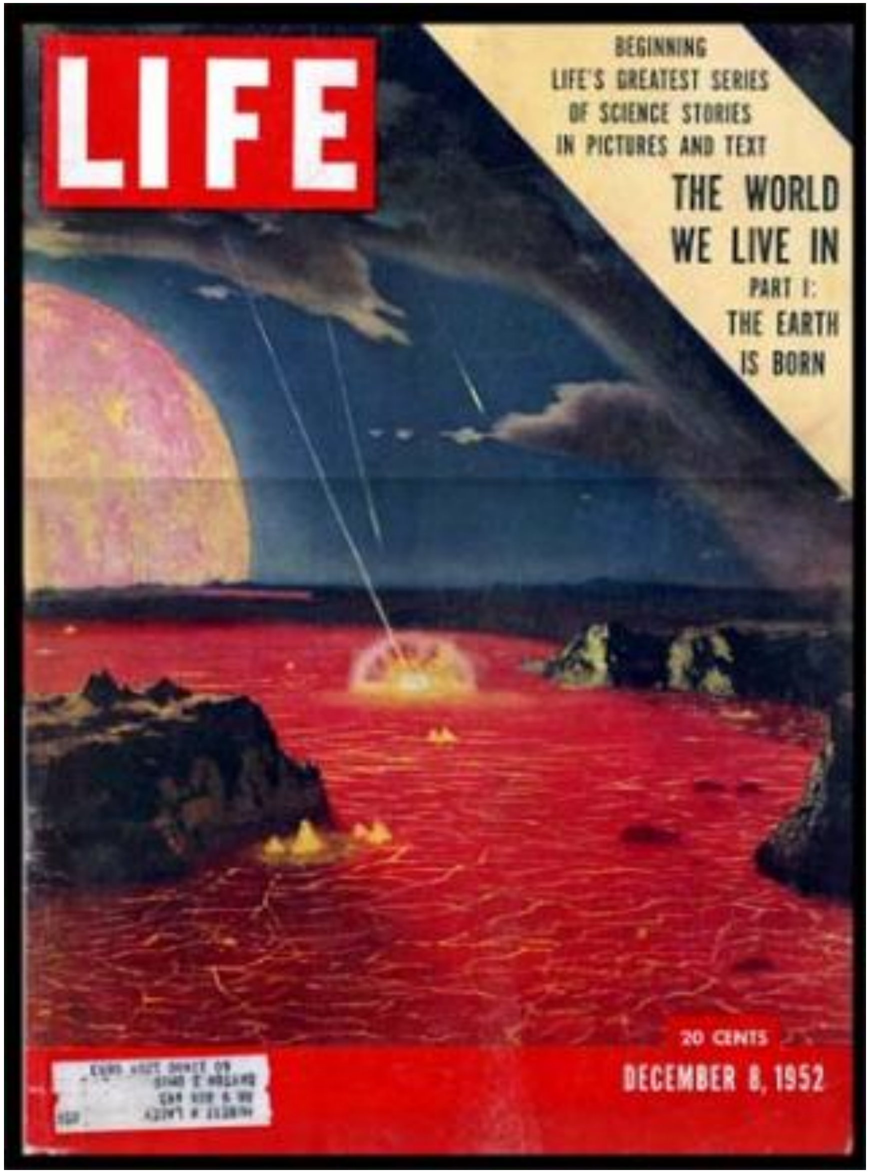
BIOGEOCHEMISTRY

Earth 281

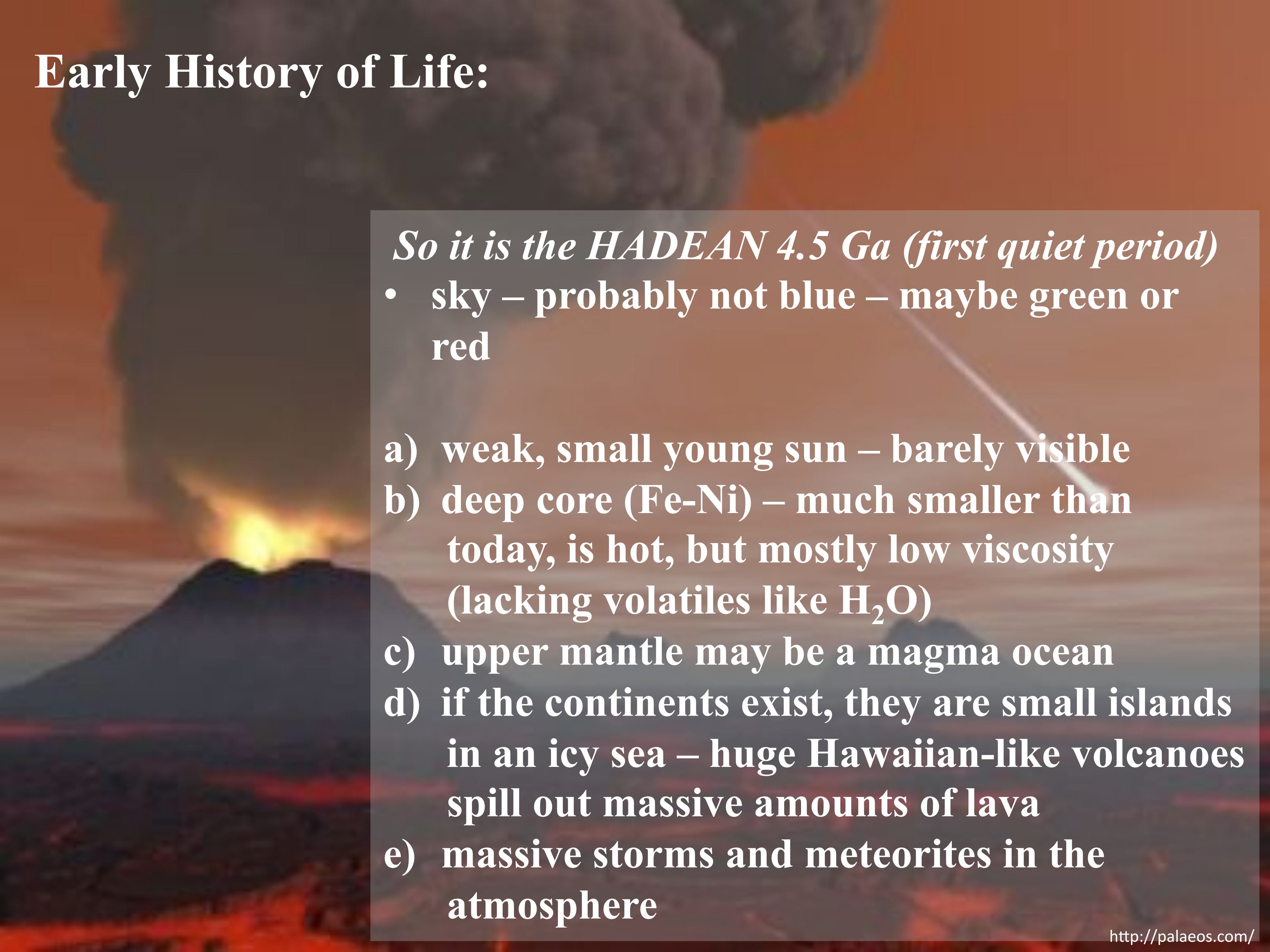
Early History of Life:

We digress to see how life as we know it evolved on Earth and how the atmosphere changed with time.



http://elements.geoscienceworld.org/

1. **What would be your idea of conditions on a young earth over 4.5 billion years ago**?



Early History of Life:

So it is the HADEAN 4.5 Ga (first quiet period)

- **sky – probably not blue – maybe green or red**

a) weak, small young sun – barely visible

b) deep core (Fe-Ni) – much smaller than today, is hot, but mostly low viscosity (lacking volatiles like H_2O)

c) upper mantle may be a magma ocean

d) if the continents exist, they are small islands in an icy sea – huge Hawaiian-like volcanoes spill out massive amounts of lava

e) massive storms and meteorites in the atmosphere

http://palaeos.com/

http://bit.ly/LBVk0d

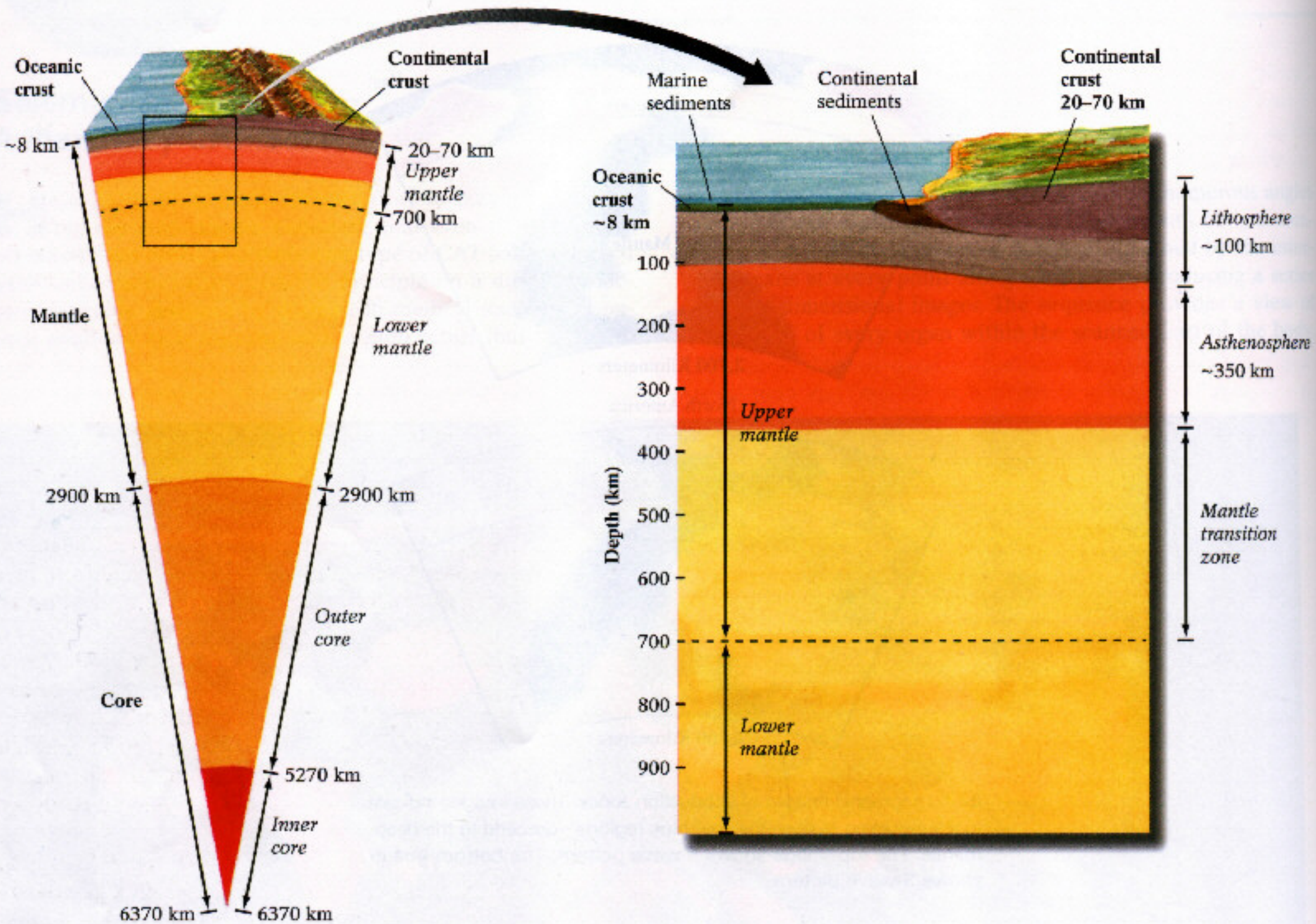


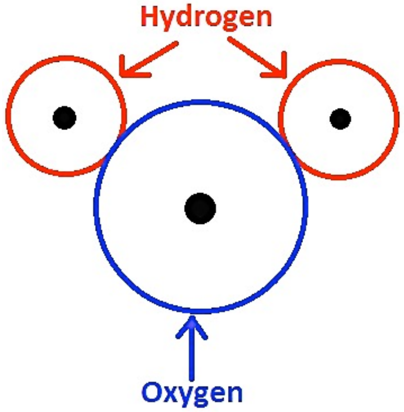
Figure 11-3 As well as delineating the three major components (crust, mantle, and core) of the Earth, seismological studies provide details about the different natures of the layers. For example, the studies reveal that continental crust is significantly thicker and less dense than oceanic crust. These studies also show the rugged topography of the Earth's core–mantle boundary.

Geology, Chernicoff and Whitney, 2002

2. **This Earth has hydrogen and oxygen in rocks and abundant carbon on the surface.**

Mineral Hornblende
$Ca_2(Mg, Fe, Al)_5 (Al, Si)_8O_{22}(OH)_2$

Abundant oxygen



http://sciencedefined.files.wordpress.com/

a) mostly in mantle minerals
b) at surface dihydrogen monoxide thus tying up hydrogen
c) Oxygen dihydride is dense so stays on Earth
d) So free water as liquid and solid probably exists
e) C, N, S are oxides and hydrides (captured) as well

3. **Bacterium and photosynthesizers would have found ways even with a green sky to exist.**

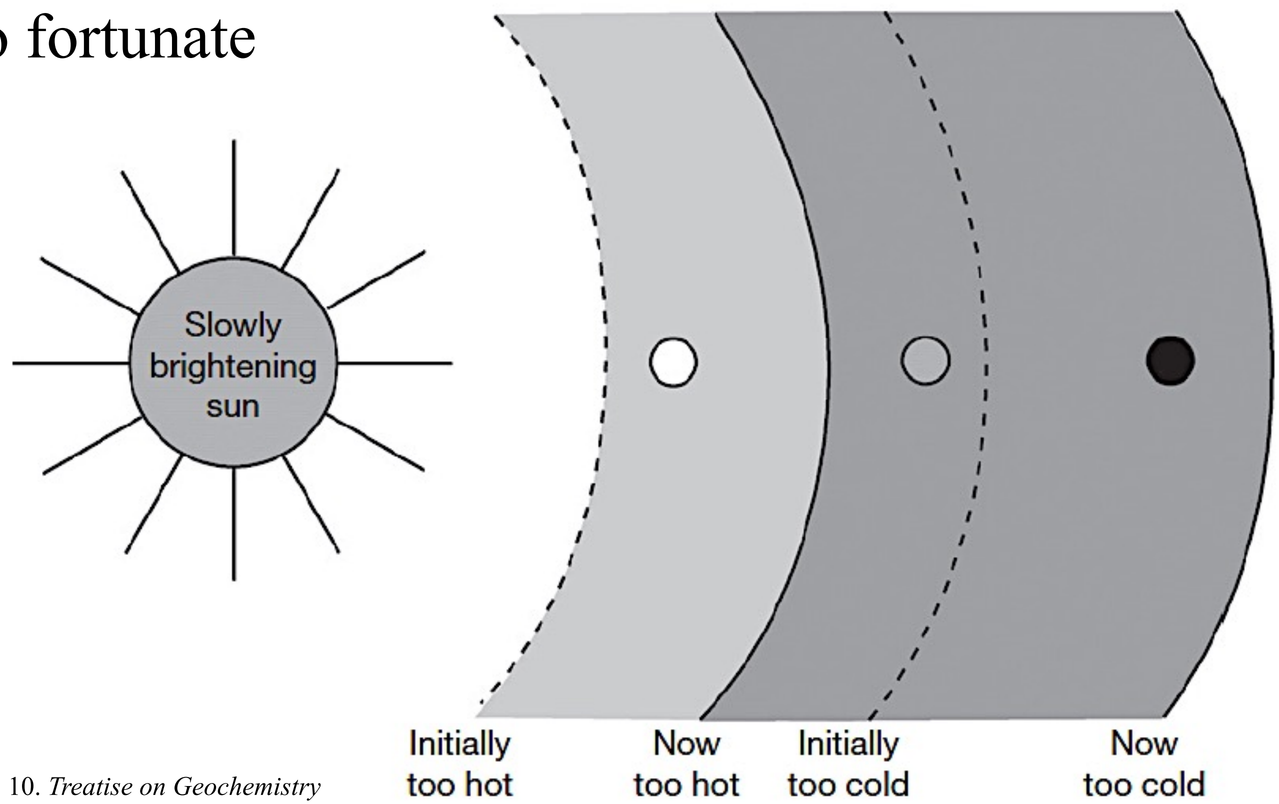
(Note: infrared radiation from that weak sun.)

