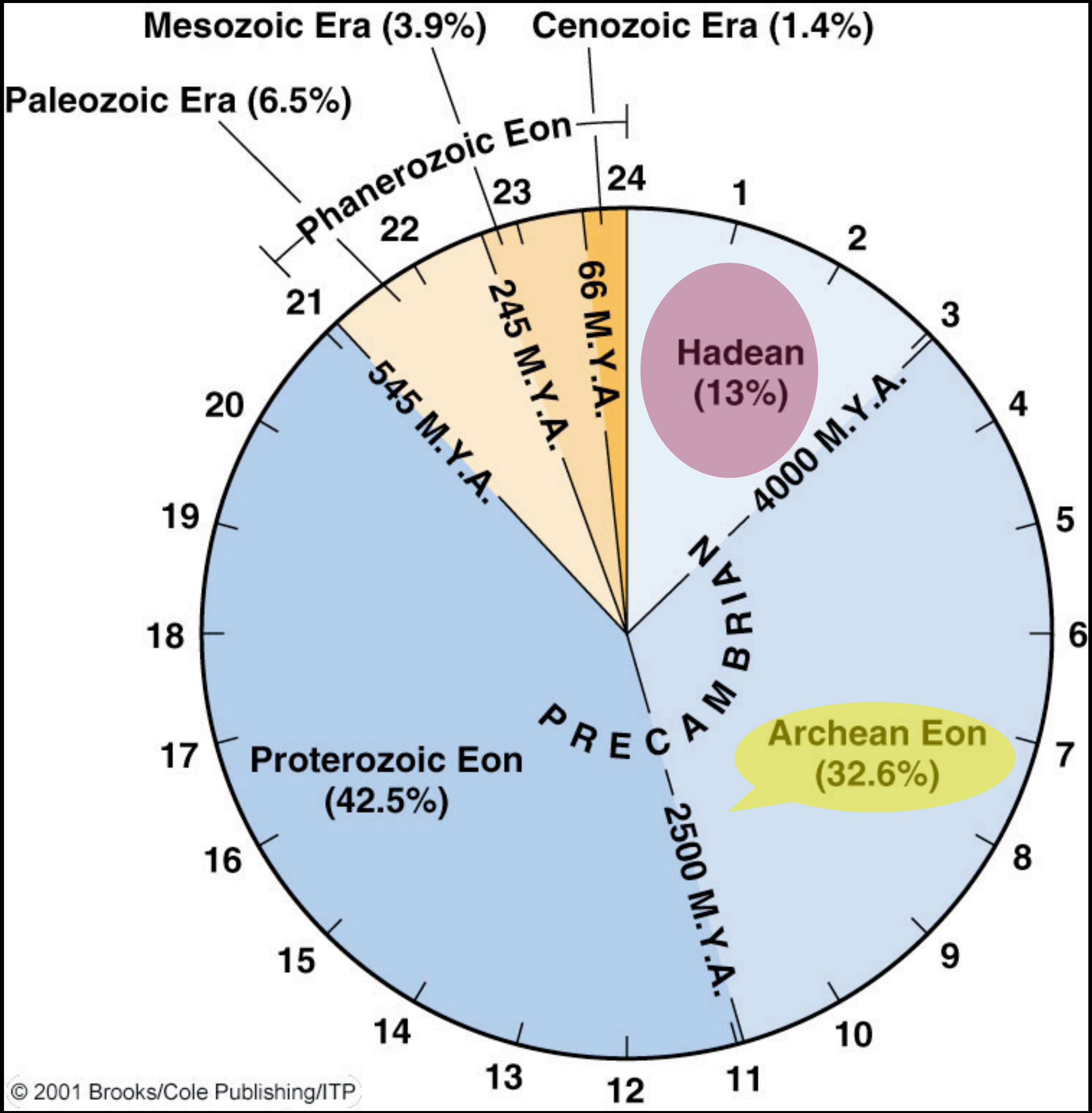
Precambrian Earth and Life History— Hadean and Archean



The Precambrian lasted for 4 b.y., 88% of estimated geologic time.

No rocks are known from the first 640 million years of geologic time, though evidence suggests their existence.

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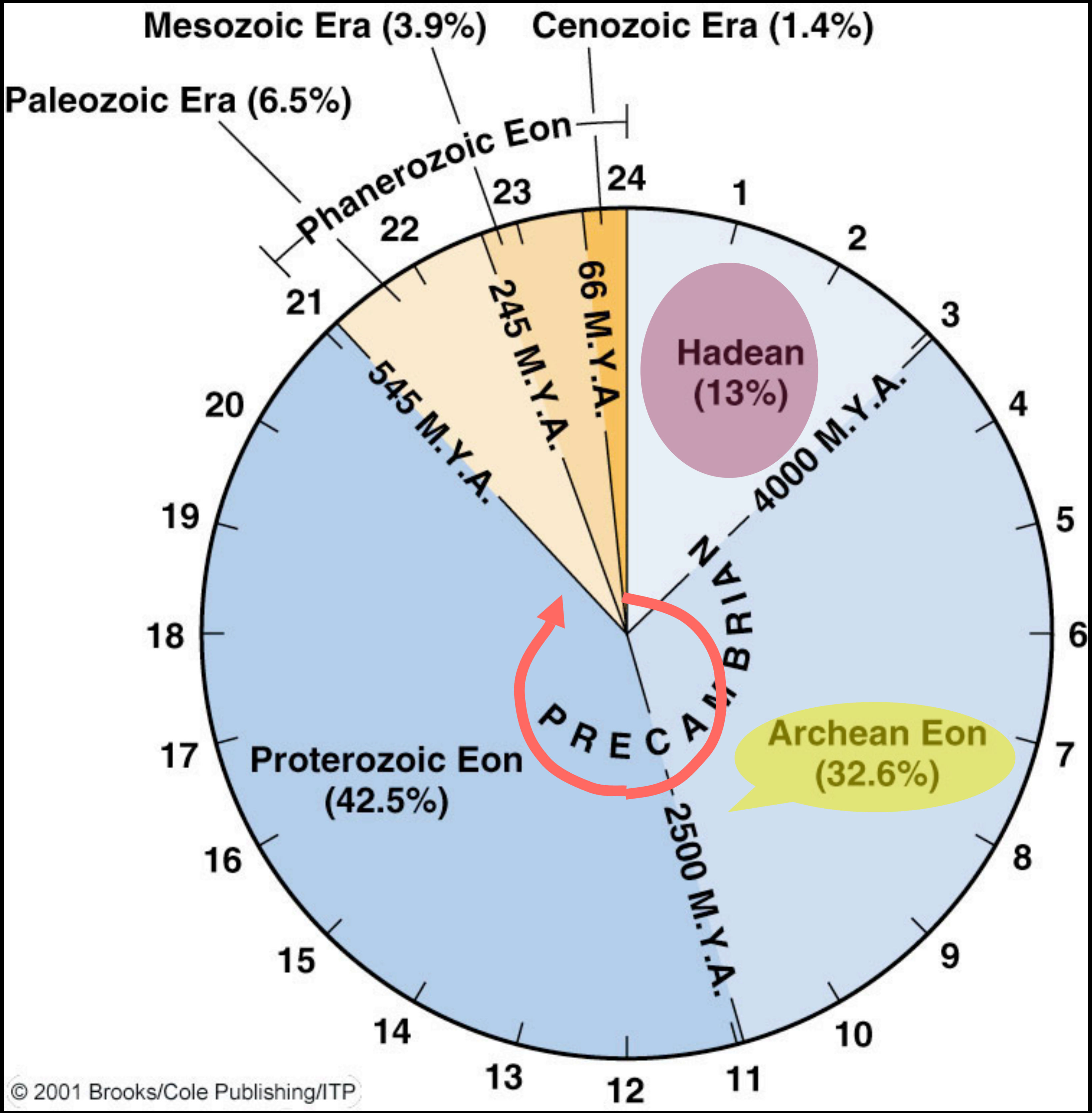

