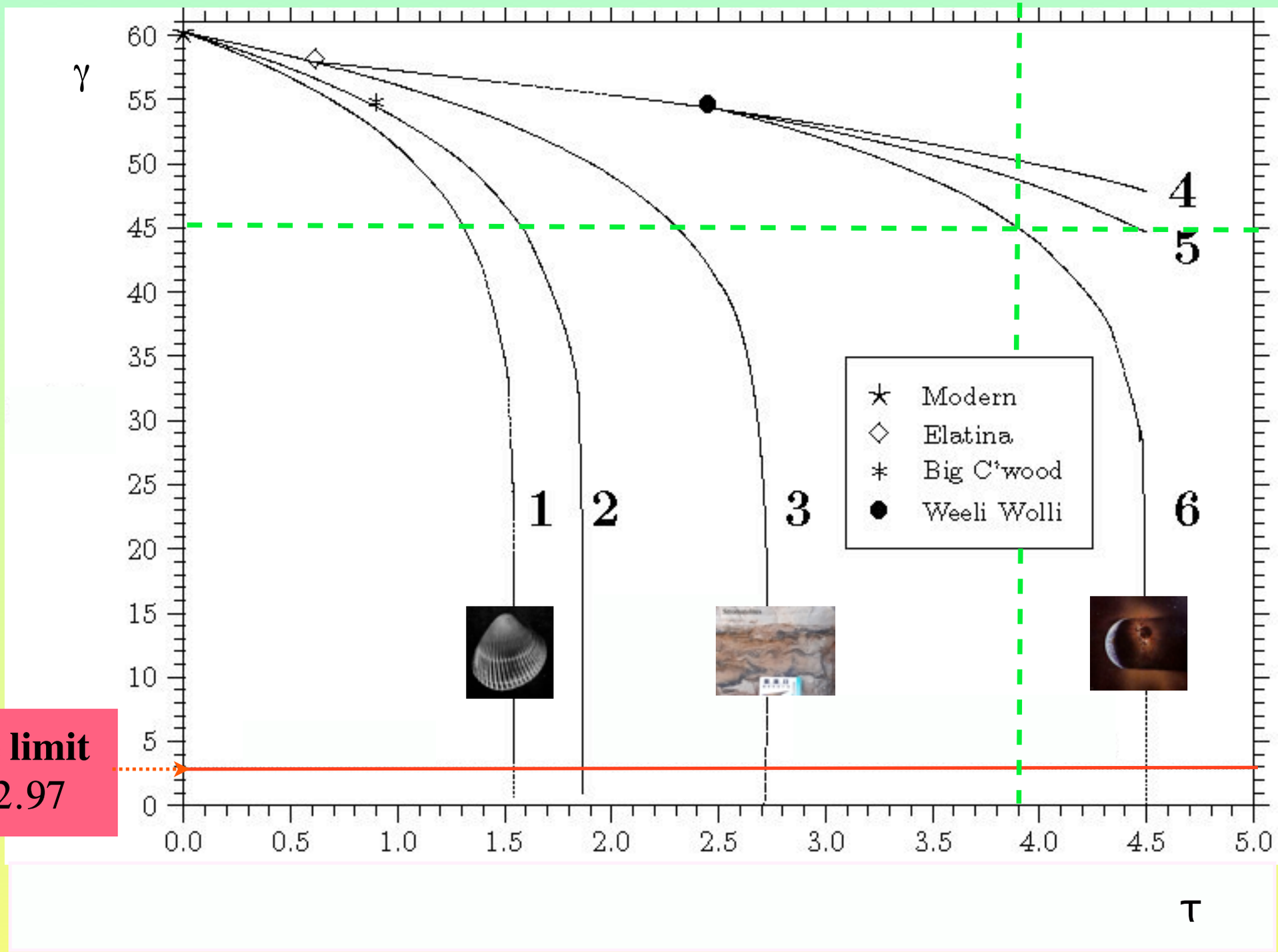
Tidal rhythmite (tidalite)



How fast was the Earth's rotation 3.9 Ga ago?



Earth-Moon distance (in Earth radii)