4. By 4.5 Ga Earth is relatively peaceful tectonically.

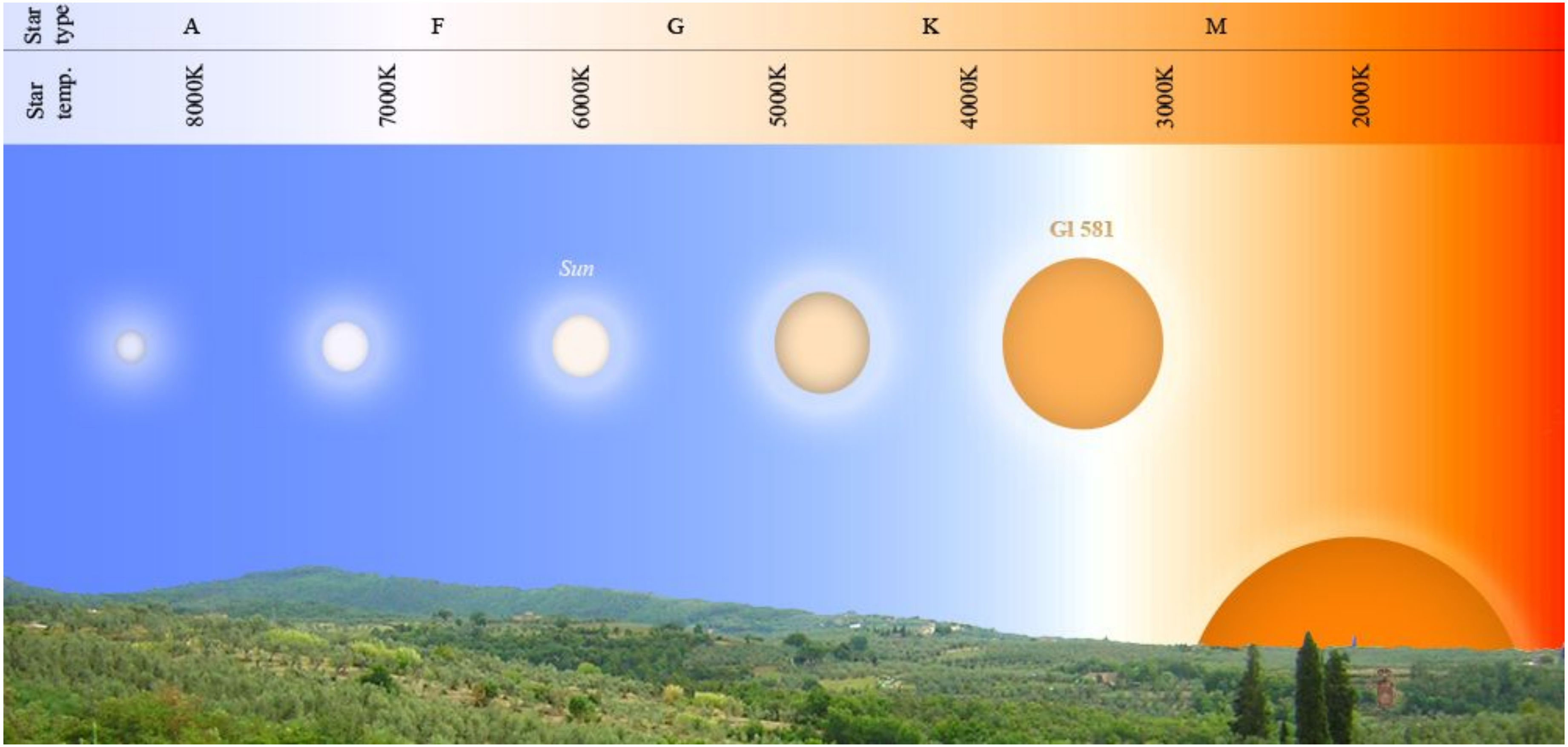
5. Earth location (Figure 1).

a) not too far way from the young sun

b) but far enough away when the sun matured, we survived, e.g. maybe Mars (never warmed, tectonics slowed? no recovery?) and certainly Venus (good for awhile then too hot, lost oceans) were not so fortunate



Nisbet and Fowler (2014) *in* Biogeochemistry, Vol. 10. *Treatise on Geochemistry*



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(used with permission)

Depending on star type, a planet with Earth's atmosphere in a habitable zone orbit would have a different colored sky and apparent size of their "Sun".

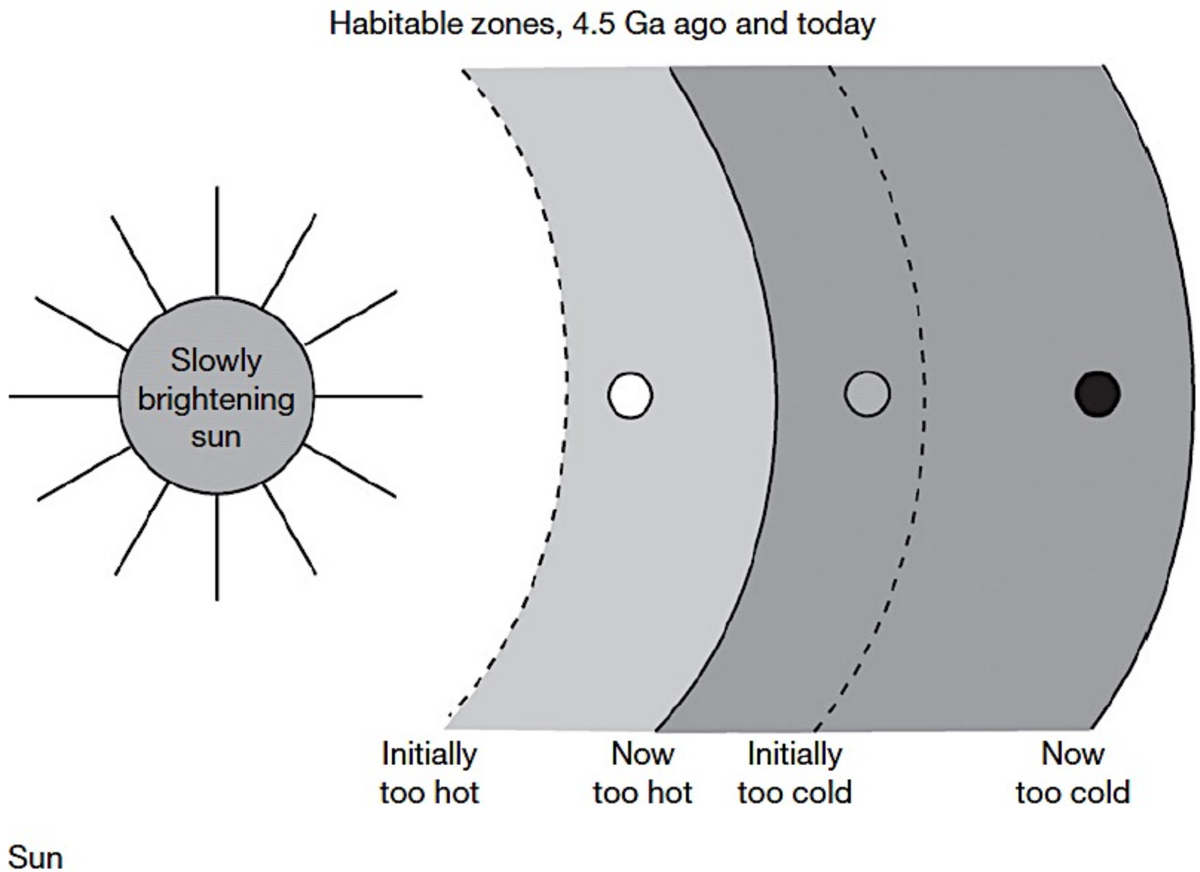
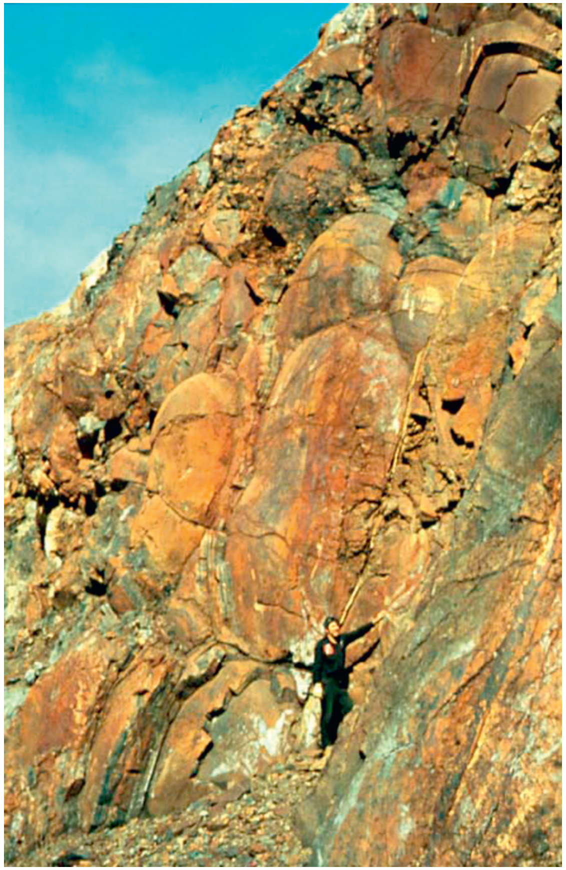


Figure 1 The habitable zone (Kasting et al., 1993). Too close to the Sun, a planet's surface is too hot to be habitable; too far, it is too cold. Early in the history of the solar system, the Sun was faint and the habitable zone was relatively close; 4.5 Ga later, with a brighter Sun, planets formerly habitable are now too hot, and the habitable zone has shifted out. Note that even given a constant star, boundaries can shift. By changing its albedo and by altering the greenhouse gas content of the air, the planet can significantly widen the bounds of the habitable zone (Lovelock, 1979, 1988).

Nisbet and Fowler (2014) *in* Biogeochemistry, Vol. 10. *Treatise on Geochemistry*

6. Early history of life: How is it determined?

a) Relics:
   i. material in rocks; (Algal Stromatolites)
   ii. meteorites (exchange of material in inner solar system)
   iii. solar system
   iv. Earth's cycles – plate tectonics renews the resources every few 100 million years, but some relics – biogenic carbon survive
   v. changes in isotopic ratios in rocks that tell us of major geochemical/biogeochemical changes



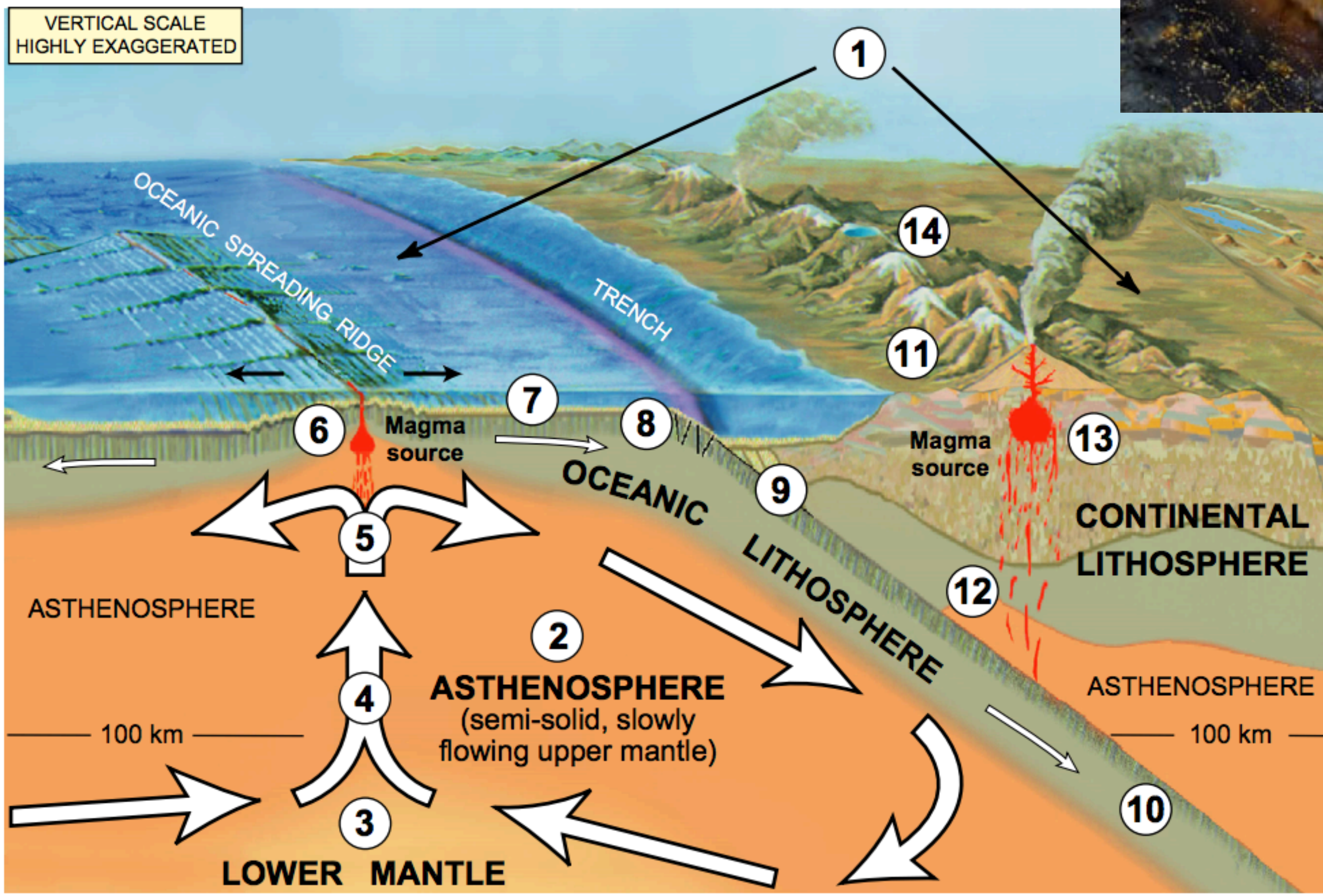
Algal stromatolites Steep Rock, Ont.

b) Modern biogeochemists and microbiologists work with radiochron daters (isotope types) and paleontologists to work a fundamental law of geology

Zimbabwe

Nisbet and Fowler (2014) *in* Biogeochemistry, Vol. 10. *Treatise on Geochemistry*