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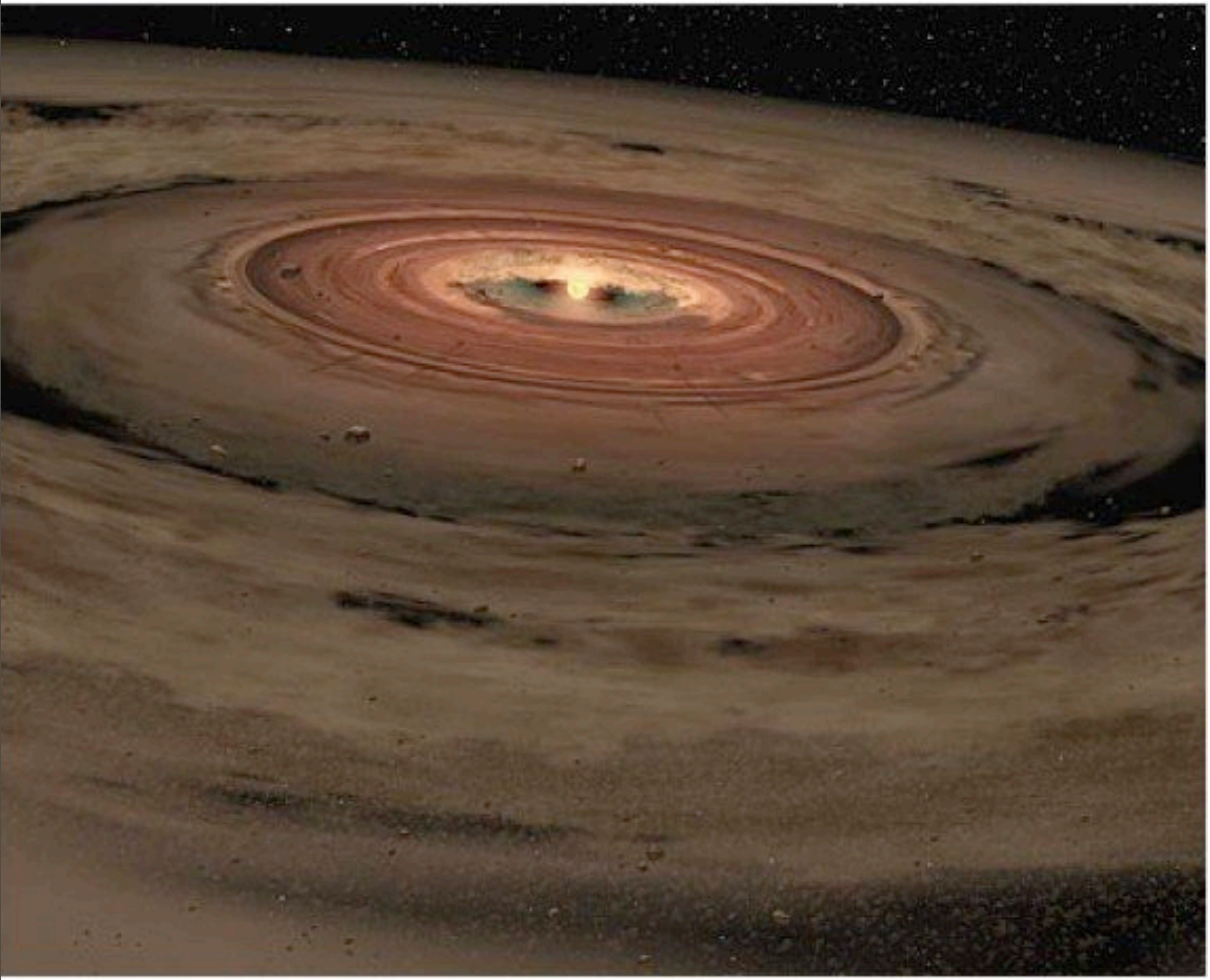


Planetary accretion of gas and fine dust

initial collisions create a few tens of Moon to Mars size planetary embryos: 0.1 to 1 Ma

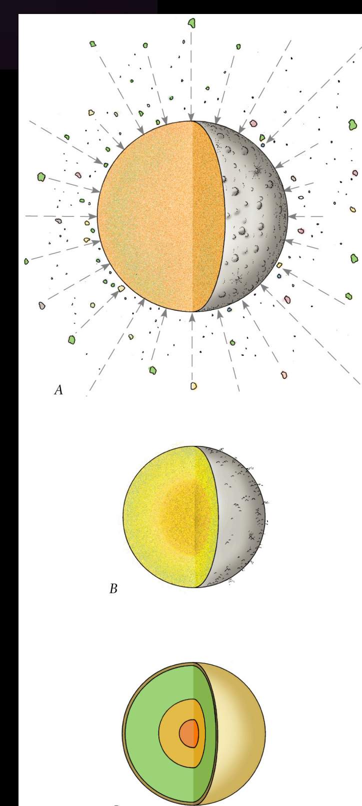
Hadean--name for Earth's first 600-800 my