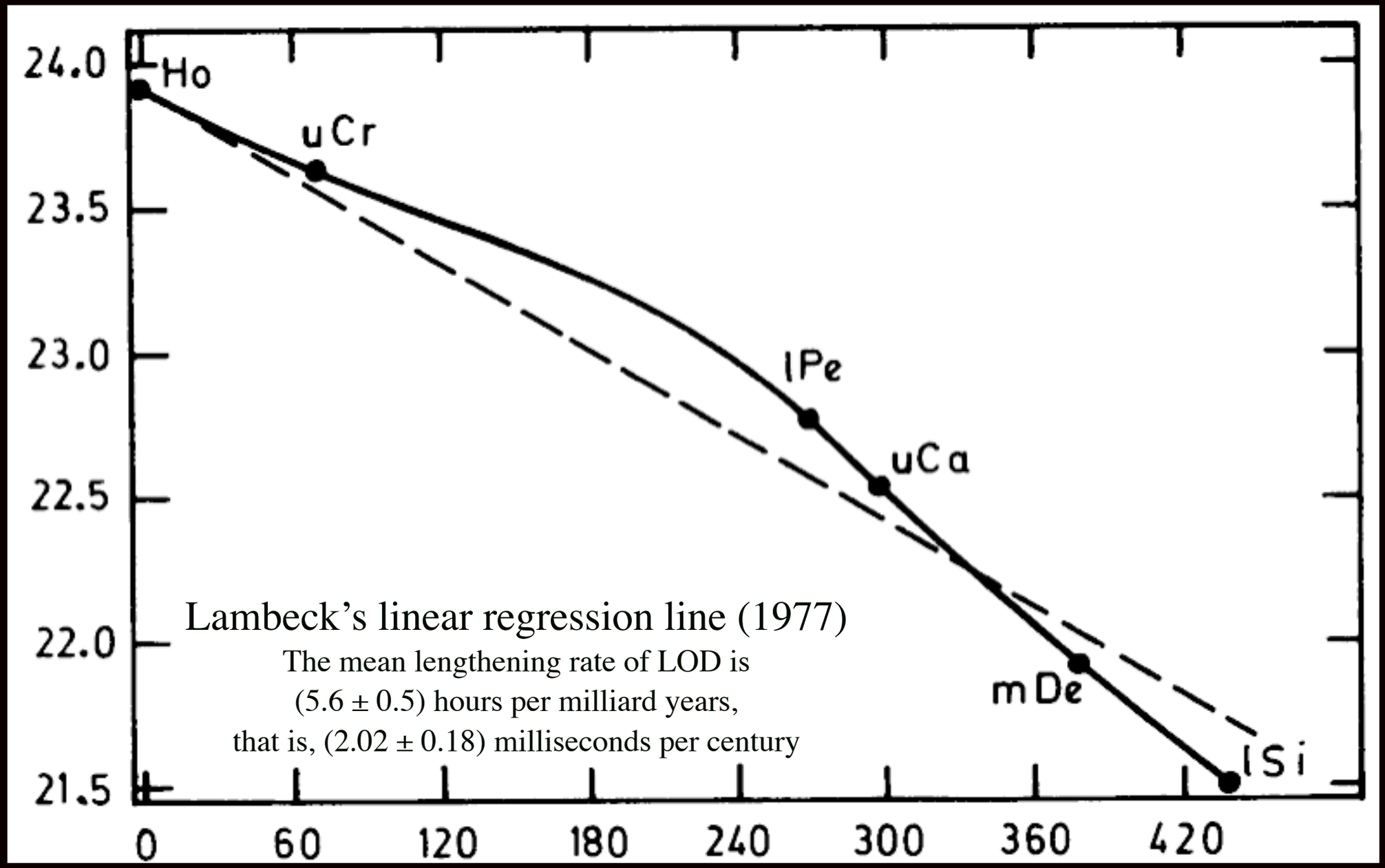


Roche limit
$\gamma = 2.97$

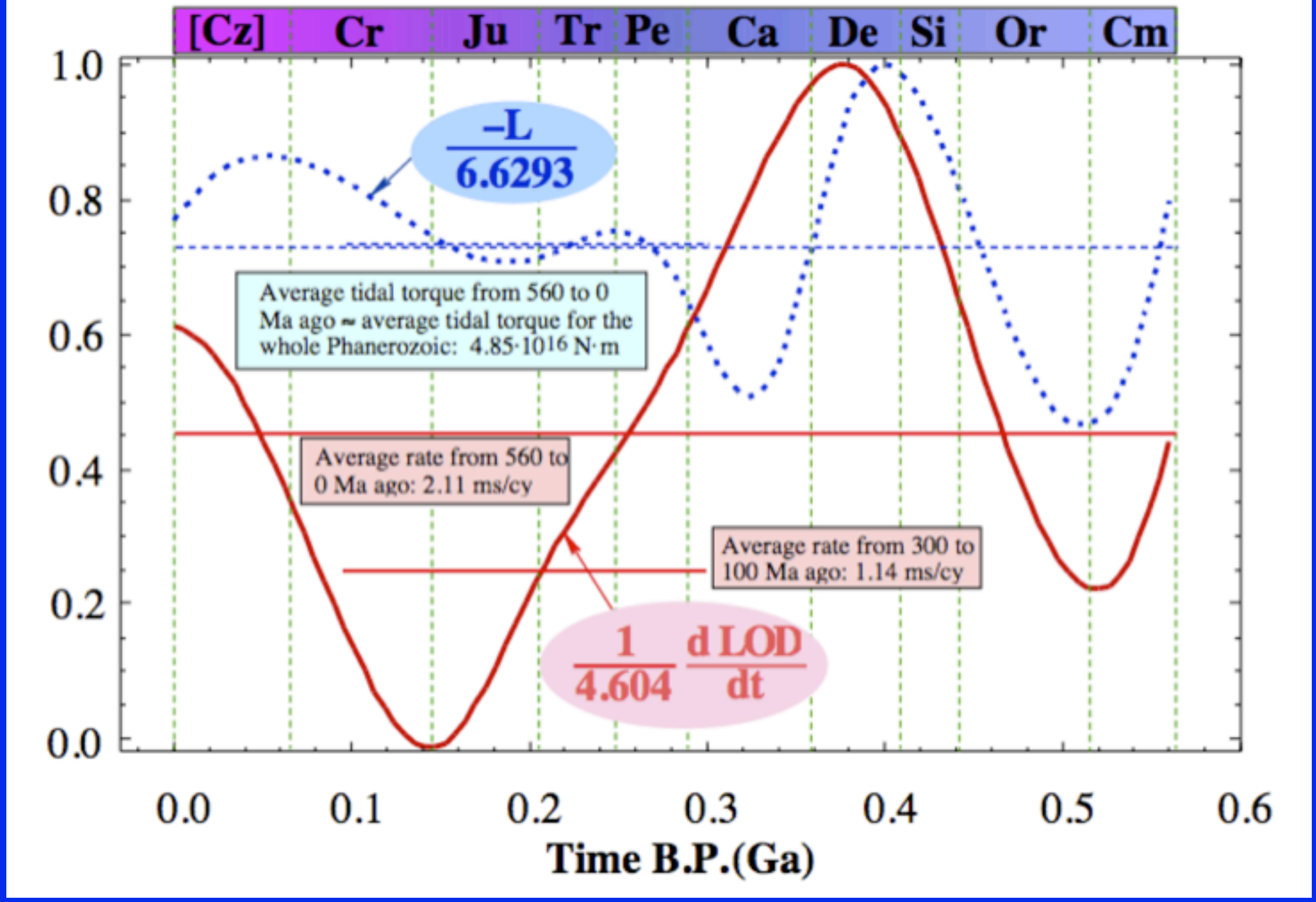
Age (in milliard years)