"*The present is the key to the past*" and vice versa

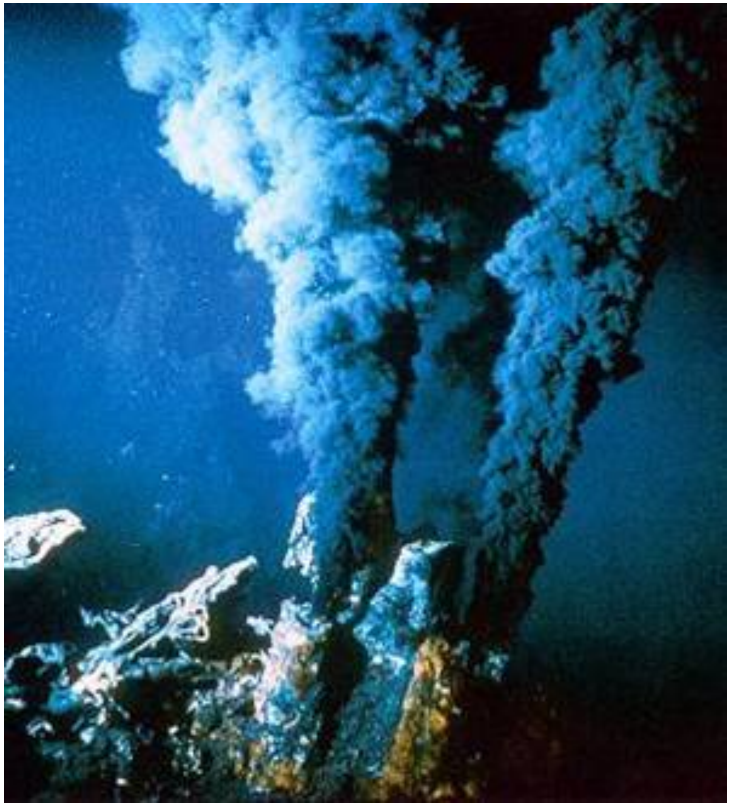

VERTICAL SCALE
HIGHLY EXAGGERATED
1
OCEANIC SPREADING RIDGE
TRENCH
14
11
6
Magma
source
7
8
9
Magma
source
13
OCEANIC
LITHOSPHERE
CONTINENTAL
LITHOSPHERE
5
ASTHENOSPHERE
2
ASTHENOSPHERE
(semi-solid, slowly
flowing upper mantle)
12
ASTHENOSPHERE
4
100 km
100 km
10
3
LOWER MANTLE

usgs.gov

c) Modeling

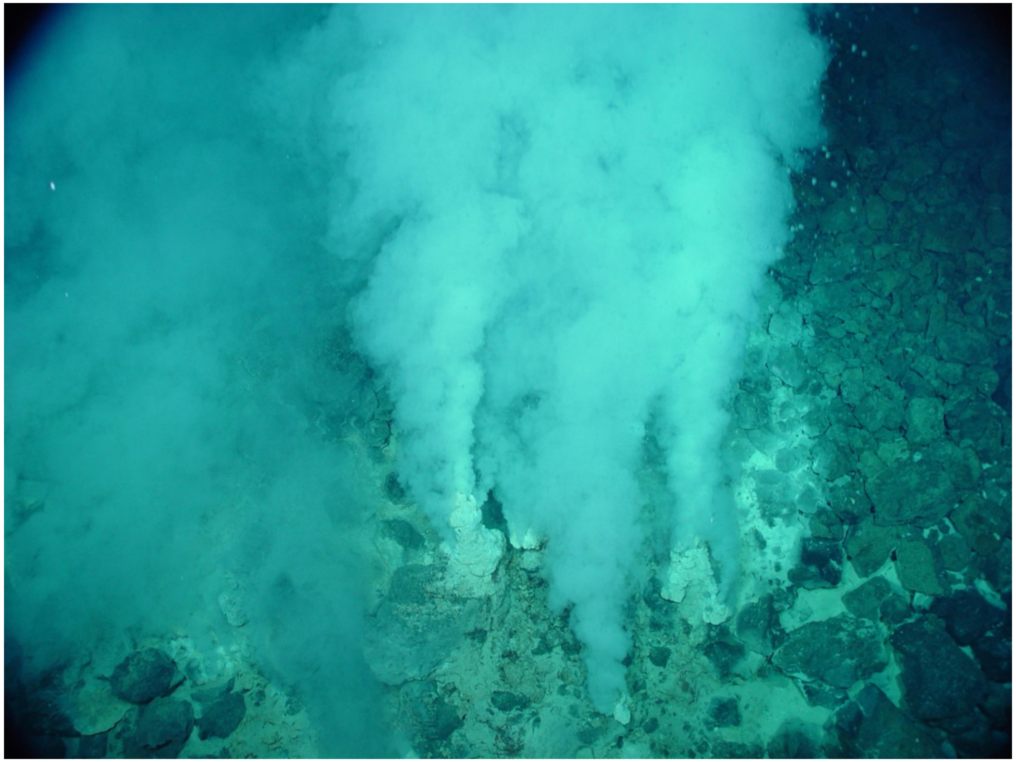
i. origin of life – what conditions exist based on <u>modern analogues</u> e.g. hot springs OR Black Smokers → insight to the middle earth.
ii. models that predict environmental settings and geological conditions are incorporated

Result is a set of possible cross-verification.



http://www.dailygalaxy.com/

Deep Ocean Vents



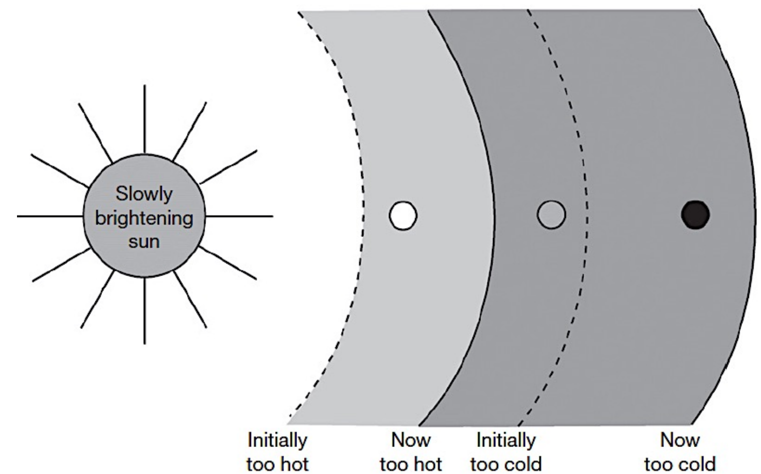
http://oceanexplorer.noaa.gov

Hot Springs

http://travel.spotcoolstuff.com/new-zealand/best-hot-springs-geothermal

http://31.media.tumblr.com/

7. What does a planet need to be habitable?



a) liquid water

b) Figure 1, not too close, not too far from the sun

c) temperature control (Venus vs. Mars)

d) geologically active (renew – recycle), e.g. exhaust PO_4 supply – what happens to you or proteins and metals (essential)

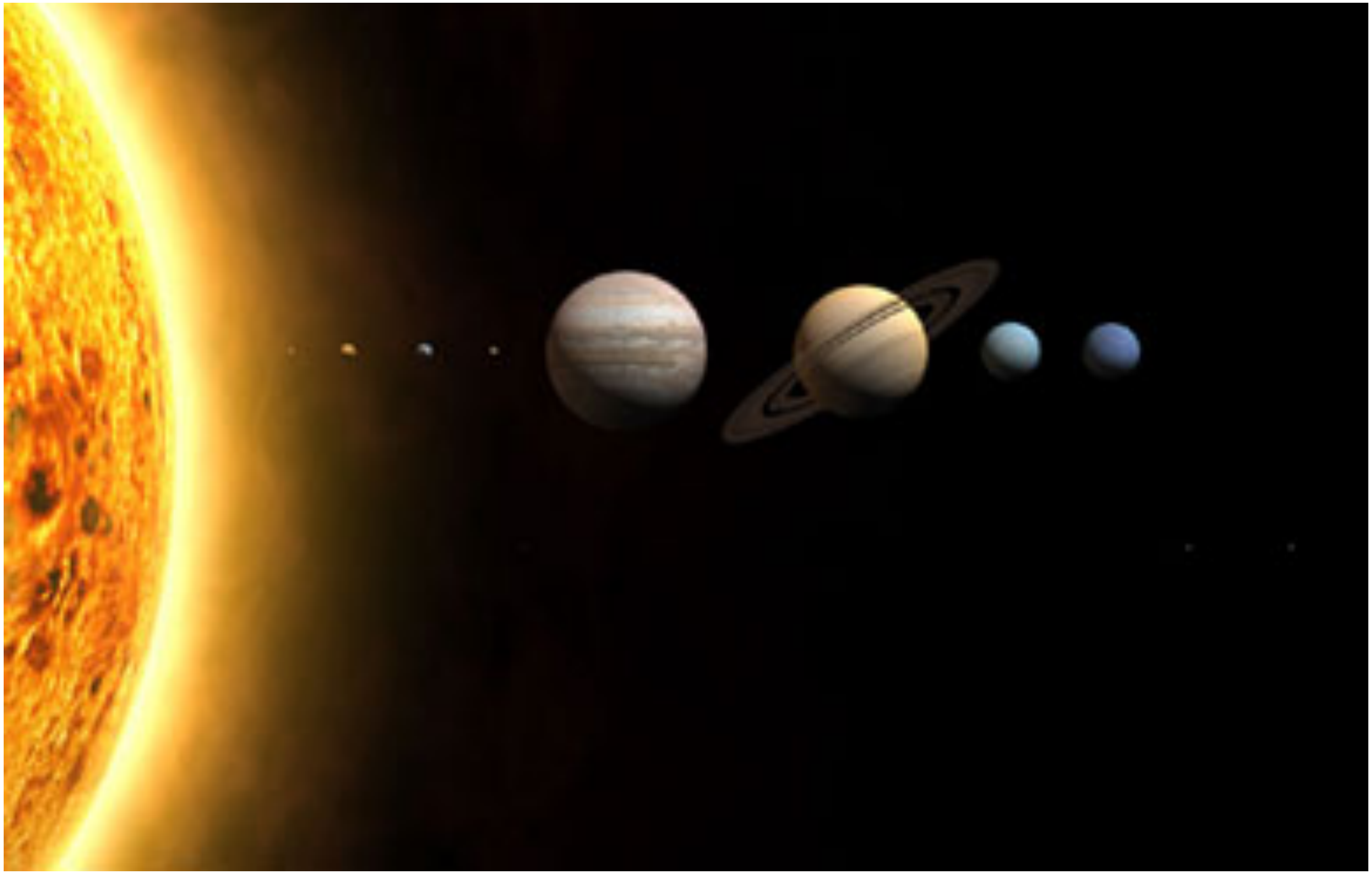
e) Moon – too small now inactive

Mars – almost dead

Mercury – may have been larger (metal rich relic)

Jupiter – too large (maybe the moons)

Only Earth and Venus are the right size.



http://media.airspacemag.com/

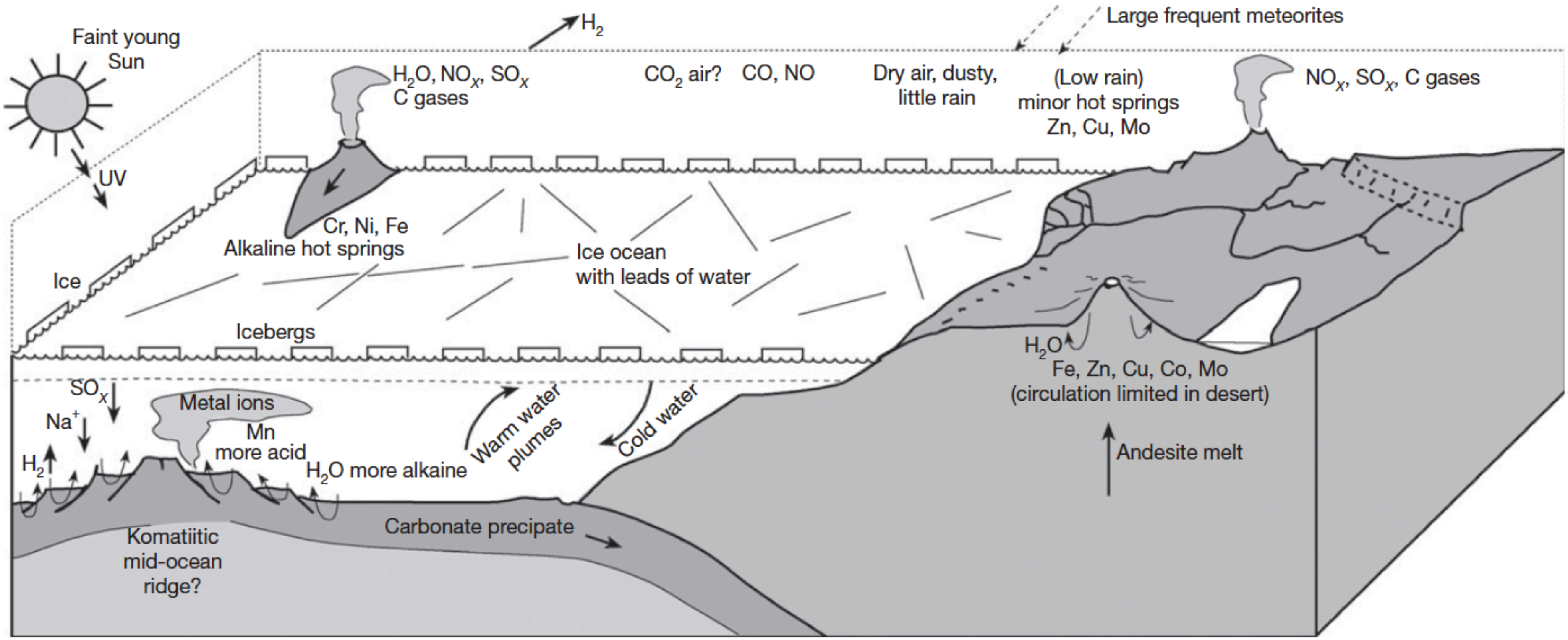
The Hadean: 4.56 → 4.0 Ga ago

First of 4 aeons in Earth history

Hadean	(short)	560 Ma
Archean		
Proterozoic		
Phanerozoic	(short)	

http://journalofcosmology.com/

Hadean



(a)

Nisbet and Fowler (2014) *in* Biogeochemistry, Vol. 10. *Treatise on Geochemistry*

1. Hadean – formation of the Earth. As previously it is a period where the Earth stabilizes and becomes ready to be a place for life.

BEST GUESS – 4.56 to 4.0 Ga

2. Oldest objects we can date: Ca-Al inclusions in meteorites at 4.566 Ga

CAI-in-chondrite.JPG#mediaviewer/File:CAI-in-chondrite.JPG

3. Hadean is the <u>first rock with a record (date) after</u> accretion of the cosmic dust – planetoids, etc.

http://www.corzakinteractive.com/

4. Hypothesis: Core separates reductive Fe center vs. oxidized mantle – REDOX is born. The more surficial environment allowed for a potentially habitable zone (Figure 8).