We know little about it directly , because there is a lack of rocks to read

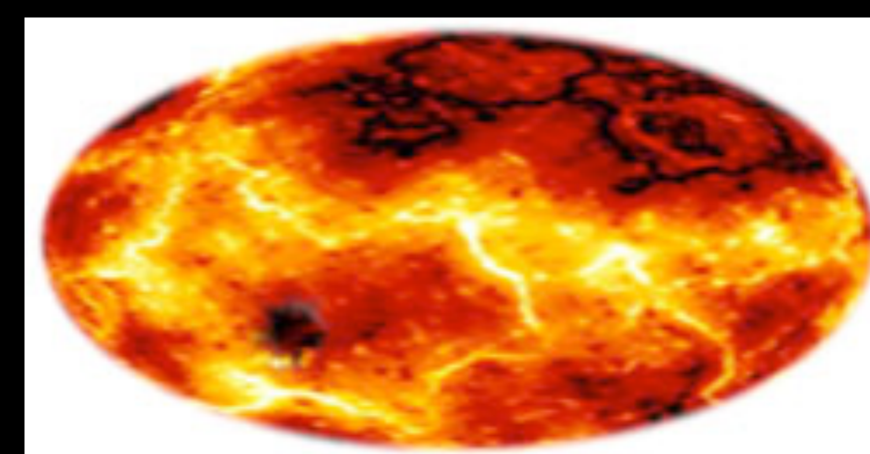
Heat from gravitational accumulation

Heat from Radioactivity

Continuing metoritic accumulation



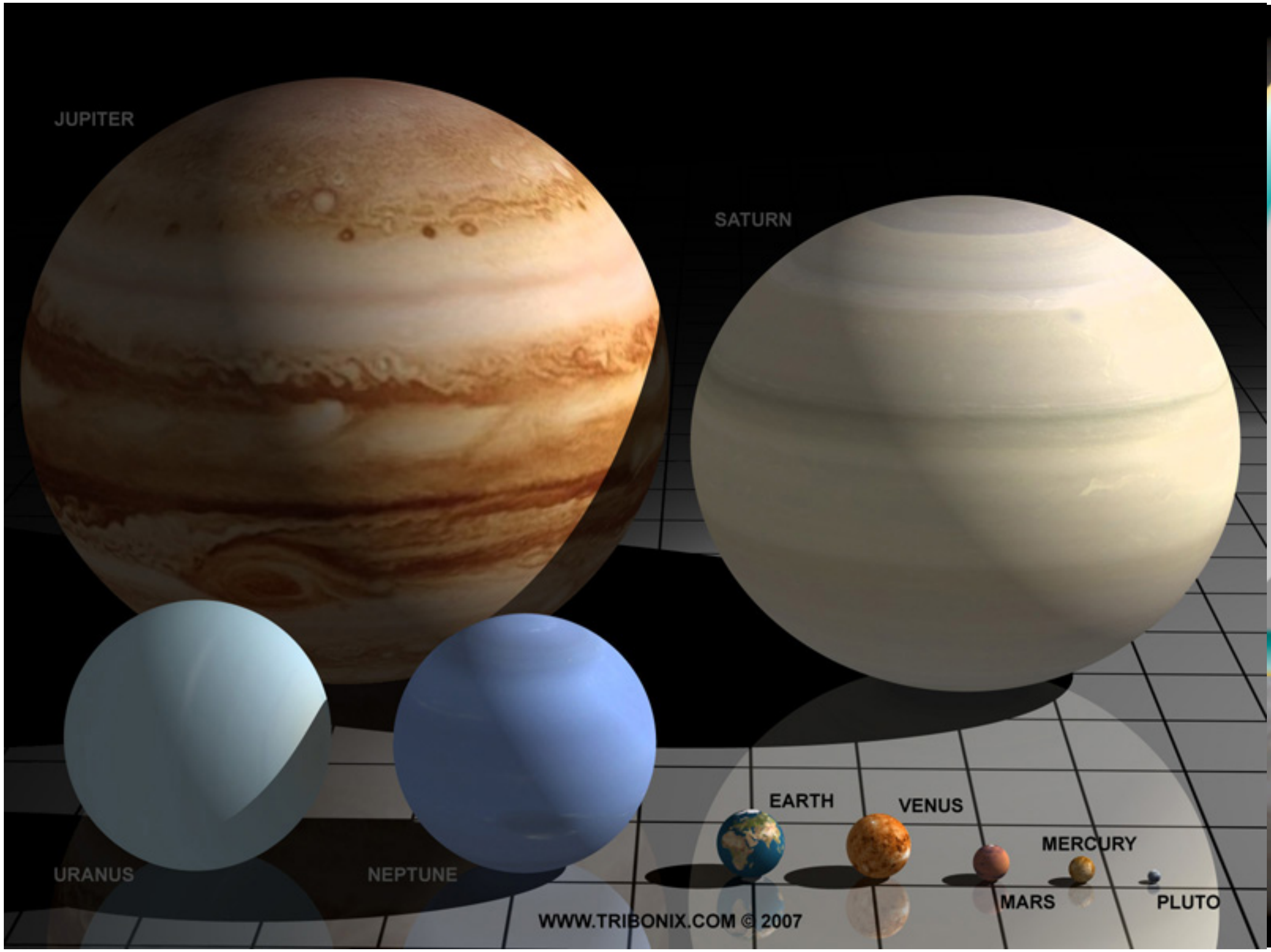
Iron Catastrophe

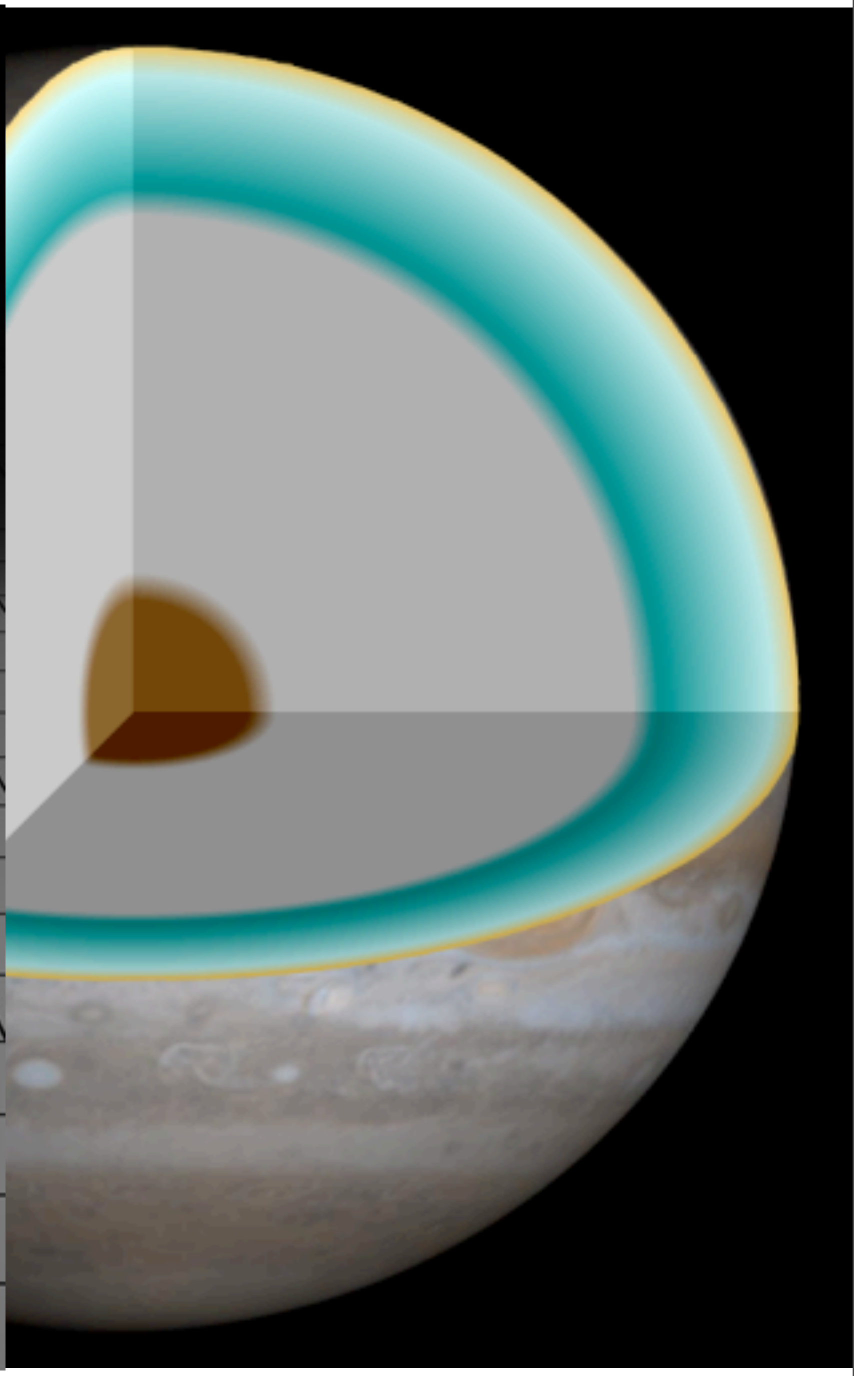


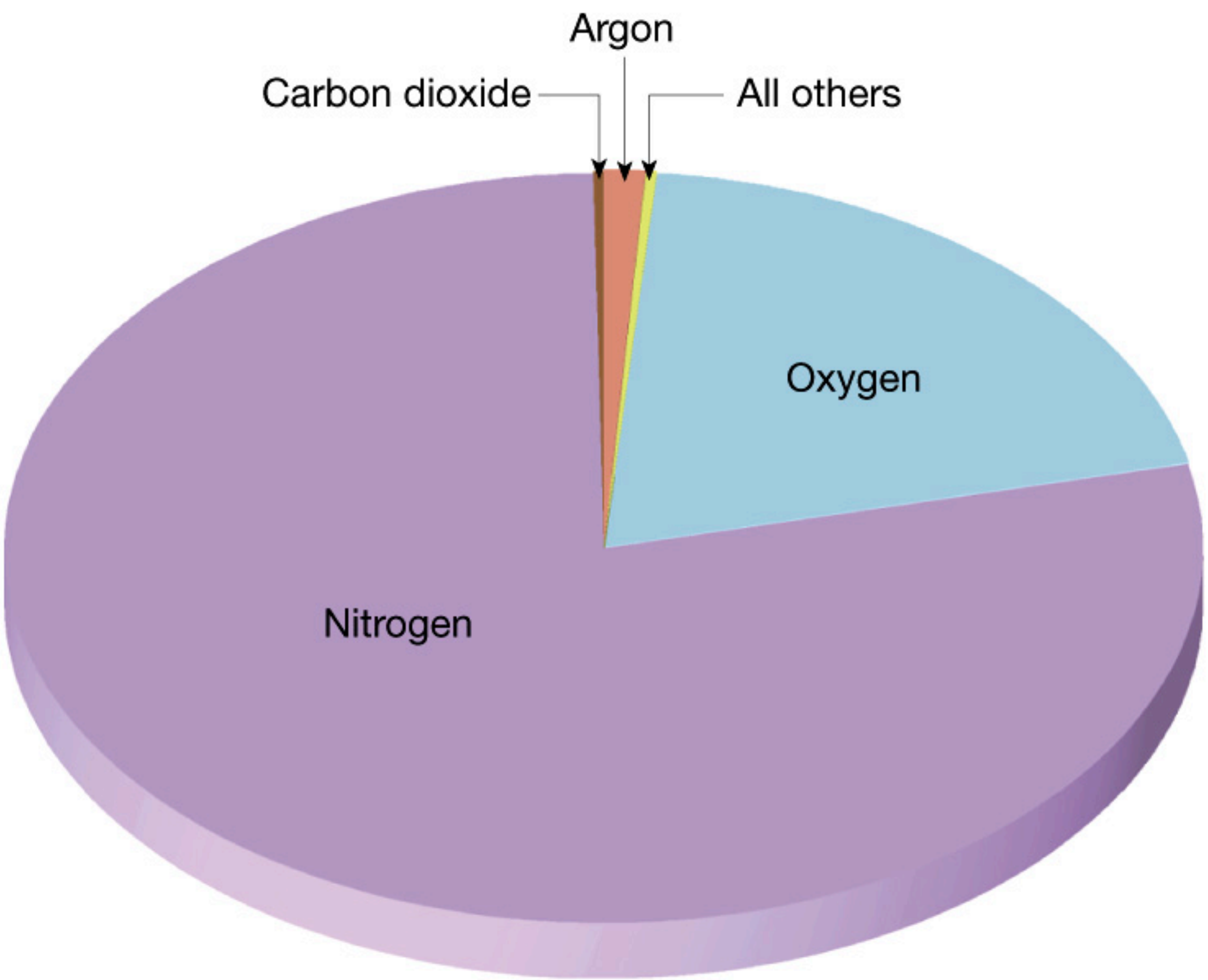
Earth's moon formation

Loss of early volatiles from Earth: :the frost line

The terrestrial planets formed close to the Sun where temperatures were well suited for rock and metal to condense. The jovian planets formed outside what is called the **frost line**, where temperatures were low enough for ice condensation.







First Atmosphere

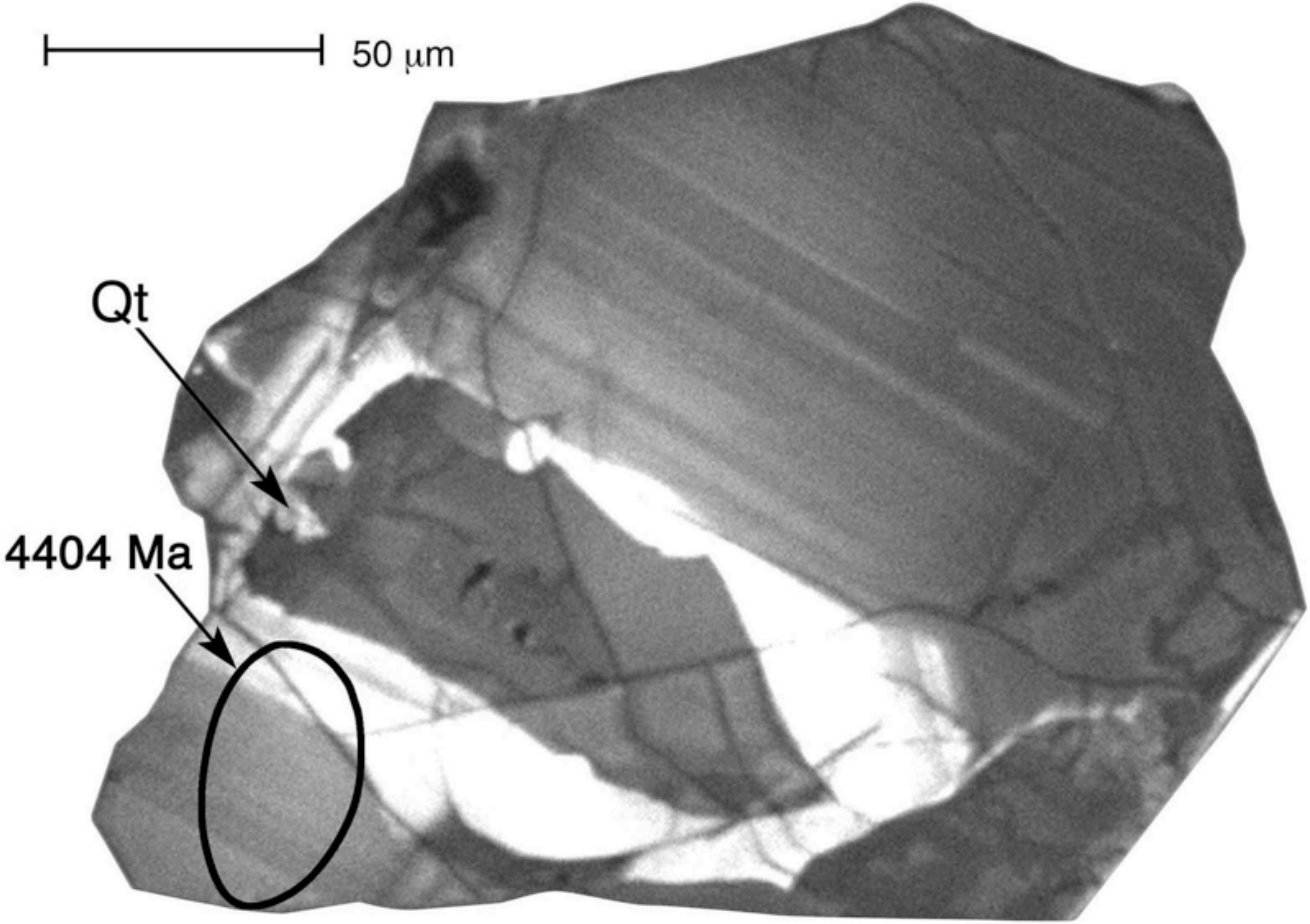
- Composition - Probably H_2, He
- These gases are relatively rare on Earth compared to other places in the universe and were probably lost to space early in Earth's history because
  - Earth's gravity is not strong enough to hold lighter gases
  - Earth still did not have a differentiated core (solid inner/liquid outer core) which creates Earth's magnetic field (magnetosphere = Van Allen Belt) which deflects solar winds.
- Once the core differentiated the heavier gases could be retained

Second Atmosphere

Produced by *volcanic out gassing*.

Gases produced were probably similar to those created by modern volcanoes (H_2O, CO_2, SO_2, CO, S_2, Cl_2, N_2, H_2) and NH_3 (ammonia) and CH_4 (methane)
No free O_2 at this time (not found in volcanic gases).

- *Ocean Formation* - As the Earth cooled, H_2O produced by out gassing could exist as liquid in the Early Archean, allowing oceans to form.
  - Evidence - pillow basalts, deep marine seds in greenstone belts.