Phanerozoic

LOD (hours)



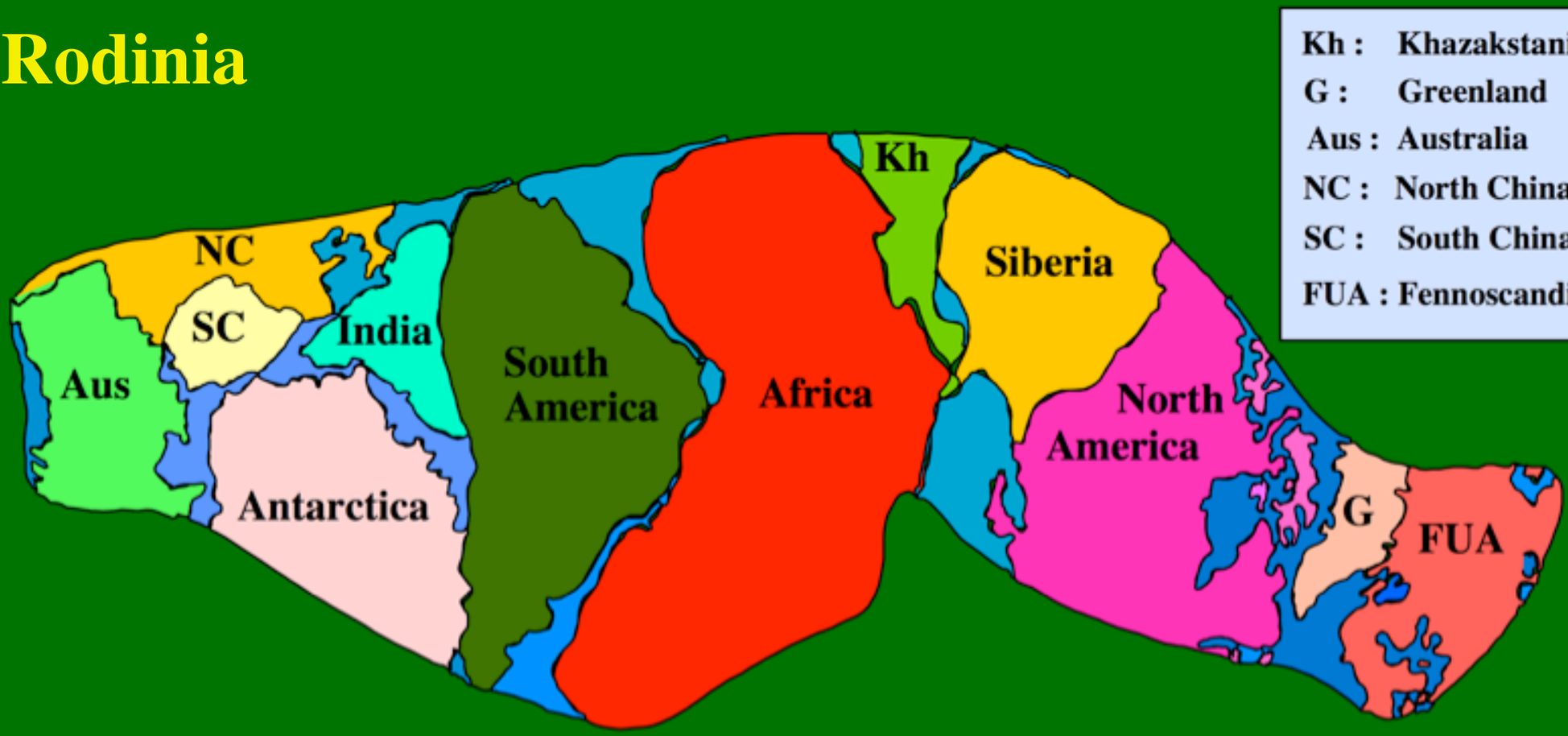
Time Before the Present (BP), in million years