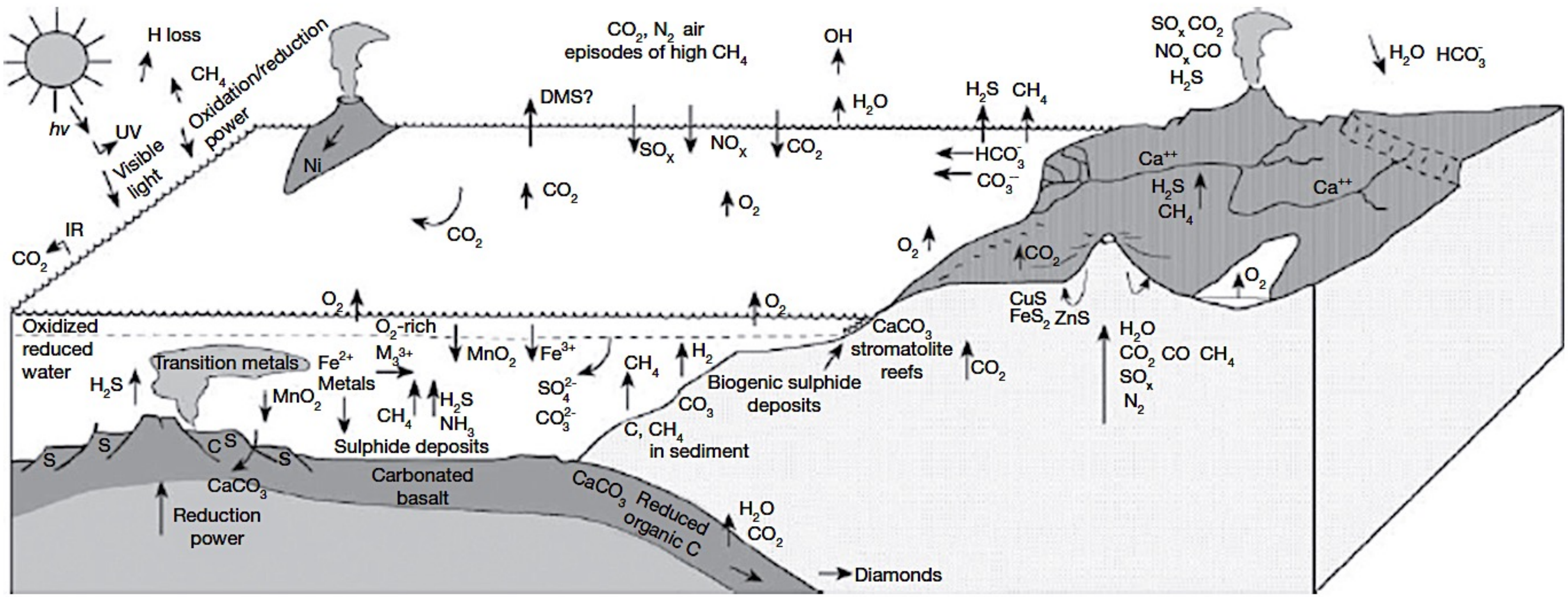


Figure 8 Sources of disequilibrium – possible geochemical (redox) resources for life in the early- to mid-Archean.

Nisbet and Fowler (2014) *in* Biogeochemistry, Vol. 10. *Treatise on Geochemistry*

5. Hypothesis: collision with Earth size mass results in core and magnetic belts, MOST IMPORTANT van Allen belts. The great control of cosmic bombardment and the earth Shields.

Earth was stripped of volatile environment and tilted (eventually winter-summer). Solar radiation now varies yearly, e.g. moon hot/cold day sides – Earth varies. Earth has many variables – night/day: winter/summer. All this and geology create the breeding ground for life.

Impact = Moon – tides, etc., a protector from meteorites. The Moon's gravity creates tides in the Earth (hydrogeology) and seismic stress

http://palaeos.com/hadean/images/NewHadean.jpg

6. Hypothesis (with geology). By ~ 4.45 Ga major accretion has stopped. We always have "cosmic" stuff raining down.

7. Hydrogen moves upwards H + O in rock = H_2O

   (We may have outgassed at the right time and kept our H and C)

8. The zircon minerals of Western Australia
   → 4.2 – 4.4 Ga in sediments 3.3 – 3.5 Ga
   → suggests erosion/weathering and redeposition or <u>recycling</u> – crust down and reincorporation in new hot rocks.

- Labrador – 4.0 Ga rocks – metamorphic (often large areas have survived)

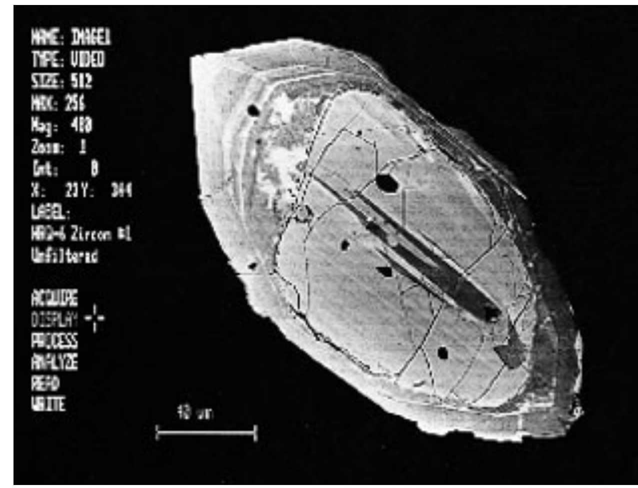


Photo courtesy of Darrell Henry

9. (Speculation) – Life – During the Hadean, planet bombardments favour life moving from say Mars to Earth on a piece of rock vs. say Venus. Or it happened here later in the Archean.

http://bit.ly/LBVk0d

http://media.screened.com/

“Primordial ooze…” Q

The Archean: 4 to 2.5 Ga

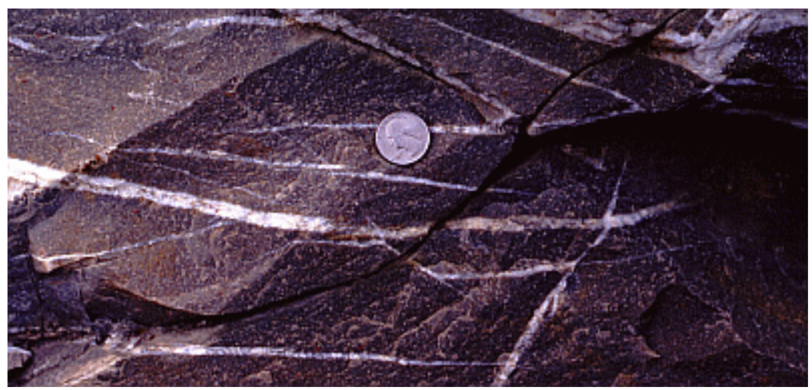
1. **The word means “beginning” in Greek.**

Many choices to define this:

a) the date of first life on Earth – carbon isotopes will eventually find the oldest evidence
b) the date of the last common ancestor – the elusive cell in a rock
c) the round number idea 4, Ga – not good
d) the oldest dated rock ~ 4 Ga – we have these and this is the main basis, but it changes as we find older rocks
e) the oldest record of a mineral crystal formed in the terrestrial environment again ~ 4.3 – 4.4 Ga

2. The Record

a) Greenland: supracrustal rocks that formed at the surface 3.6 – 3.9 Ga. Evidence of water (ocean), flow, erosion and sediments. Meteorite evidence in the rocks. Volcanic hydrothermal systems. Gas vesicles and inclusions – with coprecipitated calcite ($CaCO_3$) – fluids in the inclusions look like present day sea floor ventings.



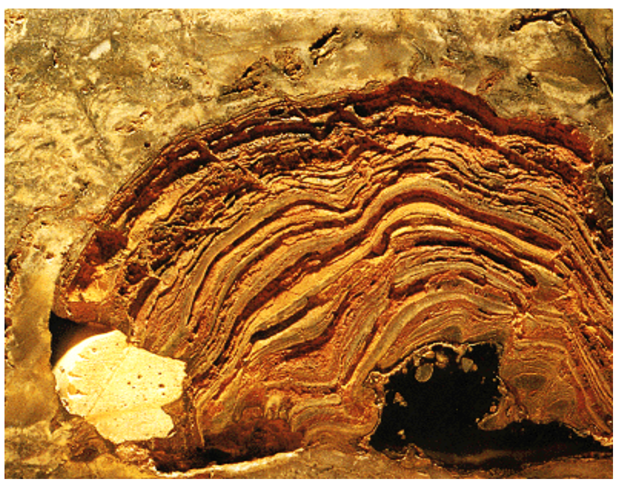
Life: graphite, depleted carbon in particles may be 3.7 Ga old "plankton"

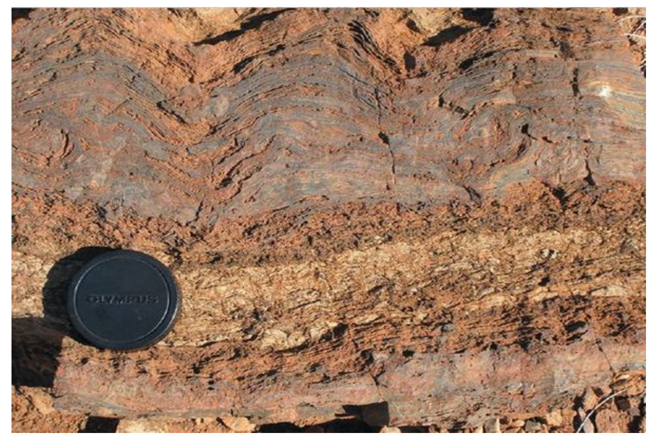
http://hudsonvalleygeologist.blogspot.ca/

b) South African, Namibia: chert (SiO_2) with structure but not positively – biogenic carbon isotopic material > 3.5 Ga

http://web.uct.ac.za/

c) Australia: may have the oldest algal stromatolites – 3.4-3.5 Ga – still debated. Some cases kerogen was found. Other areas have evidence of microbial sulphate reduction Ba SO_4 $\rightarrow$ S^{-} (3.47 Ga). Filamentous microfossils 3.23 Ga. Many younger bacterial pieces of evidence 2.8-2.5 Ga.





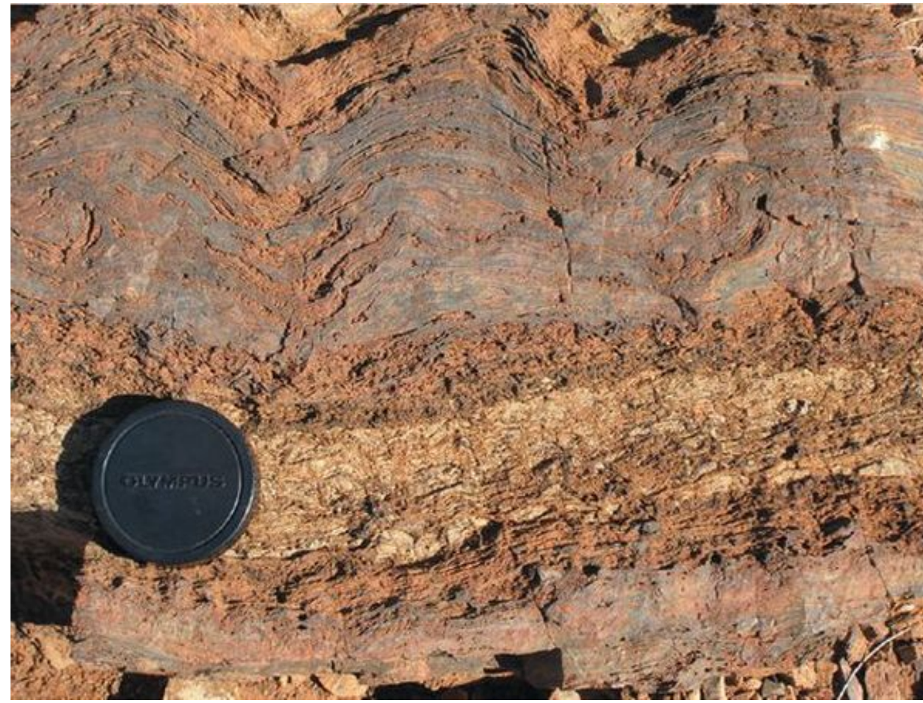
d) Steep Rock, Ontario: Pongola, South Africa
   i. 3.0 Ga – many types of stromatolites
   ii. They control $CO_2 \rightarrow CaCO_3$ reactions
   iii. Evidence of photosynthesis

http://www.geo.mtu.edu/

e) Zimbabwe: 2.7 Ga
   i. Shallow water sediments, C-S isotopic fractionation (methanogens), stromatolites, kerogen and local oil. Many types of "bugs".

http://daggerwrist.tumblr.com/

Paleo Stromatolites



http://gswadata.dmp.wa.gov.au/

http://cdn.physorg.com/

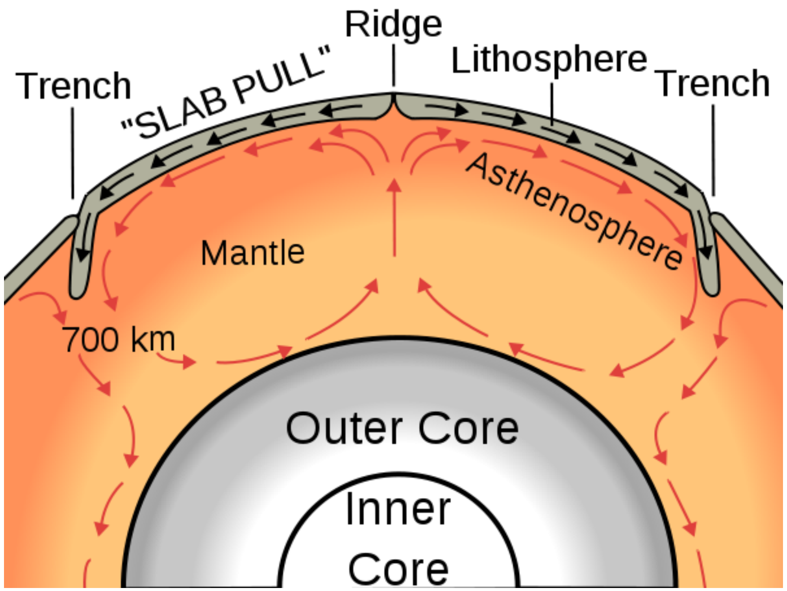
Hamelin Pools Shark Bay western Australia

http://westaust.net/

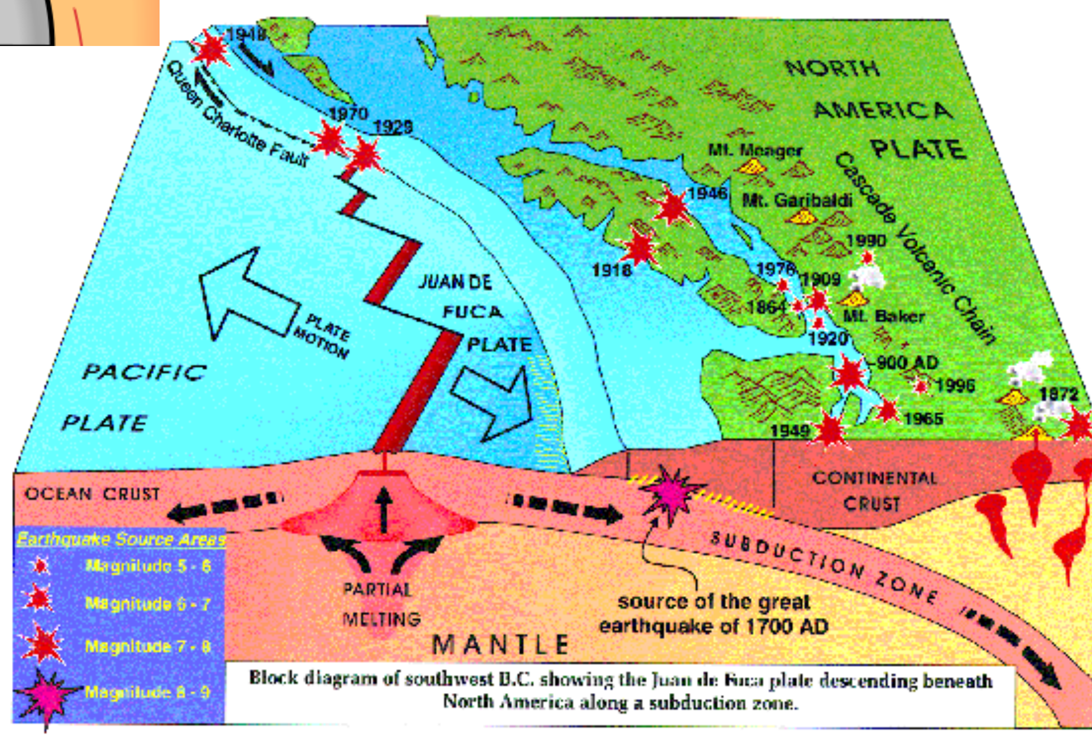
http://images.cdn.fotopedia.com

3. Surface Environment

- Oceans – similar to the present
- ongoing volcanism –much greater at times than the present
- tectonics – recycling
- CO_2 to carbonate is starting (CO_2 cycles to mantle, degas, rain out, erode and capture Ca, Mg which provide the carbonate sink to remove CO_2)
- CO_2 removal lowers the “greenhouse” effect –change pH ?
- many different geologic and geochemical terrains – most would still be hostile to life as we know
- Redox (electron transfer) and the ability to find energy (food) would have been the criteria for survival (e.g. today’s deep oceans and black smokers)