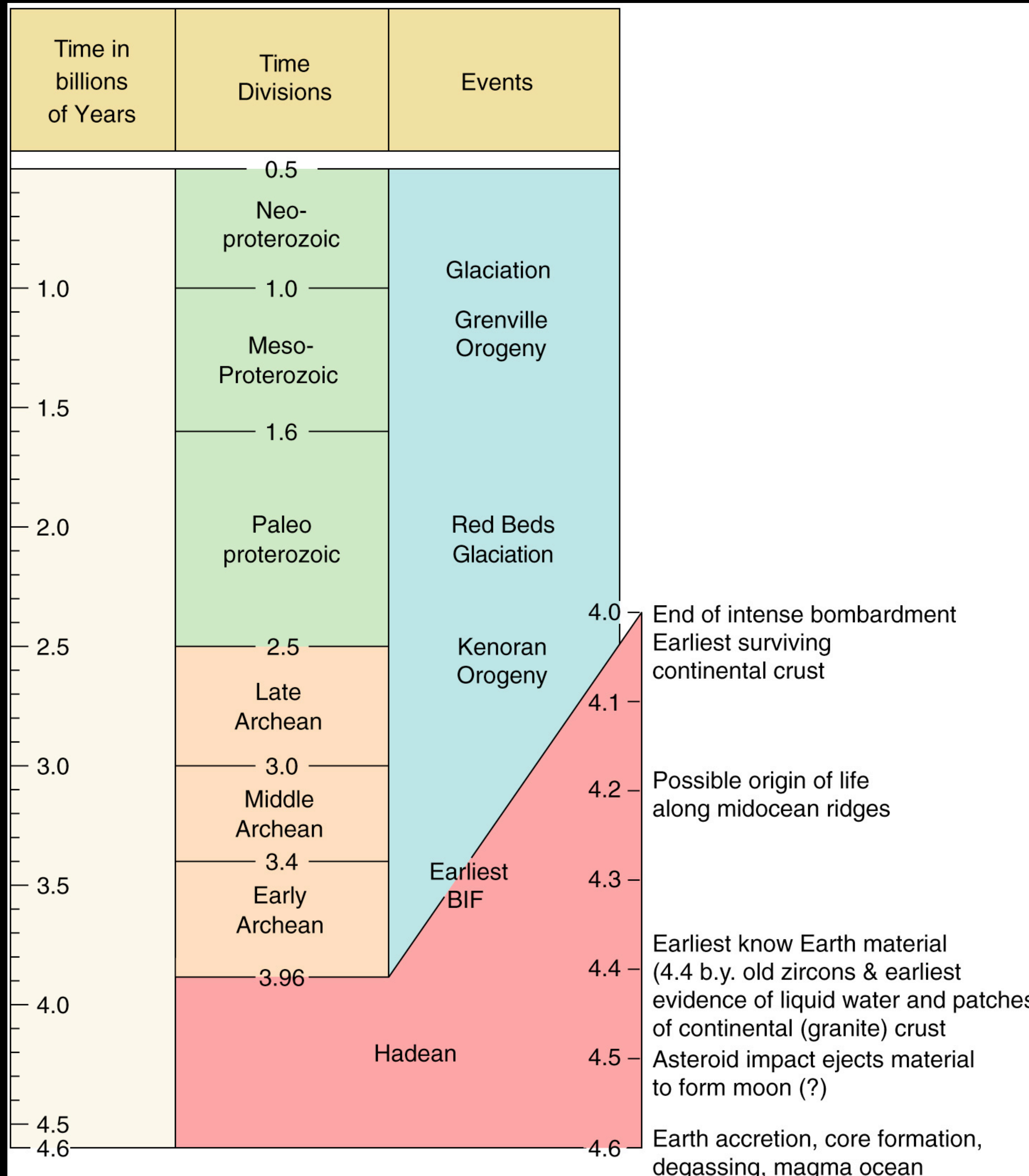


Zircon Crystal from Hadean 4.4 Ba, Jack Hills W Australia

J Valley, Univ Wisconsin Madison

Tiny zircons (zirconium silicate crystals) found in ancient stream deposits indicate that Earth developed continents and water -- perhaps even oceans and environments in which microbial life could emerge -- 4.3 billion to 4.4 billion years ago, remarkably soon after our planet formed.

Precambrian Terminology in North America



A cataclysmic collision between a Mars sized body scientists have come to call Theia and a proto-Earth is the best model that fits the conditions of our 12,700 km planet having a relatively large 3500 km moon. The impact theory was first proposed in the 1940’s and gained new life after rock samples were brought back to Earth.

Greenstone Belt Volcanic Rocks

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Pillow lavas in Ispheming greenstone at Marquette, Michigan

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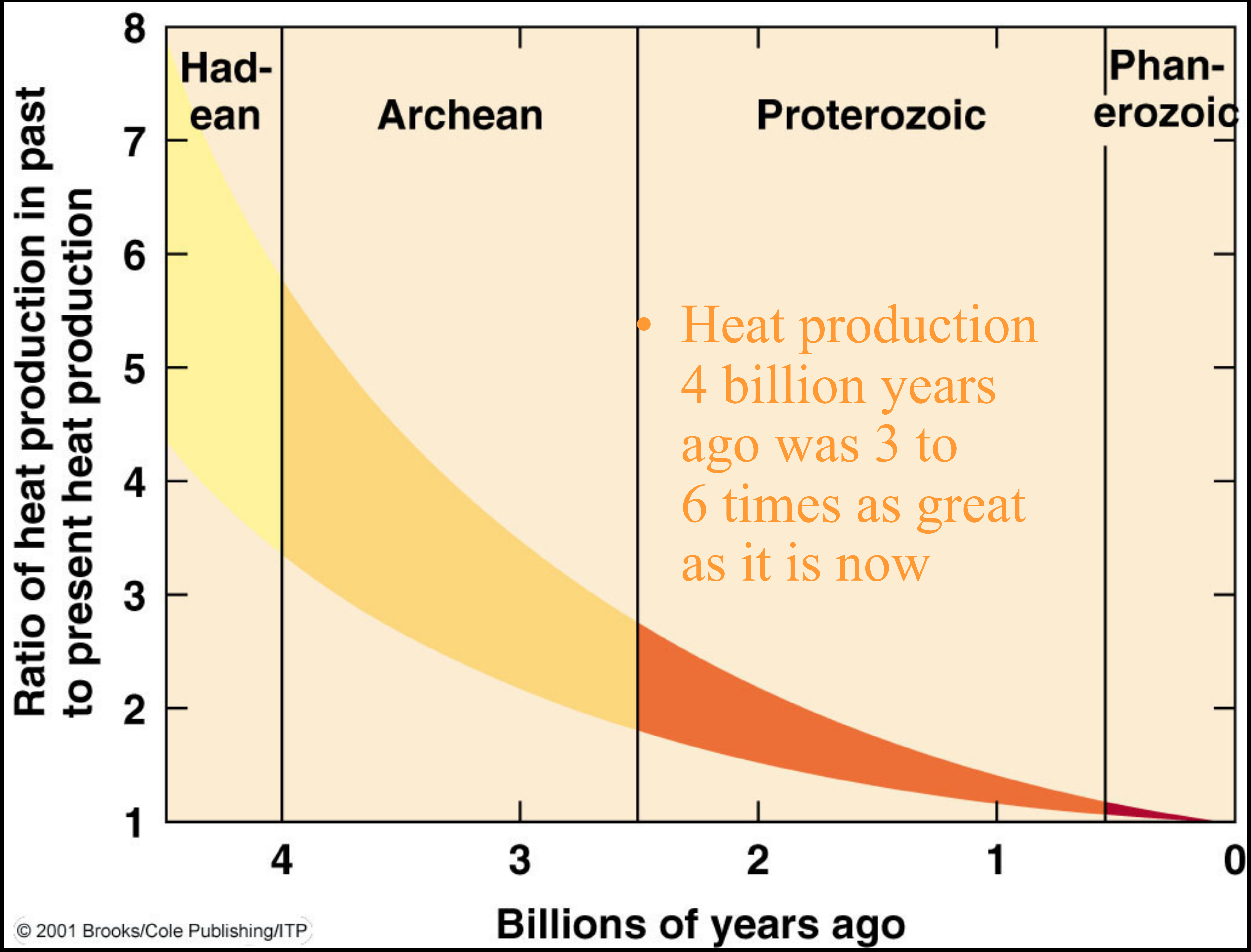
- Pyroclastic materials erupted where large volcanic centers built above sea level