[Cz]
Cr
Ju
Tr
Pe
Ca
De
Si
Or
Cm
1.0
0.8
0.6
0.4
0.2
0.0
–L / 6.6293
Average tidal torque from 560 to 0 Ma ago ≈ average tidal torque for the whole Phanerozoic: 4.85·10^16 N·m
Average rate from 560 to 0 Ma ago: 2.11 ms/cy
Average rate from 300 to 100 Ma ago: 1.14 ms/cy
1/4.604 dLOD/dt
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Time B.P.(Ga)


Eurasia
North America
Africa
South America
India
Antarctica
Australia

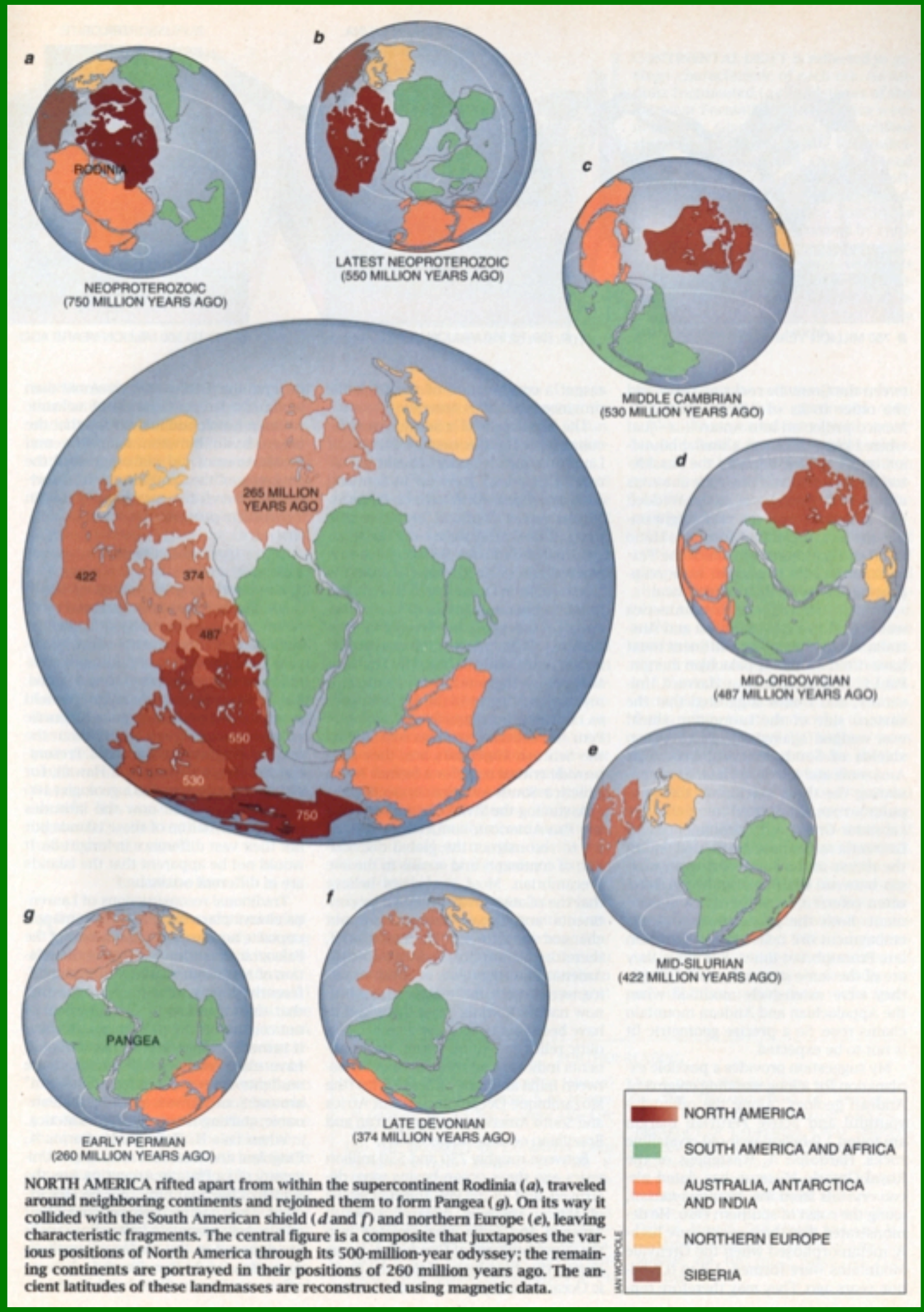
Pangaea

Rodinia

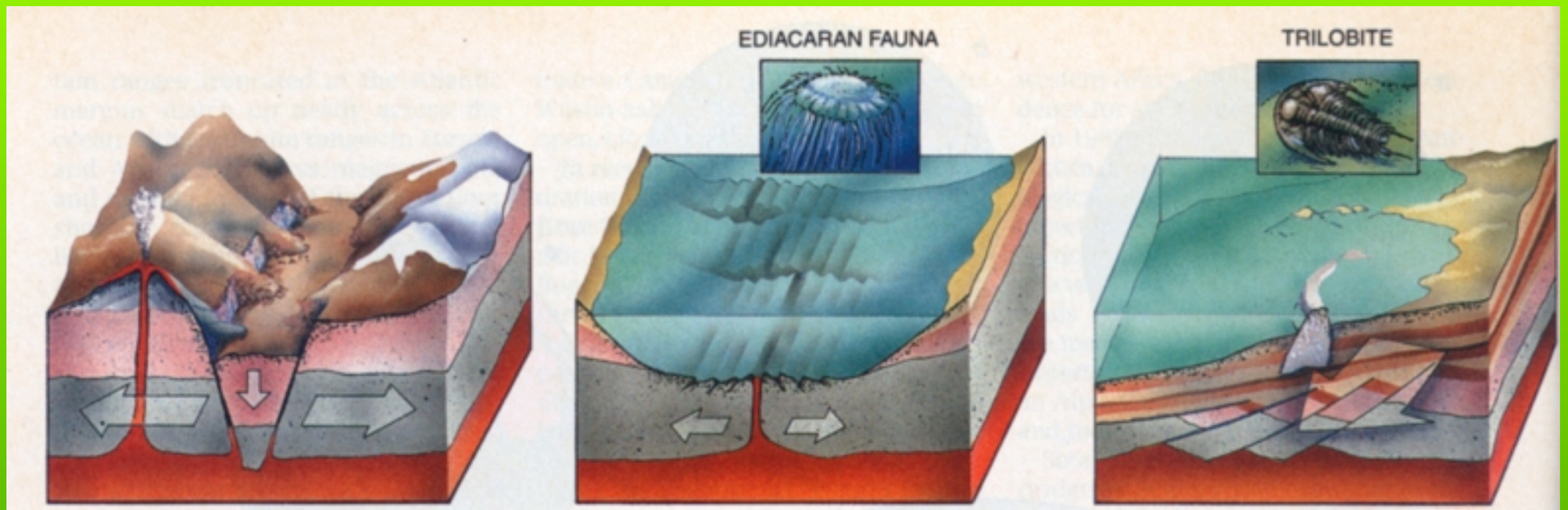