http://earthquake.usgs.gov/

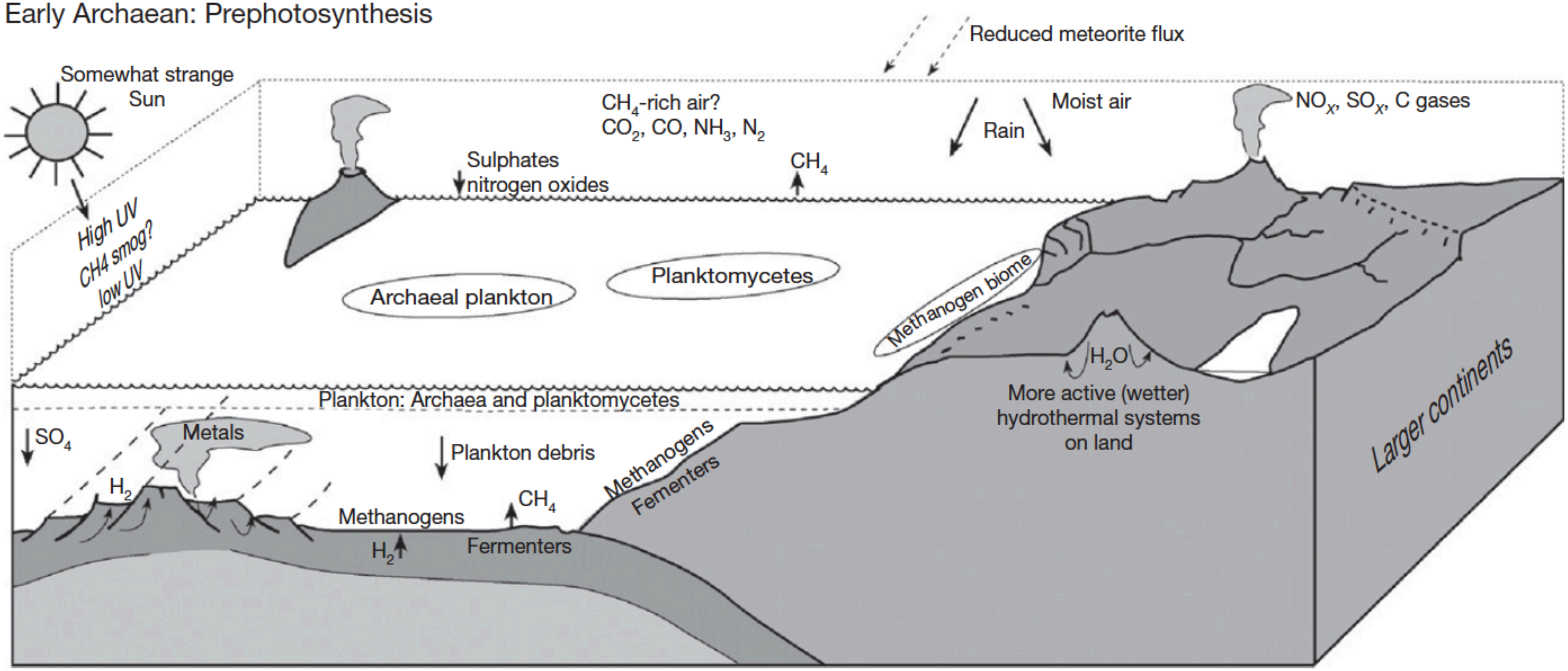


Courtesy PNSN

4. Life

a) hitchhikers on an extra terrestrial meteor/comet
b) primordial soup – evolve lipids – cells
c) minerals – clays, iron oxides, zeolites (layers where H_2O, OH^-, metals could allow organic compounds to form and grow) – eventually evolve proteins
d) RNA in vesicles in the rock (a rock with redox, fluxes of fluid/gas, etc. ultramafics? H + C = methane)

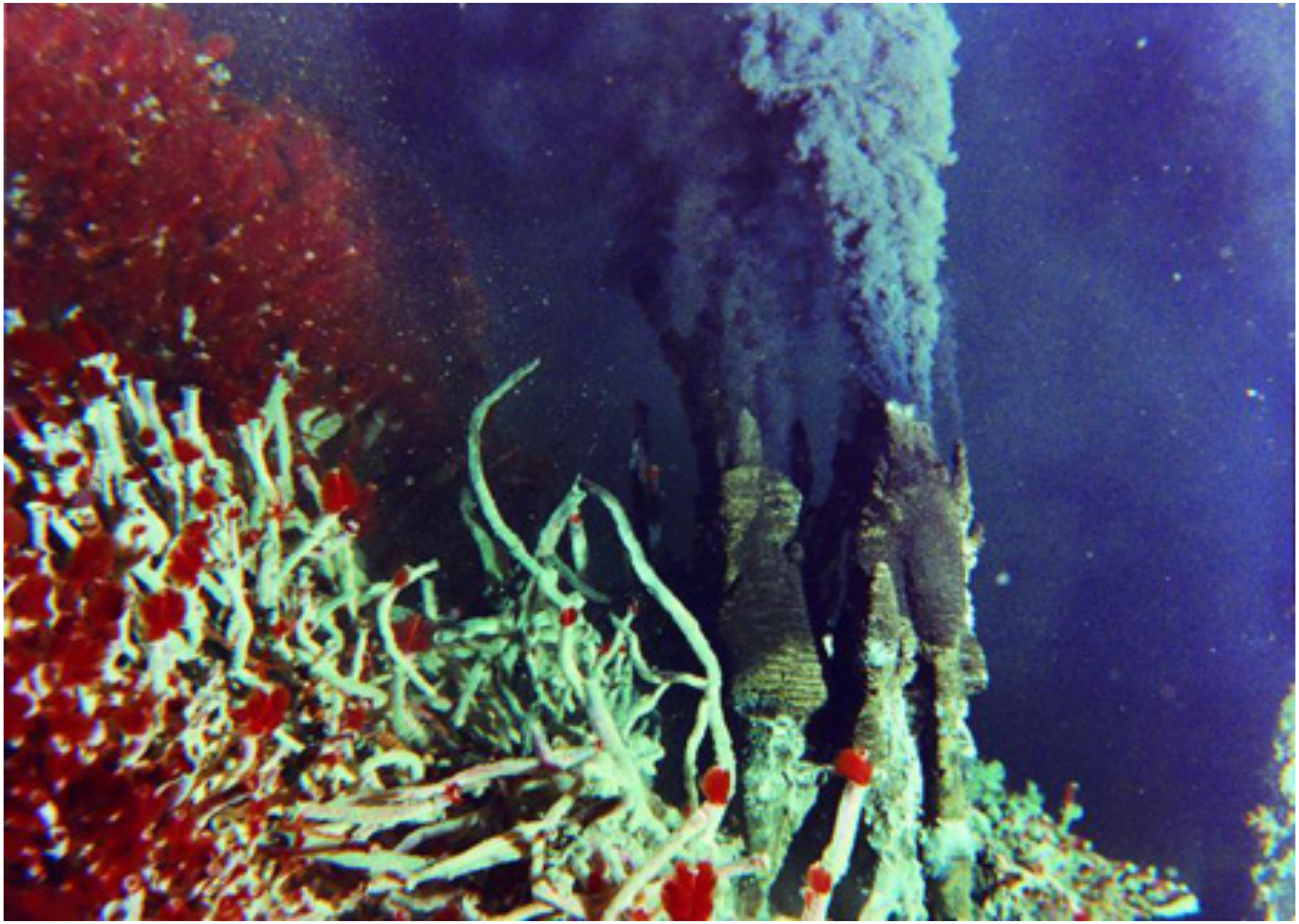
Early Archaean: Prephotosynthesis



(b)

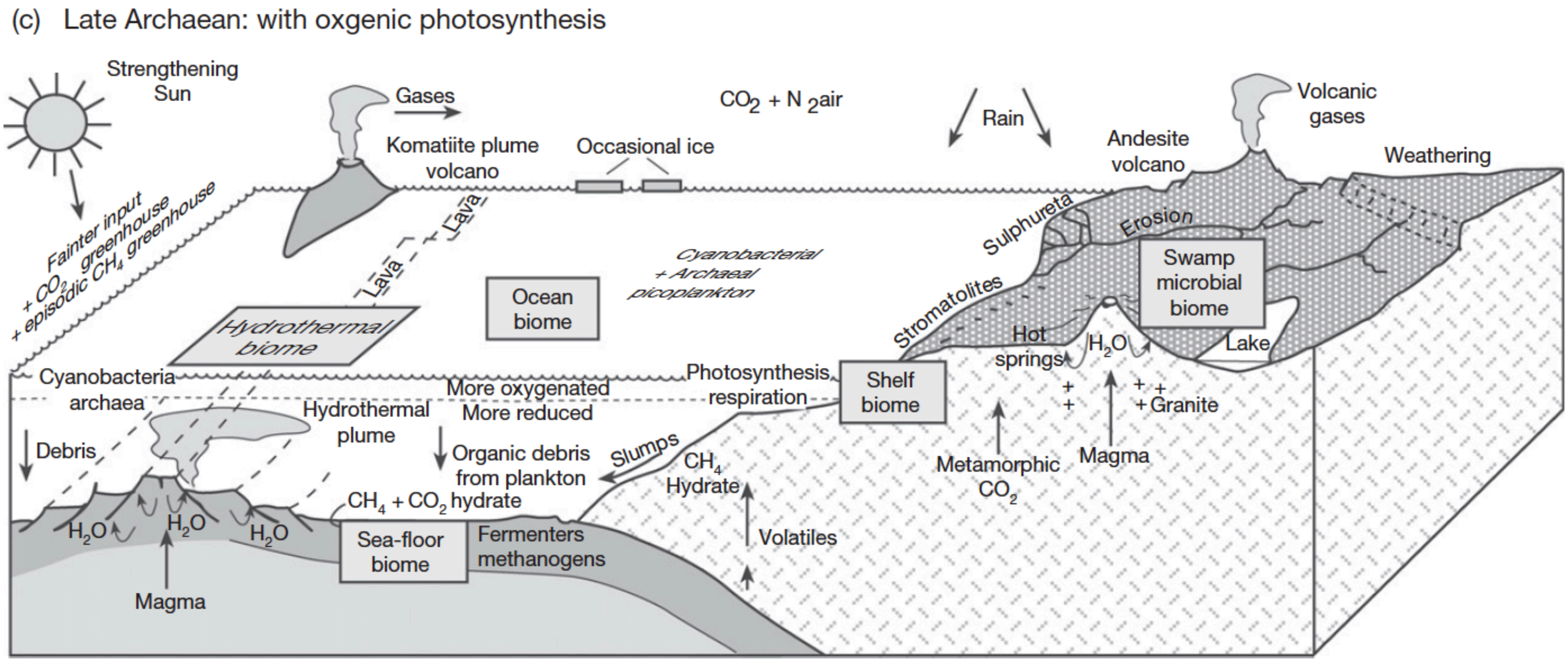
Figure 9 Model of the evolution of the planetary surface: (a) Hadean surface, possibly glacial (apart from rare very hot events after major meteorite impact); (b) early Archean surface, before the onset of photosynthetic processing of the air; and (c) late Archean surface, assuming that the major biochemical pathways had evolved and that the main groups of prokaryotes had evolved.

Nisbet and Fowler (2014) *in* Biogeochemistry, Vol. 10. *Treatise on Geochemistry*



http://mail.colonial.net/

Modern sea vent with life surrounding it



Nisbet and Fowler (2014) *in* Biogeochemistry, Vol. 10. *Treatise on Geochemistry*