Pillow lavas in Ispheming greenstone at Marquette, Michigan

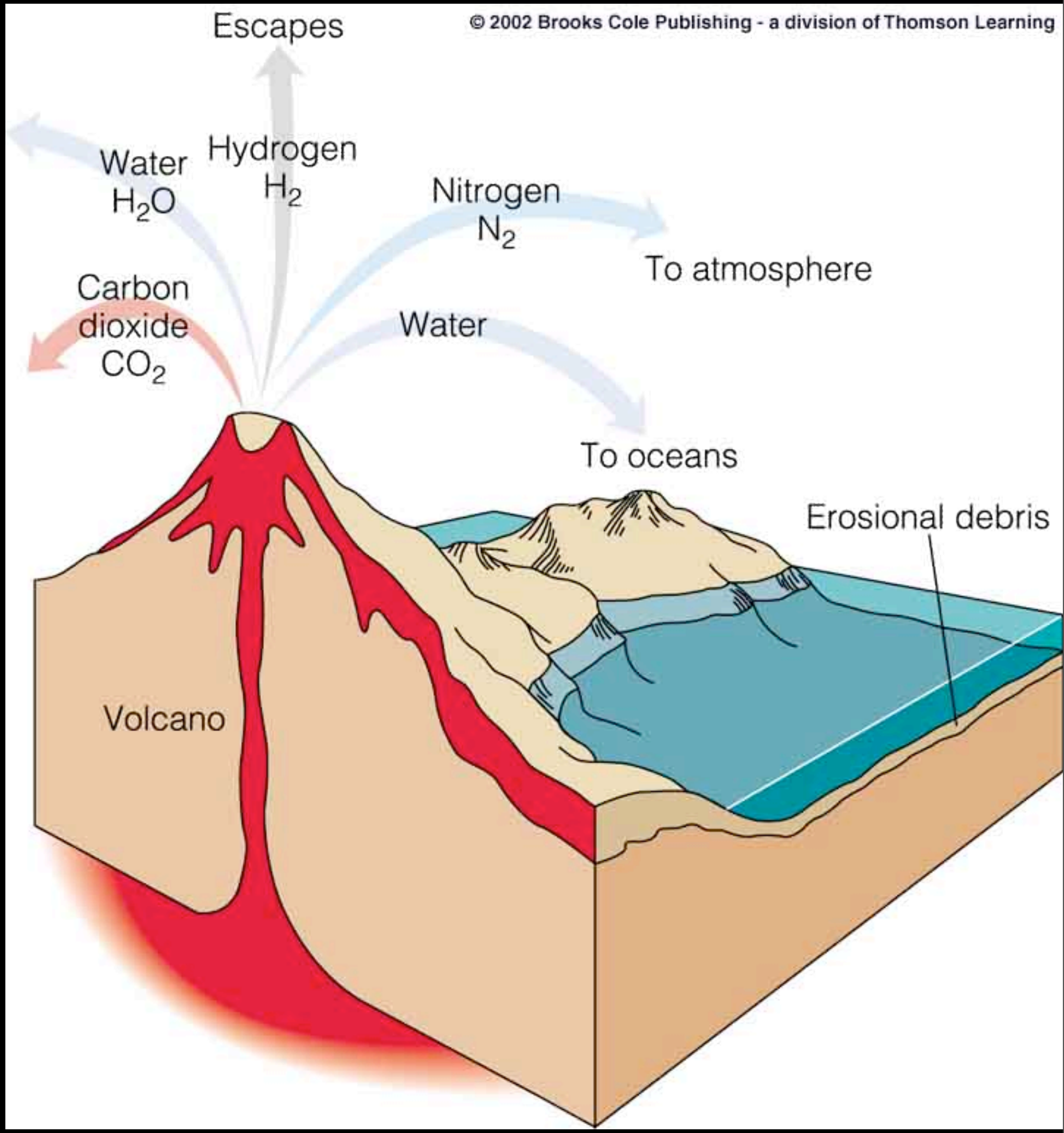
Radioactive heat, which drives the earth's tectonic system, declines markedly in the Hadean and Archean



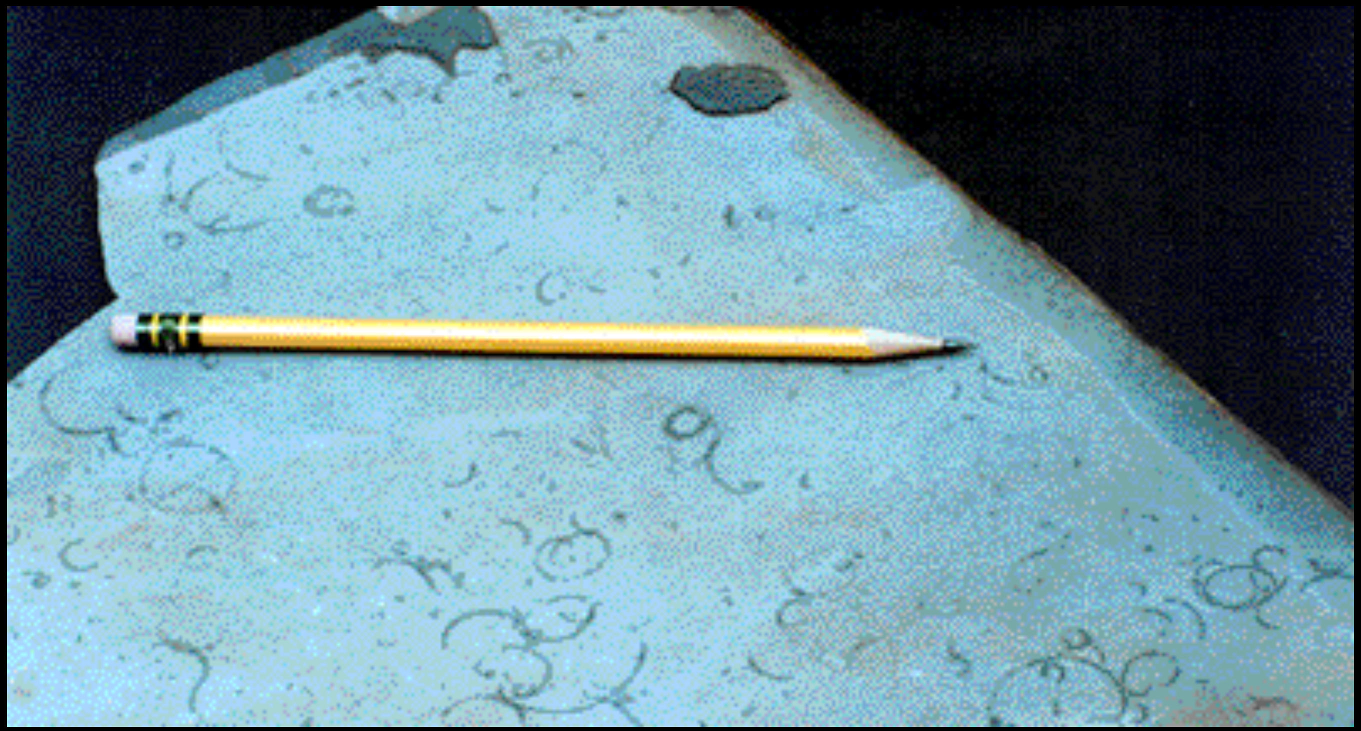
- Heat production 4 billion years ago was 3 to 6 times as great as it is now