The Proterozoic supercontinent (here drawn after Piper, 1990, p.239) seems to be responsible for the relatively low tidal dissipation during the Proterozoic aeon, for it favoured diurnal (O_1) tides rather semi-diurnal (M_2) tides. A similar phenomenon has occurred during the Mesozoic epoch (Varga et al., 1998; Denis et al., 2002), when the coastlines of Pangaea enhanced strongly the O_1 tide with respect to the M_2 tide, and caused a relative minimum in the rate of increase of LOD.

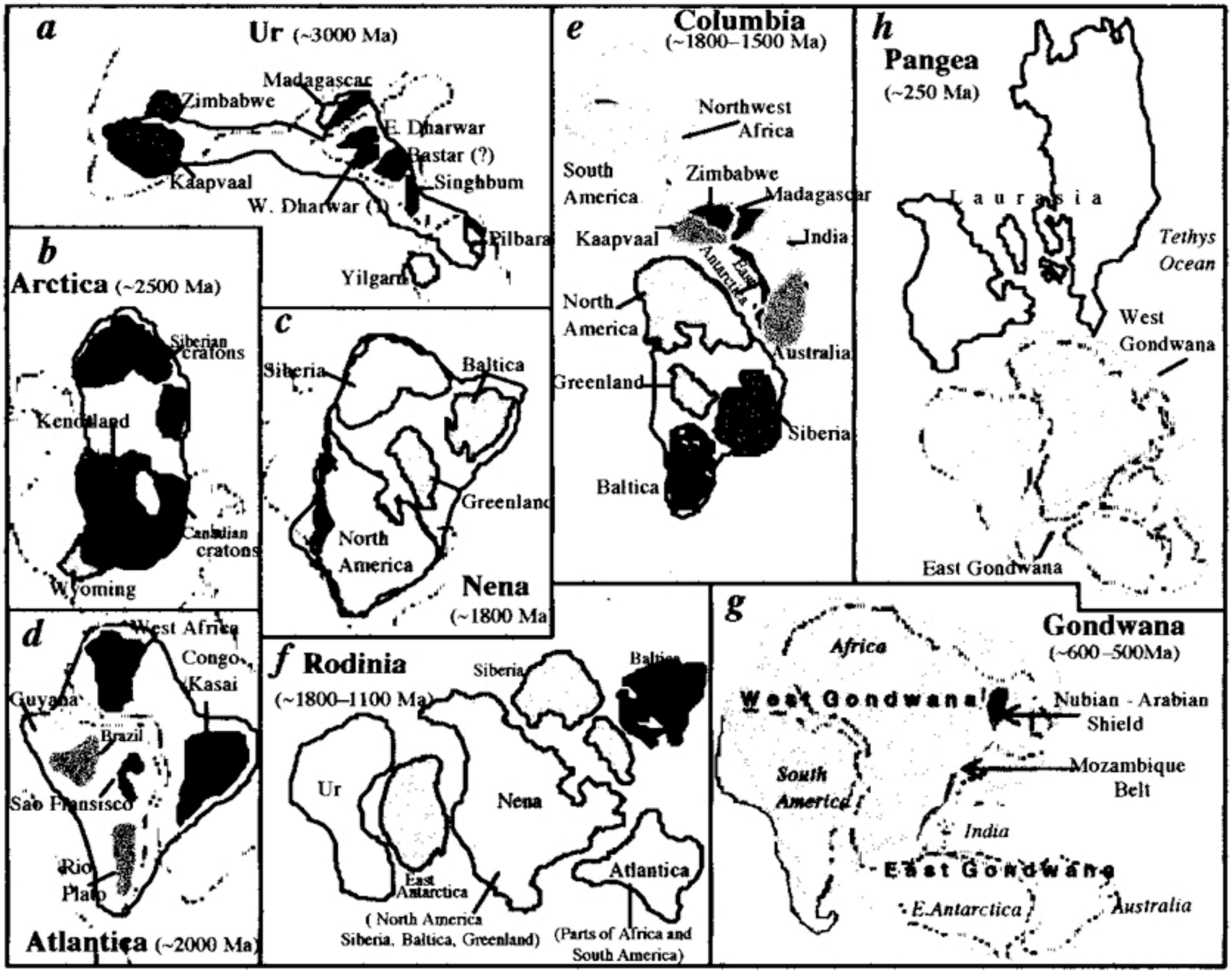
Minimal tidal friction leads to a lengthening rate of LOD not smaller than 0.9 ms/cy