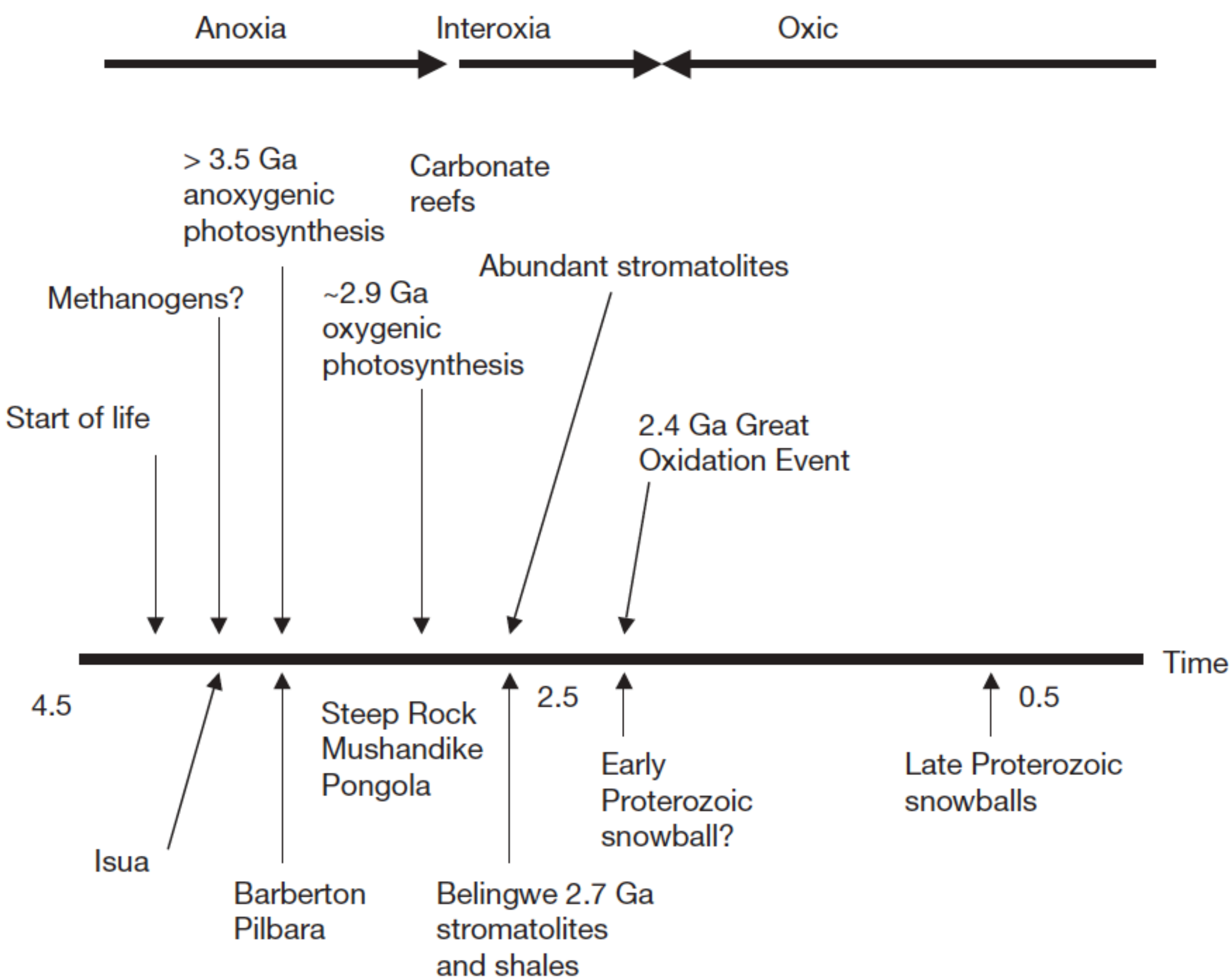


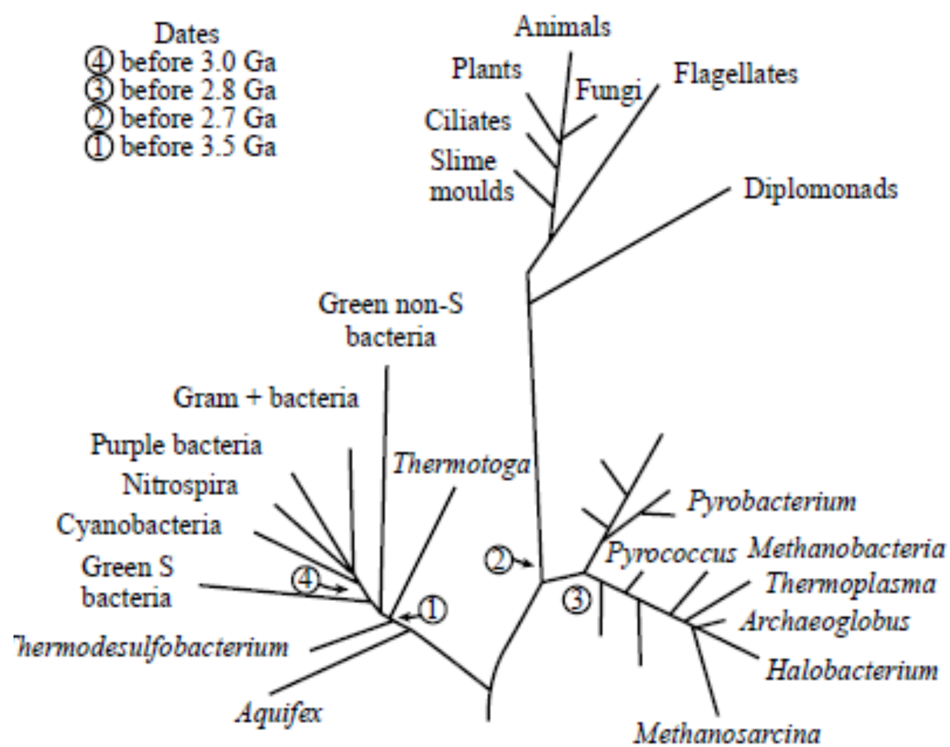
Figure 12 Simplified event chart to show the possible history of oxygen in the air. Modified from Nisbet EG and Fowler CMR (2011) The Evolution of the Atmosphere in the Archean and early Proterozoic. *Chinese Science Bulletin* 55: 1–10.

Nisbet and Fowler (2014) *in* Biogeochemistry, Vol. 10. *Treatise on Geochemistry*

5. The last common ancestor (Figure 7) (most debate is in hands of biologists/biogeochem)

a) evidence best supports a hypthermophile living in hot (>85°C) conditions near a hydrothermal system (again those serpentinizing ultramafics (e.g. black smokers or Zimbales ophiolites)

b) the Hunt for deep life, e.g. NASA group, Lake Vostok, under Antarctica



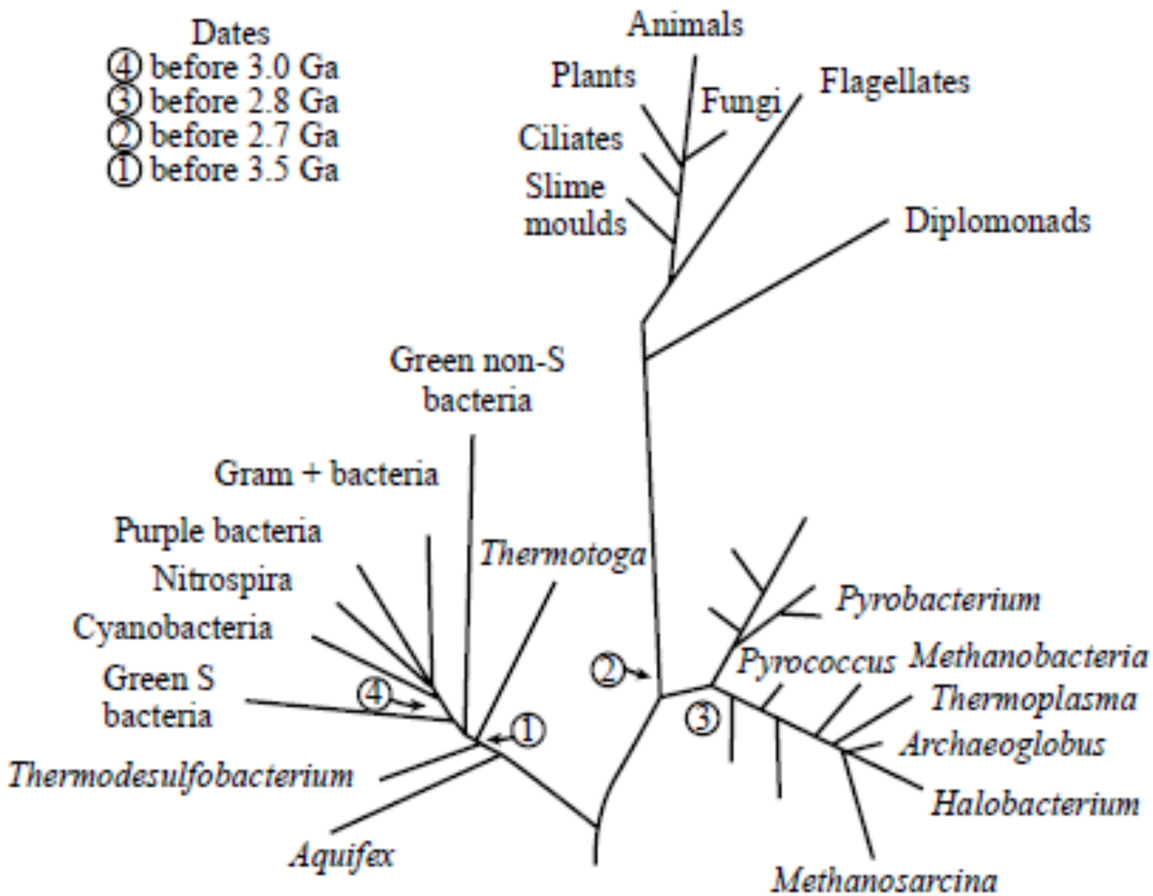
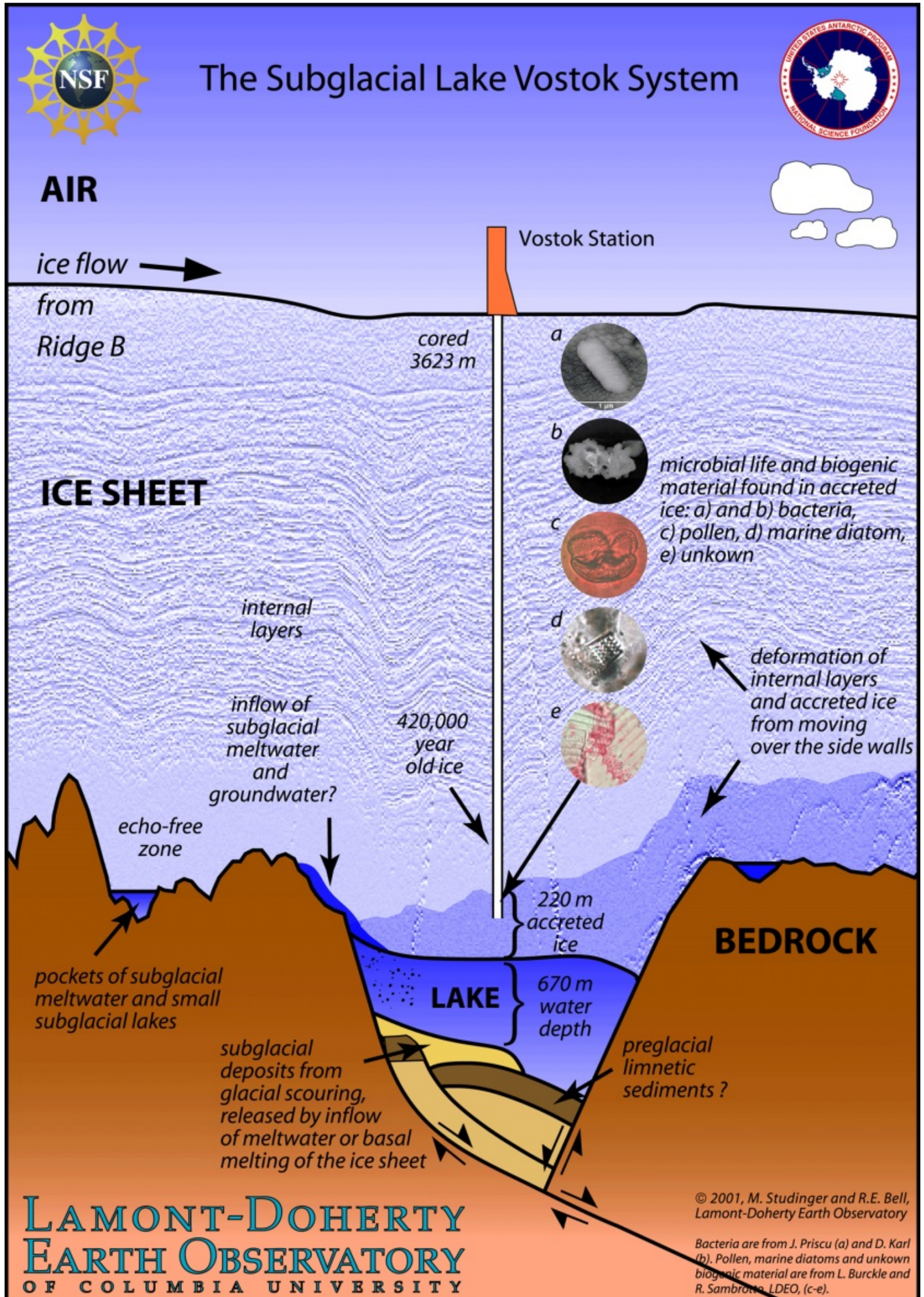


Figure 7 Model of the descent of life following the "standard" model of Woese (1987), as calibrated by the geological evidence (source Shen *et al.*, 2001, and other evidence). See Figure 11 for alternative model.

Nisbet and Fowler (2005) *in* Biogeochemistry, Vol. 8. *Treatise on Geochemistry*


NSF
The Subglacial Lake Vostok System
UNITED STATES ANTARCTIC PROGRAM
NATIONAL SCIENCE FOUNDATION
AIR
ice flow
from
Ridge B
Vostok Station
cored
3623 m
ICE SHEET
a
b
c
d
e
microbial life and biogenic material found in accreted ice: a) and b) bacteria, c) pollen, d) marine diatom, e) unkown
internal layers
deformation of internal layers and accreted ice from moving over the side walls
inflow of subglacial meltwater and groundwater?
420,000 year old ice
echo-free zone
220 m accreted ice
BEDROCK
pockets of subglacial meltwater and small subglacial lakes
LAKE
670 m water depth
subglacial deposits from glacial scouring, released by inflow of meltwater or basal melting of the ice sheet
preglacial limnetic sediments ?
LAMONT-DOHERTY EARTH OBSERVATORY
OF COLUMBIA UNIVERSITY
© 2001, M. Studinger and R.E. Bell, Lamont-Doherty Earth Observatory
Bacteria are from J. Priscu (a) and D. Karl (b). Pollen, marine diatoms and unkown biogenic material are from L. Burckle and R. Sambrotto, LDEO, (c-e).

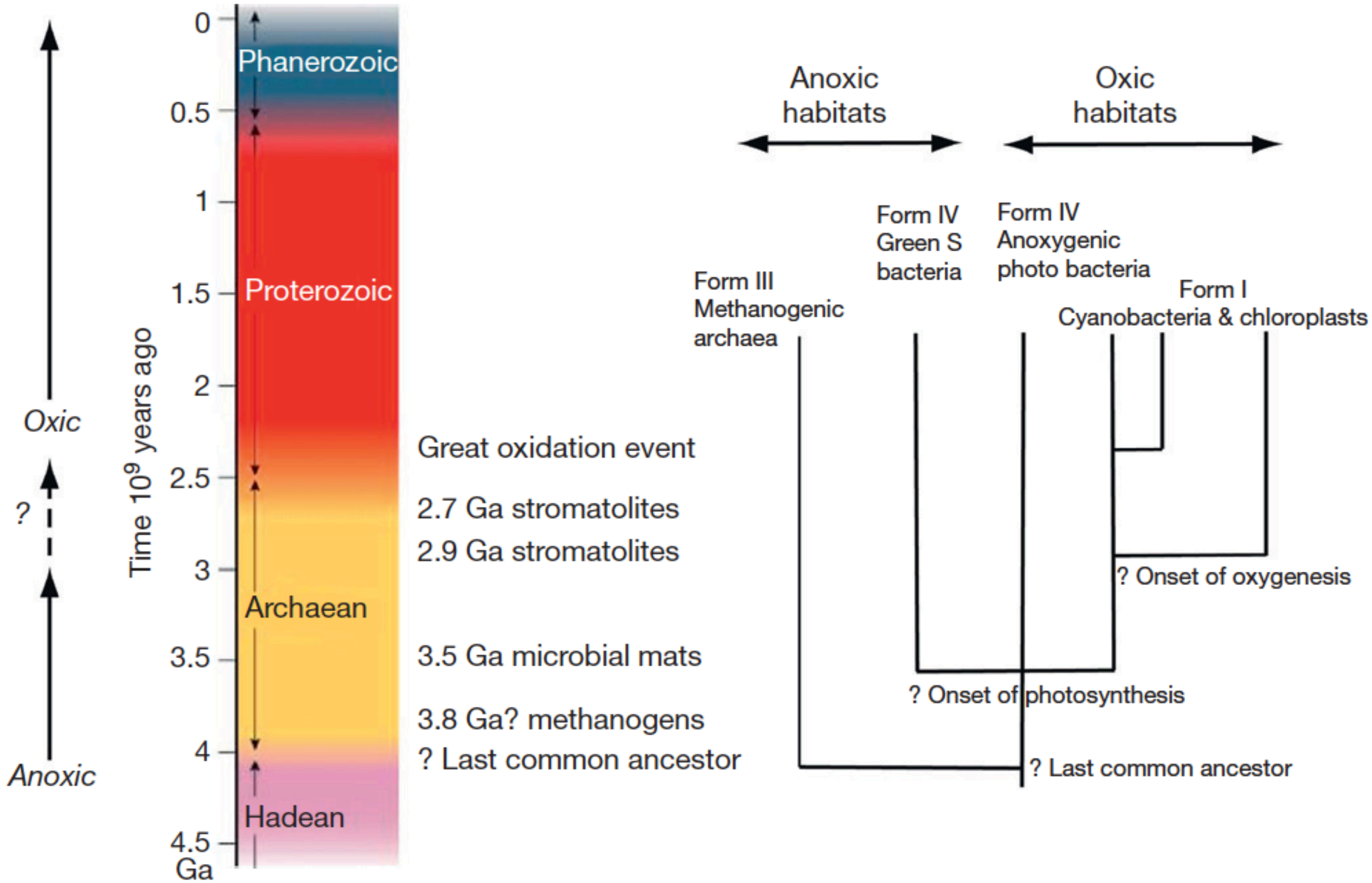


Figure 11 (left) Geological aeons. Note that the Greek word ἀρχή (e.g., in St. John's gospel, 1.1), transliterated 'Archæ' in Latin and thus leading in UK English to Archæ-an, or Archaean, is normally concatenated to 'Archean' in US spelling. All three spellings are correct. (right) The forms of rubisco. Forms III, and rubisco-like protein Form IV occur in anaerobic organisms and may be older in evolutionary terms. Form II in anoxygenic bacteria and Form I in cyanobacteria and plant chloroplasts both occur in aerobic organisms. Modified from Nisbet EG and Fowler CMR (2011) The Evolution of the Atmosphere in the Archean and early Proterozoic. *Chinese Science Bulletin* 55: 1–10; Nisbet EG and Sleep NH (2001) The habitat and nature of early life. *Nature* 409: 1083–1091.