Outgassing associated with volcanism

- Once a core-generated magnetic field protected Earth, gases released during volcanism began to accumulate
  - Called **outgassing**
- Water vapor is the most common volcanic gas today
  - also emitted carbon dioxide, sulfur dioxide, hydrogen sulfide, carbon monoxide, hydrogen, hydrogen chloride, nitrogen

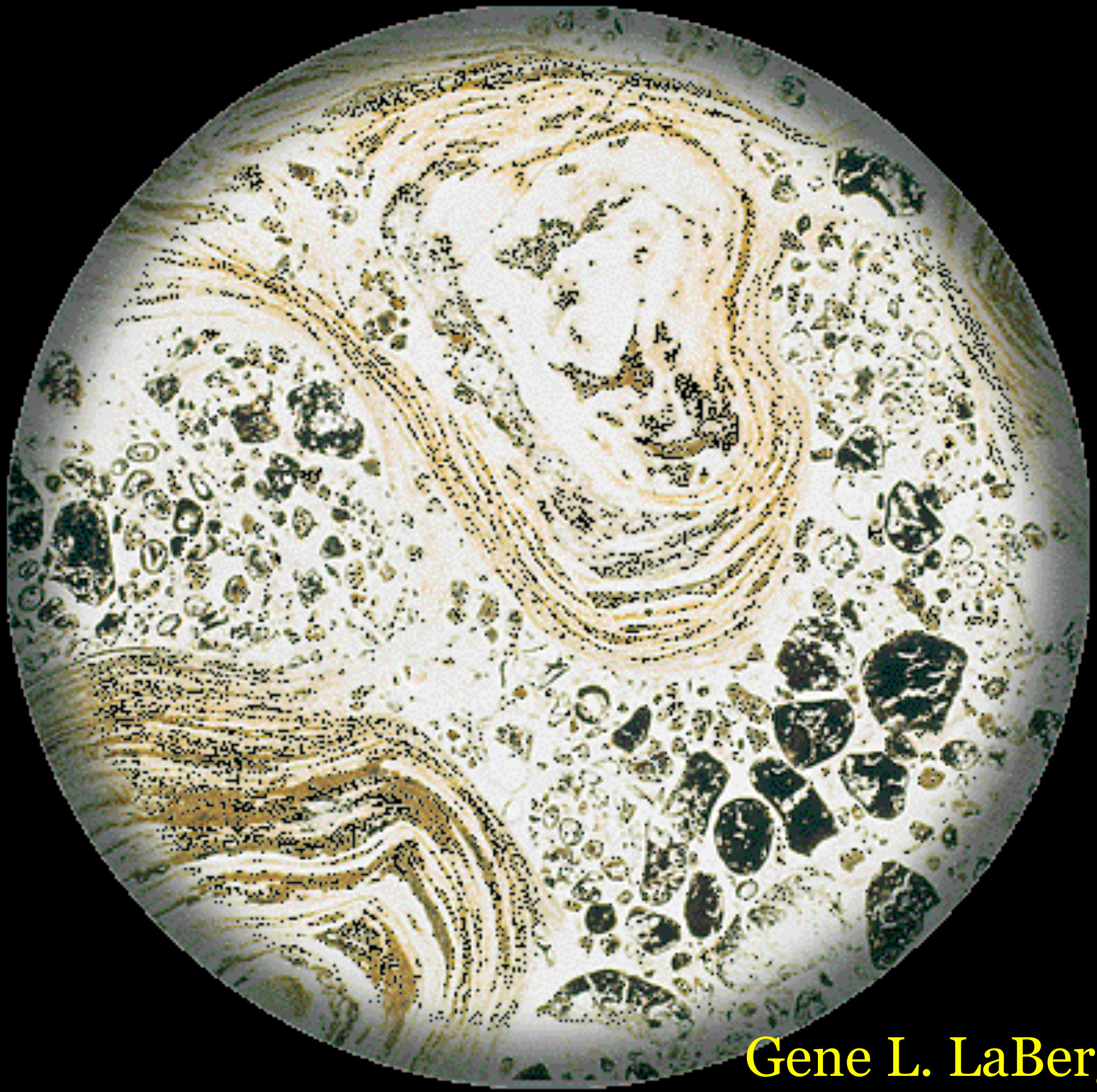


Gracefully coiled filaments are easily seen by the naked eye in these 2.1-billion-year-old fossils from the Upper Peninsula's Empire iron mine. They are possibly the oldest "megascopic" formations of life forms ever found.



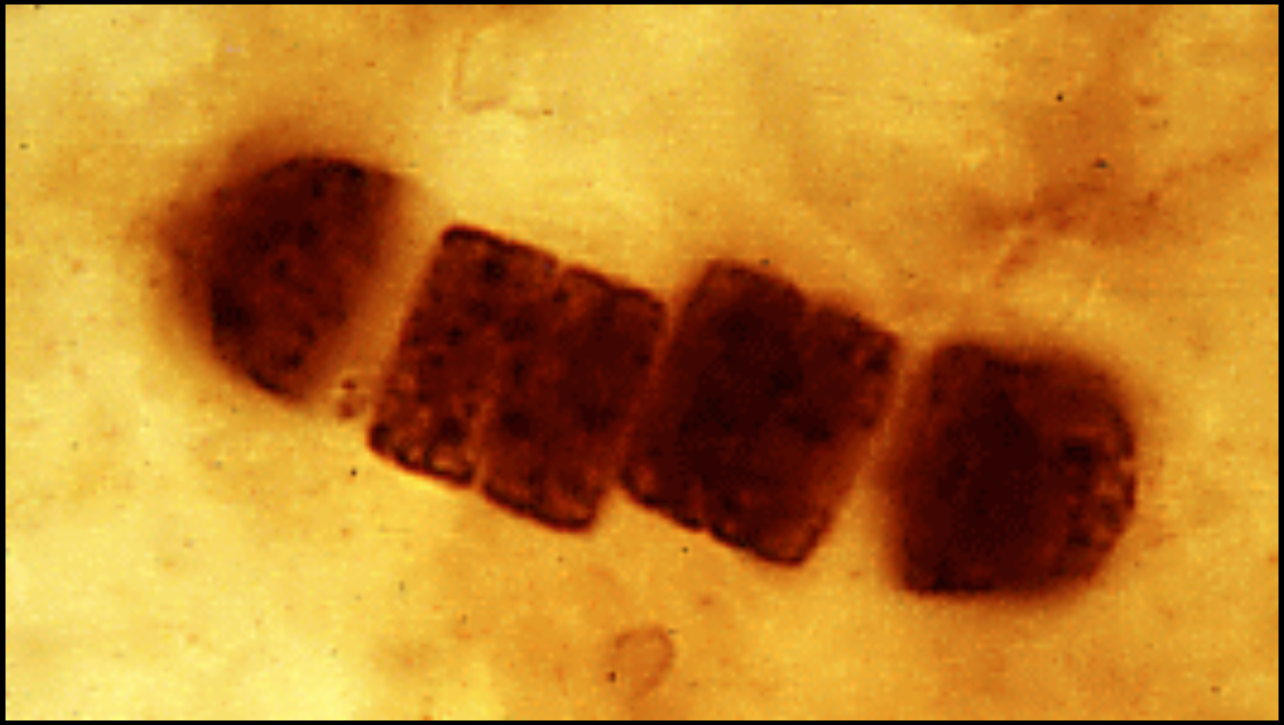
Tsu-Ming Han, Cleveland Cliffs Inc.