NORTH AMERICA rifted apart from within the supercontinent Rodinia (*a*), traveled around neighboring continents and rejoined them to form Pangea (*g*). On its way it collided with the South American shield (*d* and *f*) and northern Europe (*e*), leaving characteristic fragments. The central figure is a composite that juxtaposes the various positions of North America through its 500-million-year odyssey; the remaining continents are portrayed in their positions of 260 million years ago. The ancient latitudes of these landmasses are reconstructed using magnetic data.



CONTINENTAL DRIFT is reflected in geology characteristic of each era. As Rodinia fragmented (*a*), sandstones of the Patuxent Formation in Antarctica were deposited. Glaciers lined the uplifted shoulders of the rift. In late Precambrian times (*b*), the Pacific Ocean opened up by spreading of the seafloor. Soft-bodied fauna simultaneously developed. Oceans advanced over the continents in Cambrian times (*c*), inhabited by hard-bodied trilobites and reef-forming Archaeocyatha. By the time tetrapods roamed, the continents had amalgamated into Pangea (*d*). The Atlantic and Indian oceans opened as Pangea broke apart (*e*) into today's world.


a
Ur (~3000 Ma)
Madagascar
Zimbabwe
E. Dharwar
Bastar (?)
Kaapvaal
Singhbum
W. Dharwar (?)
Pilbara
Yilgarn
b
Arctica (~2500 Ma)
Siberian cratons
Kenoland
Canadian cratons
Wyoming
c
Siberia
Baltica
Greenland
North America
Nena
(~1800 Ma
d
West Africa
Congo
Kasai
Guyana
Brazil
Sao Fransisco
Rio Plato
Atlantica (~2000 Ma)
e
Columbia
(~1800–1500 Ma)
Northwest Africa
South America
Zimbabwe
Madagascar
Kaapvaal
India
Antarctica
East
North America
Australia
Greenland
Siberia
Baltica
f
Rodinia
(~1800–1100 Ma)
Siberia
Ur
Nena
Atlantica
East Antarctica
(North America
Siberia, Baltica, Greenland)
(Parts of Africa and
South America)
g
Gondwana
(~600–500Ma)
Africa
West Gondwana
Nubian - Arabian Shield
Mozambique Belt
South America
India
East Gondwana
E.Antarctica
Australia
h
Pangea
(~250 Ma)
Laurasia
Tethys Ocean
West Gondwana
East Gondwana

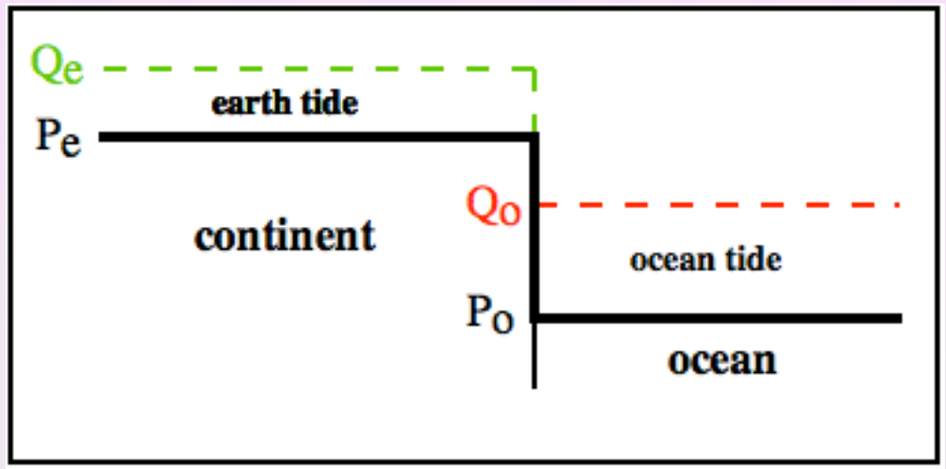
How large were the tides 3.9 Ga ago?