Nisbet and Fowler (2014) *in* Biogeochemistry, Vol. 10. *Treatise on Geochemistry*

6. Redox conditions (Figure 8) Geological support. Disequilibrium creates energy.

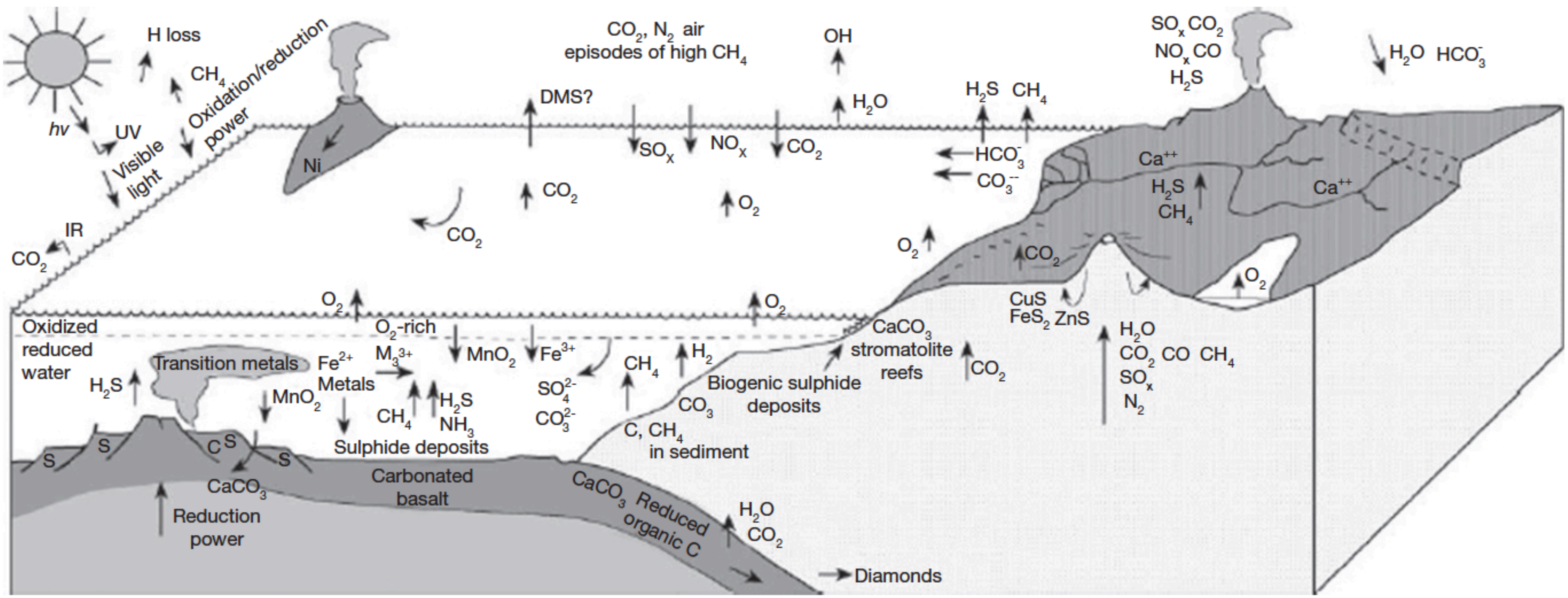


Figure 8 Sources of disequilibrium – possible geochemical (redox) resources for life in the early- to mid-Archean.

Nisbet and Fowler (2014) *in* Biogeochemistry, Vol. 10. *Treatise on Geochemistry*

7. Metabolism

For example, role of hydrogen

a) Archaea and bacteria (knallgas reaction)

$$\tfrac{1}{2}\, O_2 \text{ aqueous} + H_2 \text{ aqueous} \rightarrow H_2O$$

b) OR reduce sulphur

$$S + H_2 \text{ (aqueous)} \rightarrow H_2S \text{ (aqueous)}$$

c) Methanogensis

$$CO_2 \text{ (ag)} + 4\, H_2 \text{ (ag)} \rightarrow CH_4 \text{ (ag)} + 2\, H_2O$$

d) Microbes might then:

$$CH_4 + SO_4^{-} \rightarrow HCO_3^{-} + HS^{-} + H_2O$$

e) or planctomycetes might use ammonium, nitrogen

$$NO_2^{-} + NH_4^{+} \rightarrow N_2 + 2\, H_2O$$

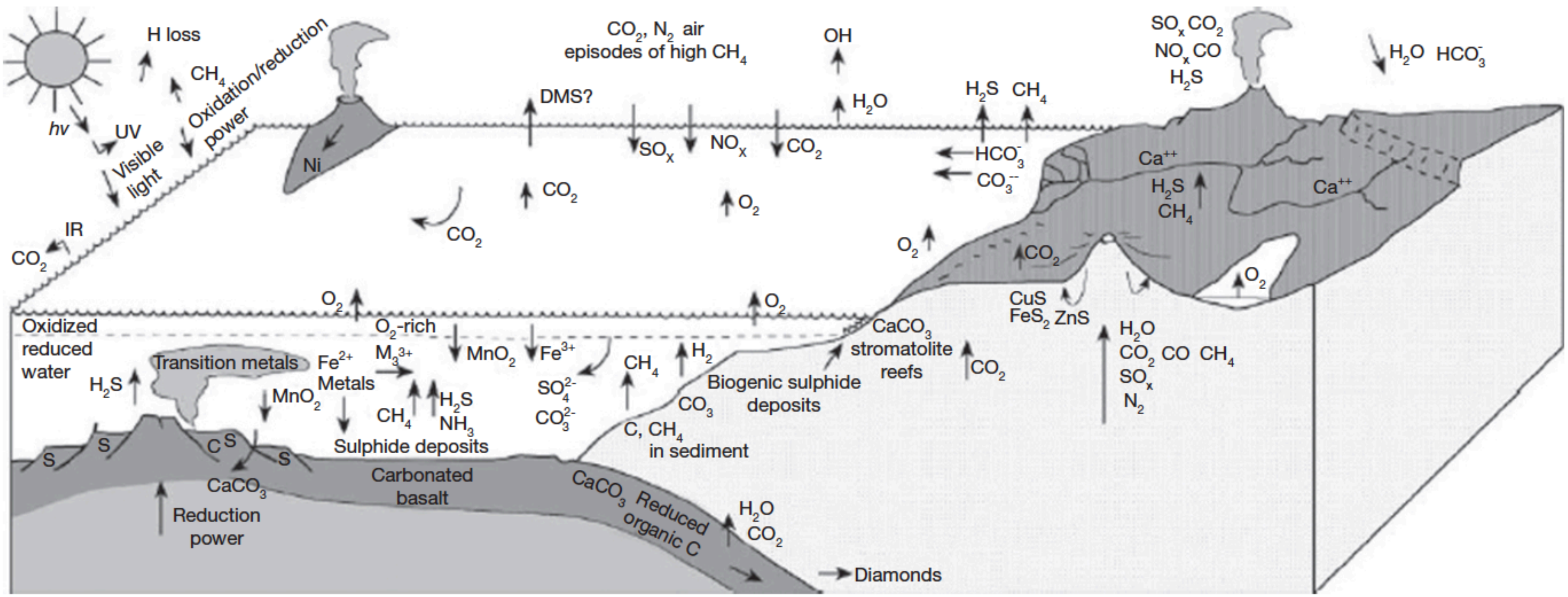


Figure 8 Sources of disequilibrium – possible geochemical (redox) resources for life in the early- to mid-Archean.

Nisbet and Fowler (2014) *in* Biogeochemistry, Vol. 10. *Treatise on Geochemistry*

8. Organisms – Time – Habitat

a) Early – hydrothermal vents – fringes

As they replicate they change the habitat

b) Methanogenesis

- predate photosynthesizers
- use hydrogen
- release CH_4 to the air
- CH_4 = greenhouse effect and temperature rise – smog;
- all protects early cells and life
- CH_4 may have forced nitrogen fixation – change ocean pH

c) Photosynthetics – Redox

Gases $\rightarrow$ O_2

O_2 $\rightarrow$ oxides

Begin to store and remove many compounds that are not suitable to present day life.

Evolution of Photosynthesis (Geological Evidence)

a) Very depleted or negative ^{13}C results (some of the compounds that drive anaerobic CO_2 fixation are found in ocean vent systems – very old)

Rubisco II
Rubisco I newer and is an aerobic fixer

The distinctive isotopic fingerprint of Rubisco I in ancient carbonates ~ 0‰, $\delta\ ^{13}C$ tells us that aerobic conditions prevailed in many areas.

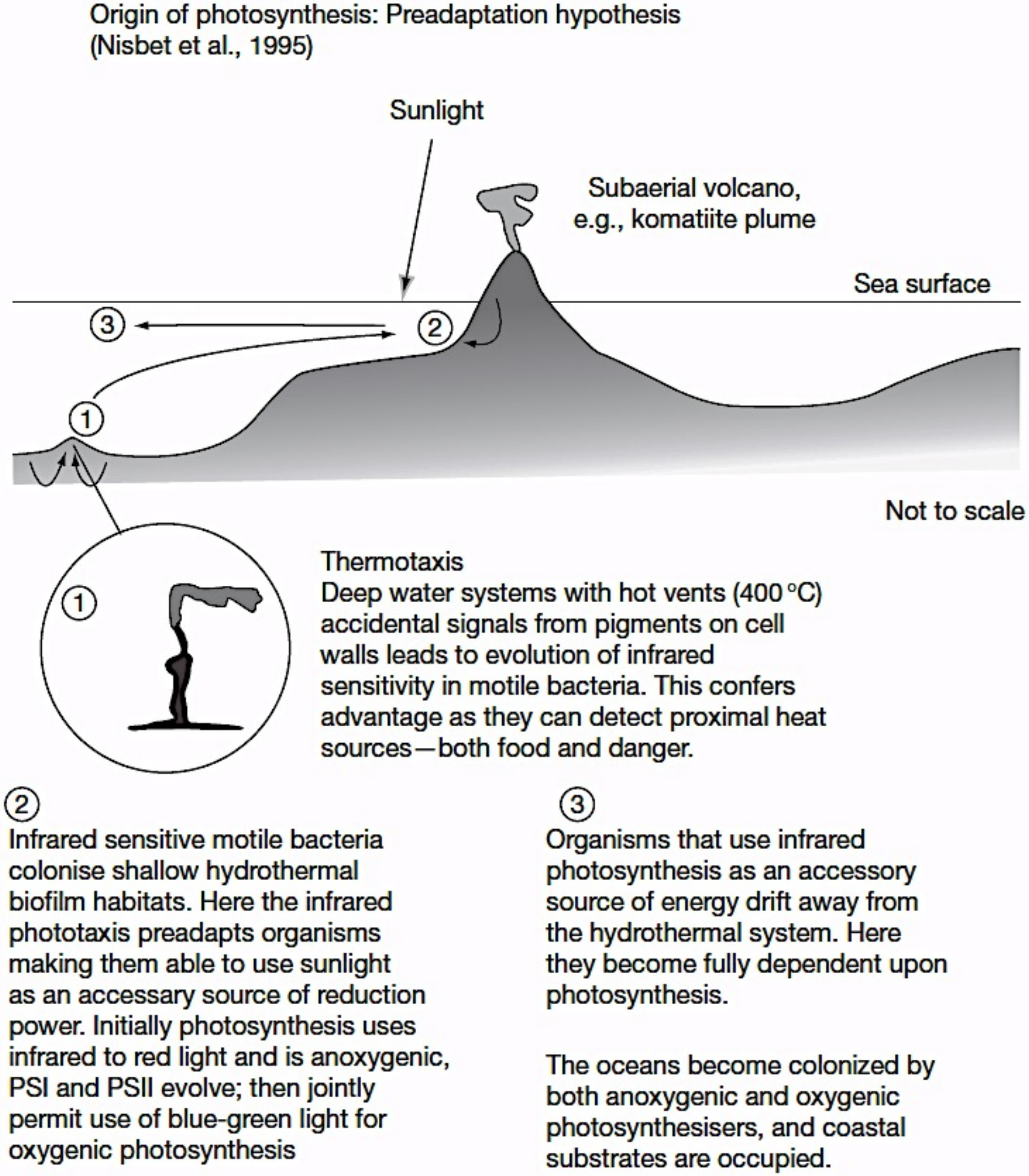


Figure 10 Possible evolutionary chain leading to photosynthesis: hypothesis of preadaptation for infrared thermotaxis. Derived from Nisbet EG, Cann JR, and van Dover CL (1995) Origins of photosynthesis. *Nature* 373: 479–480.

Nisbet and Fowler (2014) *in* Biogeochemistry, Vol. 10. *Treatise on Geochemistry*

b) Ocean vents at 350-400°C, deep and dark BUT emit infrared (IR). Organisms move closer or farther depending on intensity. Tectonics moves vents or creates in shallow seas the organism are positioned to use solar IR and eventually light.

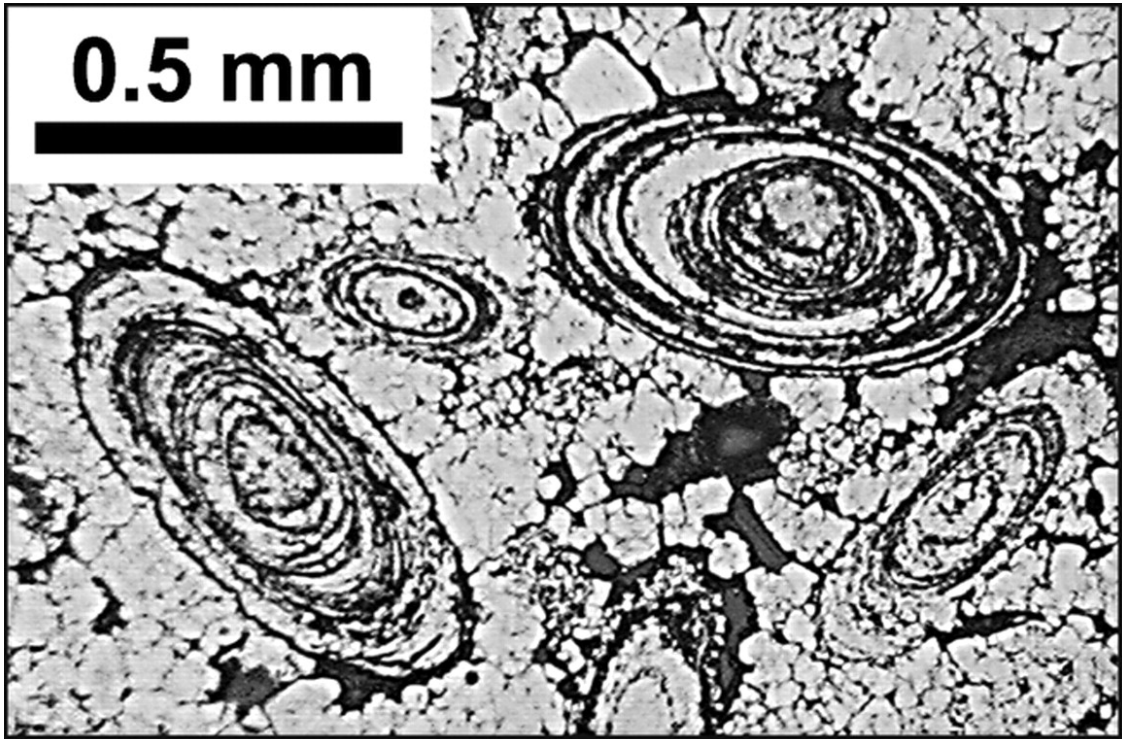
c) Many theories and types of photosynthesis