Equilibrium body tides

Dynamic (resonant) body tides

Equilibrium ocean tides

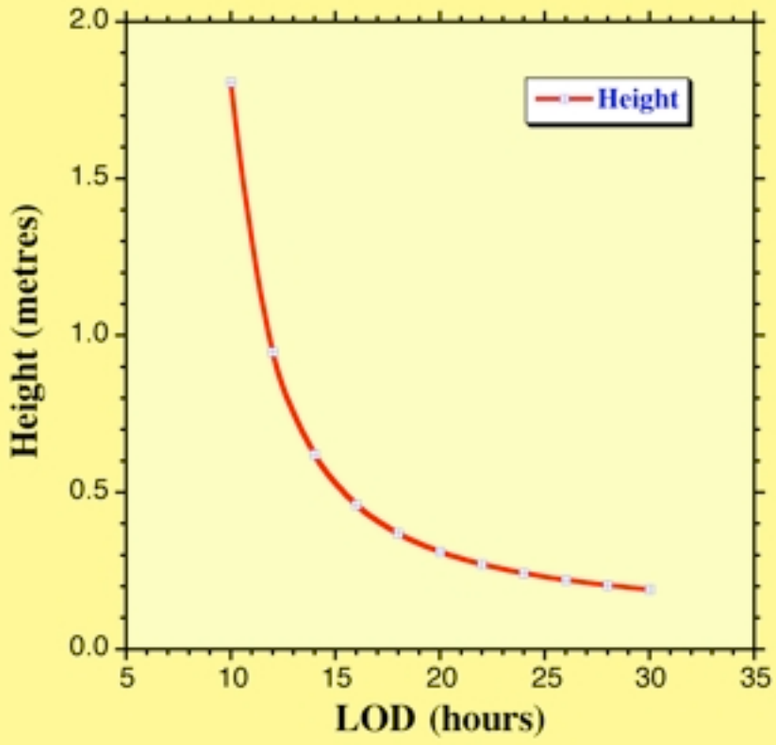
Resonant marine tides

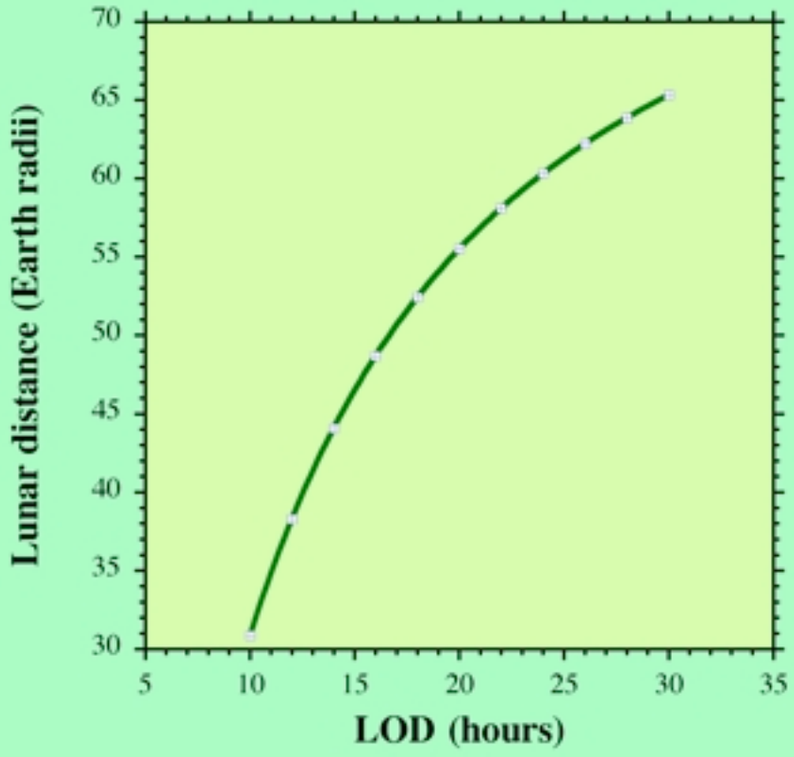


$$\Delta P_O P_e = Q_O Q_e - P_O P_e = P_O Q_O - P_e Q_e$$

$$P_O Q_O - P_e Q_e = (1 + k)\, W/g - h\, W/g = \gamma\, W/g$$

$$\gamma = 1 + k - h \approx 0.68$$





0 LOD	1 Height	2 gamma
10.00	1.807	30.891
12.00	0.948	38.308
14.00	0.621	44.093
16.00	0.461	48.699
18.00	0.369	52.440
20.00	0.311	55.532
22.00	0.271	58.128
24.00	0.243	60.337
26.00	0.221	62.238
28.00	0.204	63.890
30.00	0.191	65.340