Sulphur

- reducers made in H_2S for SO_4 (energy)
- BUT photosynthetic oxidizers used H_2S

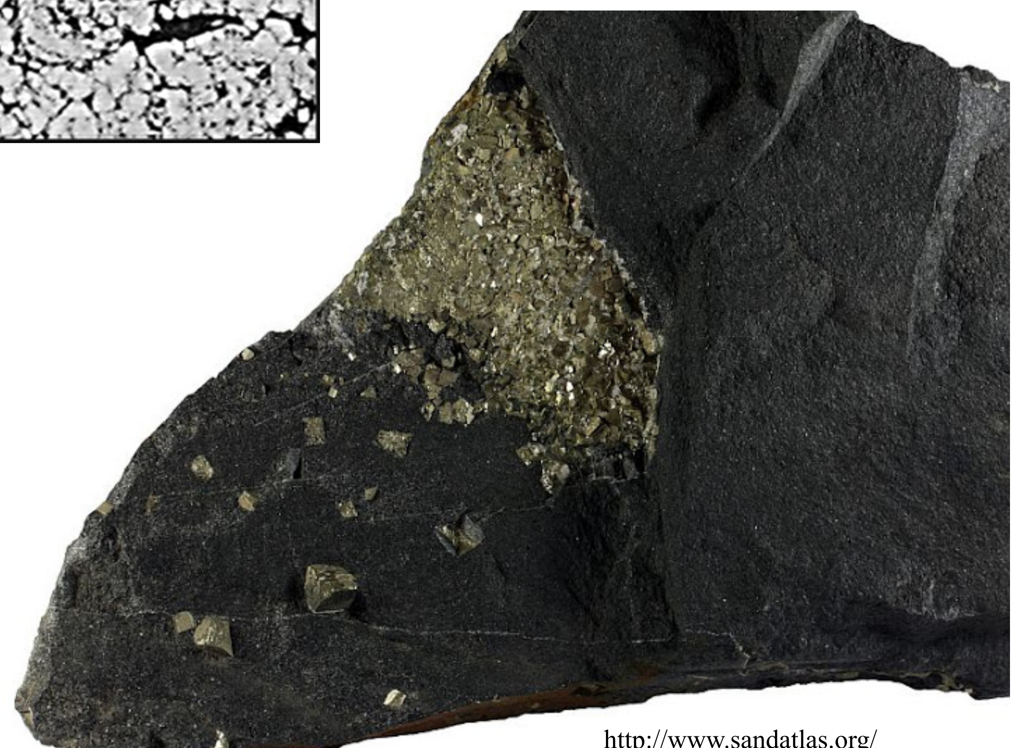
  $$6\ CO_2 + 12\ H_2S \rightarrow C_6\ H_{12}\ O_6 + 6\ H_2O + 12\ S^\circ$$

- make organic compounds, water and deposit sulphide (geologists can measure this → black shales and pyrite
- end result – cleaner oceans and atmosphere



http://geology.gsapubs.org/

Black Shales - pyrite



http://www.sandatlas.org/

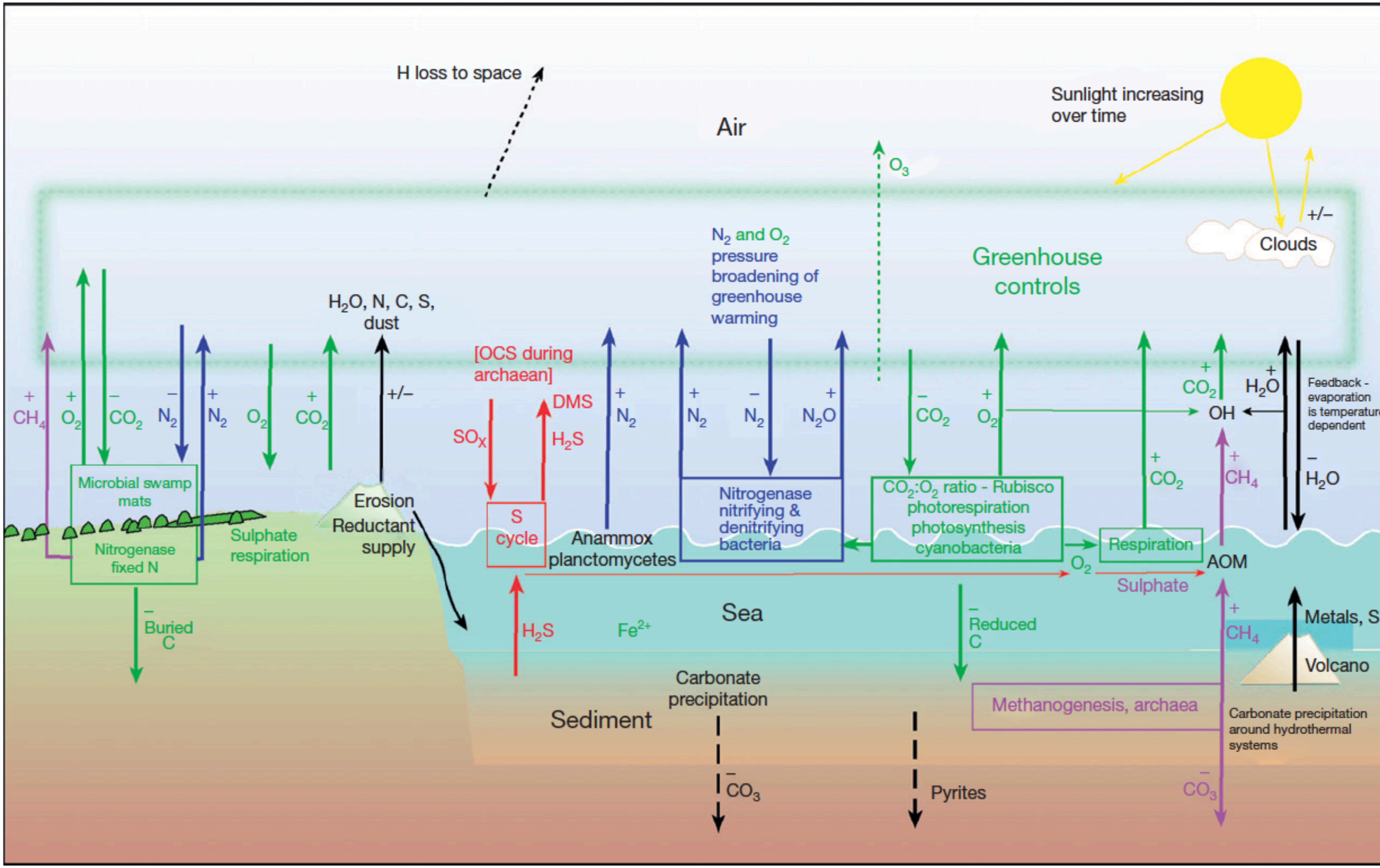


Figure 13 Reservoirs and fluxes in the atmosphere/ocean/sediment system showing biological controls on atmospheric composition, pressure, and temperature. Positive and negative temperature forcing is shown by + and – symbols. Green shading on land represents photosynthetic life. Abbreviations: AOM – anaerobic methane oxidation and AIR – natural mix, now mainly N_2 and O_2, but prior to the Great Oxidation Event ~2.4 Ga ago anoxic and richer in CO_2 and CH_4; other letters are chemical species. (Reproduced with permission from Nisbet et al. (2012); modified from Nisbet et al. (2012)).

Nisbet and Fowler (2014) *in* Biogeochemistry, Vol. 10. *Treatise on Geochemistry*

Summary

1. Surface temperature

    a) The sun and slow evolution – the Earth's position
    b) Tectonics, degassing, the early greenhouse CO_2 – CH_4 when the sun is weak

2. Sequestering – How the Earth slowly stored CO_2 $\rightarrow$ carbonates; N $\rightarrow$ safe soluble compounds and gas; CH_4 $\rightarrow$ carbon compounds; SO_4 – S to sulphides and rock.

3. Without the proper geological history, rocks we could be Venus or Mars and life would not be very evolved if around at all.

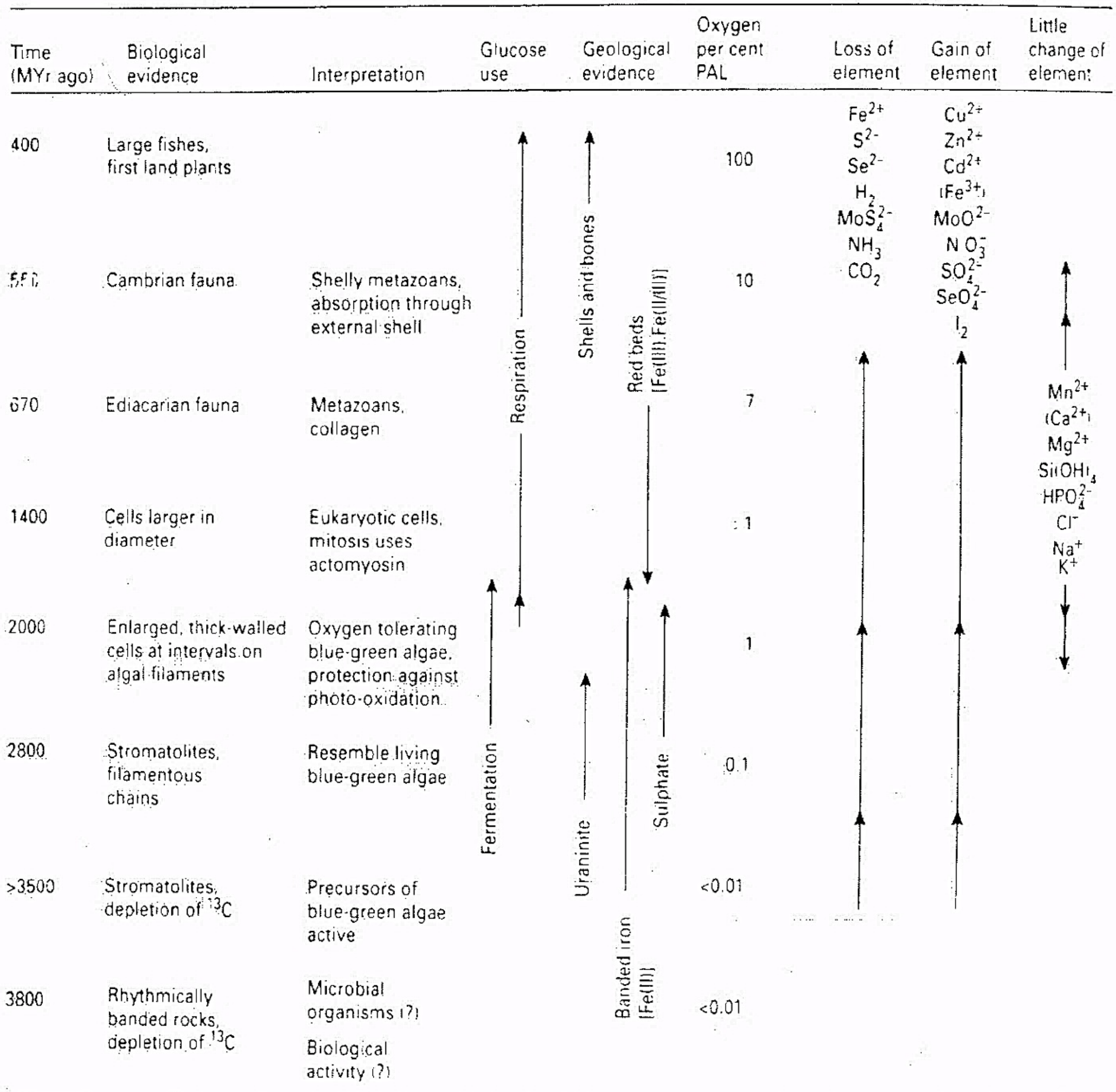
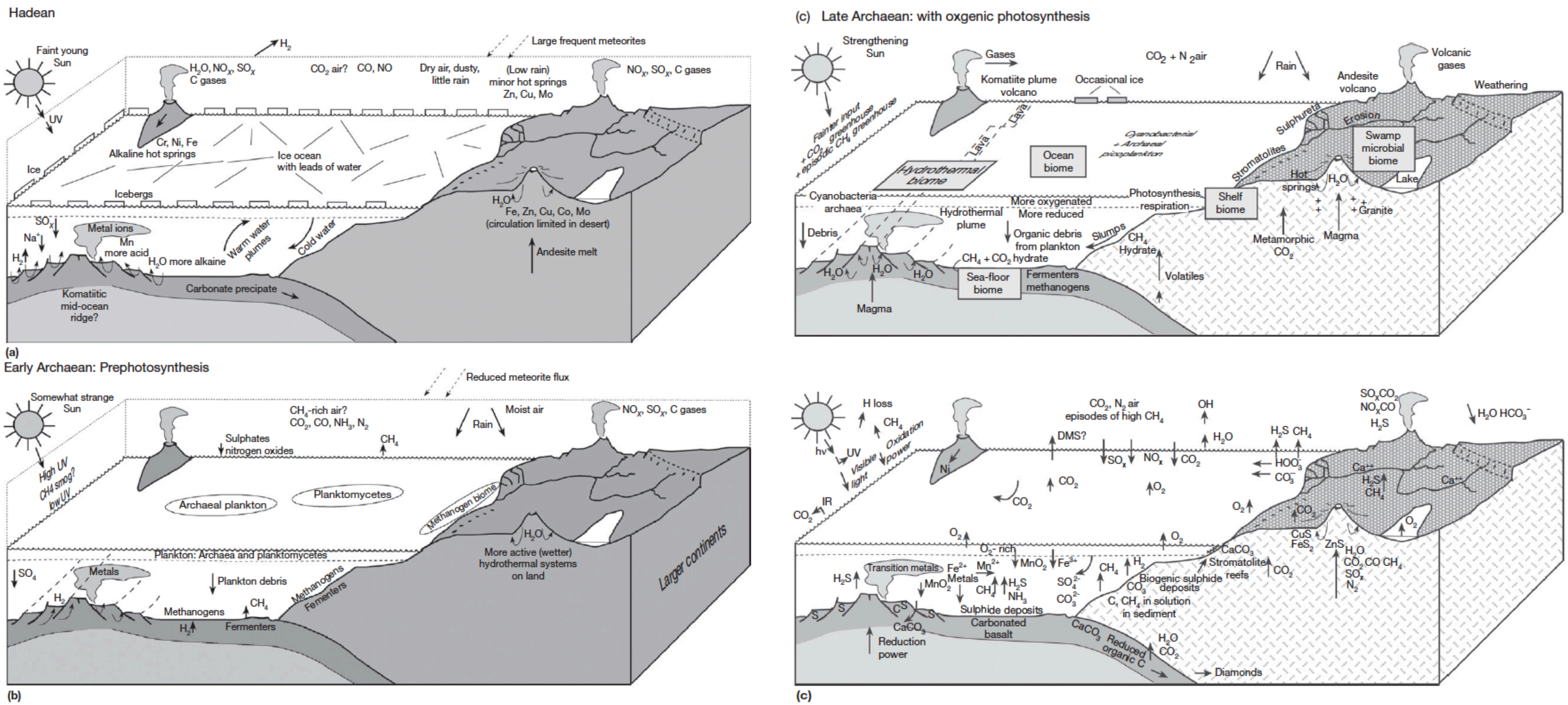


FIGURE 16 The simultaneous sequence of the evolution of Earth and life.



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