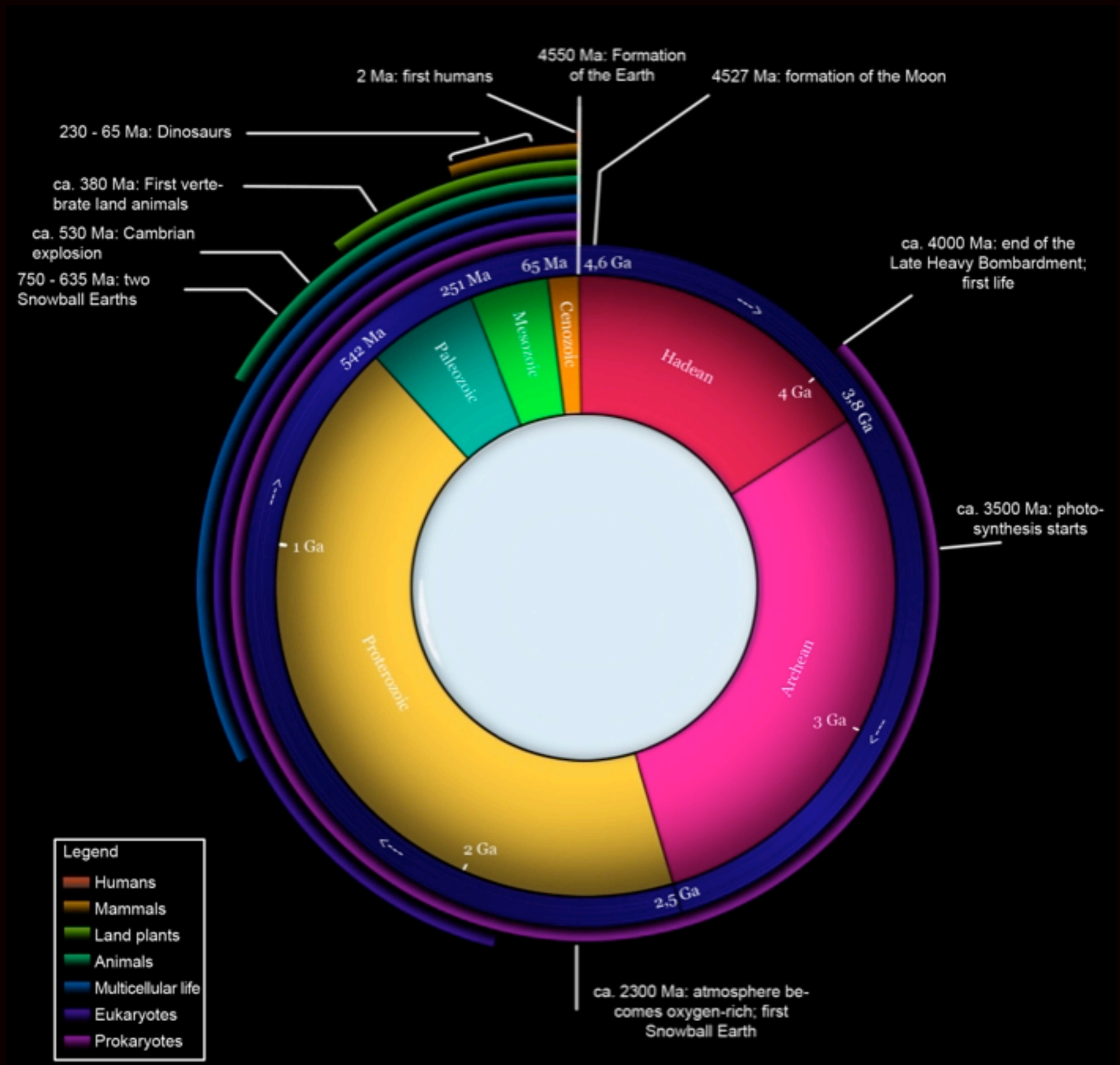
Conclusions

- If the Moon resulted from a great impact, the LOD when life formed 3.9 Ga ago was at least 10 hr, but more likely > 14 hr.

- The great impactor theory is, however, very unlikely. It is much more probable that LOD 3.9 Ga ago was comprised between 16 and 18 hr.

- There is no reason to believe that the oceanic tides were at any time as huge as supposed by Lathe, although the equilibrium tides of the geoid 3.9 Ga ago were somewhat larger.

- The oceanic tides may have played an important rôle in the birth of the earliest life forms, but not via the scenario suggested by Richard Lathe.

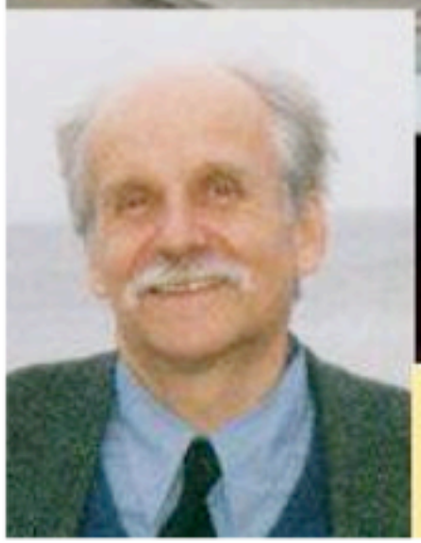


Geological Clock

[Courtesy: en.wikipedia]

Does life exist on Earth?

Thanks for listening !



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Rafal Rybicki

Carlo Denis

Garfield