A microscopic cross section of columnar stromatolite at the Mary Ellen Mine, Biwabik, Minnesota.

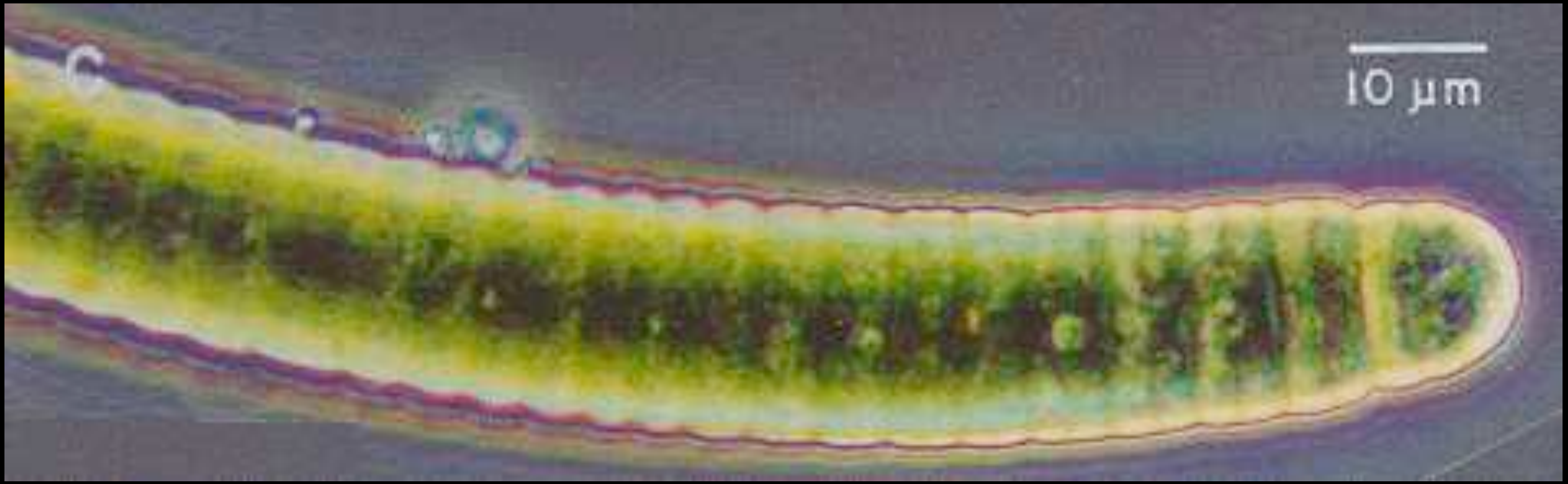


Gene L. LaBerge

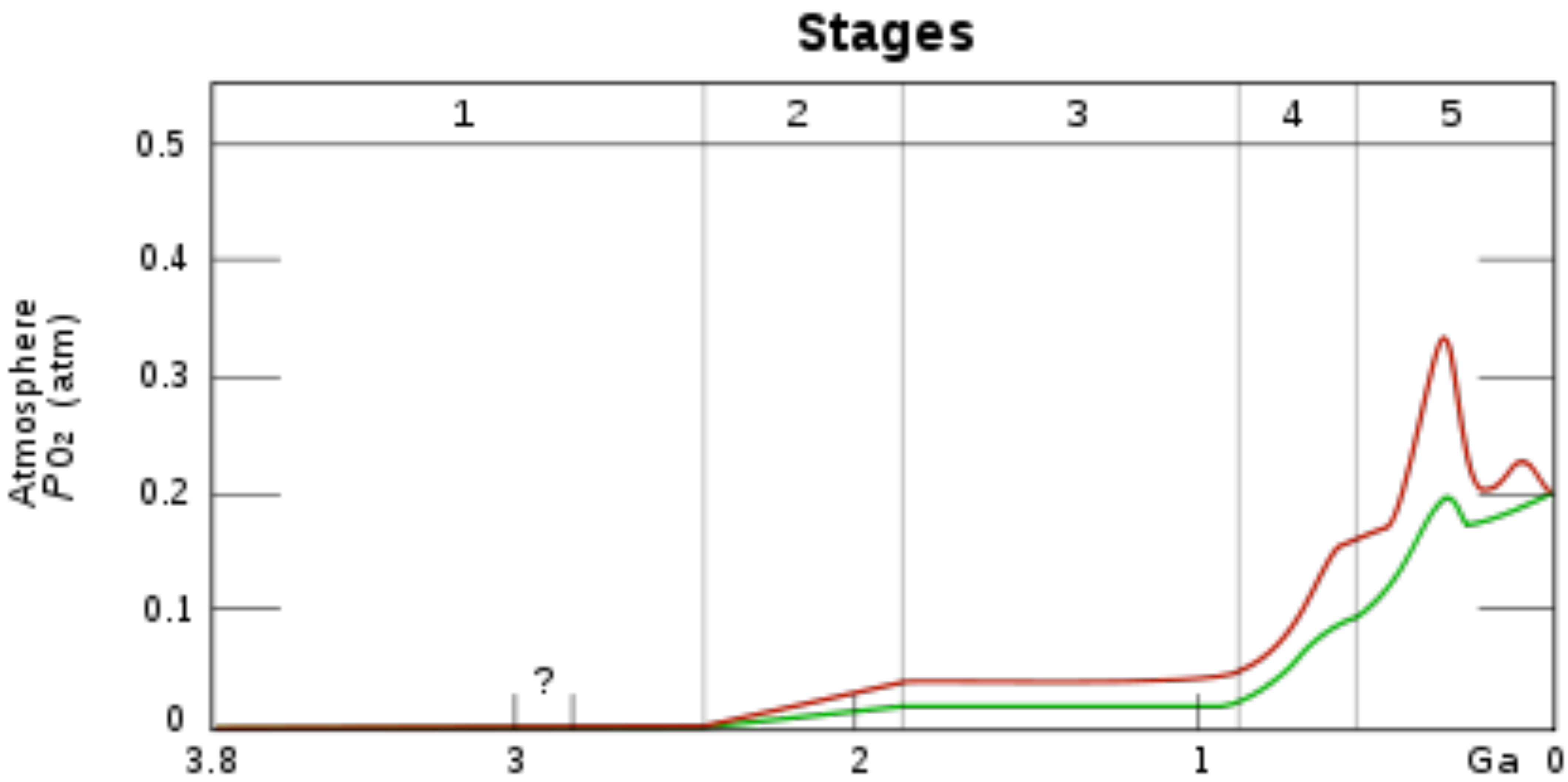
Traces of life forms are found in Archean rocks. Life may have begun before 3.8Ba and photosynthesis started by 2.7 Ba



The picture above is a short chain of cyanobacterial cells, from the Bitter Springs Chert of northern Australia (about 1 billion years old). Very similar cyanobacteria are alive today; in fact, most fossil cyanobacteria can almost be referred to living genera. Compare this fossil cyanobacterium with this picture of the living cyanobacterium *Oscillatoria*



The **Great Oxygenation Event (GOE)**, also called the **oxygen catastrophe** or **oxygen crisis** or **Great Oxidation**, was the appearance of free oxygen (O_2) in Earth's atmosphere. This major environmental change happened around 2.4 billion years ago.



O_2 build-up in the earth's atmosphere. Red and green lines represent the range of the estimates while time is measured in billions of years ago (Ga).

Banded Iron Formations--BIF

Hematite layers alternate with shale and chert

Seasonal? or cyclic oscillation

Most voluminous BIF is about 2.4 Ga

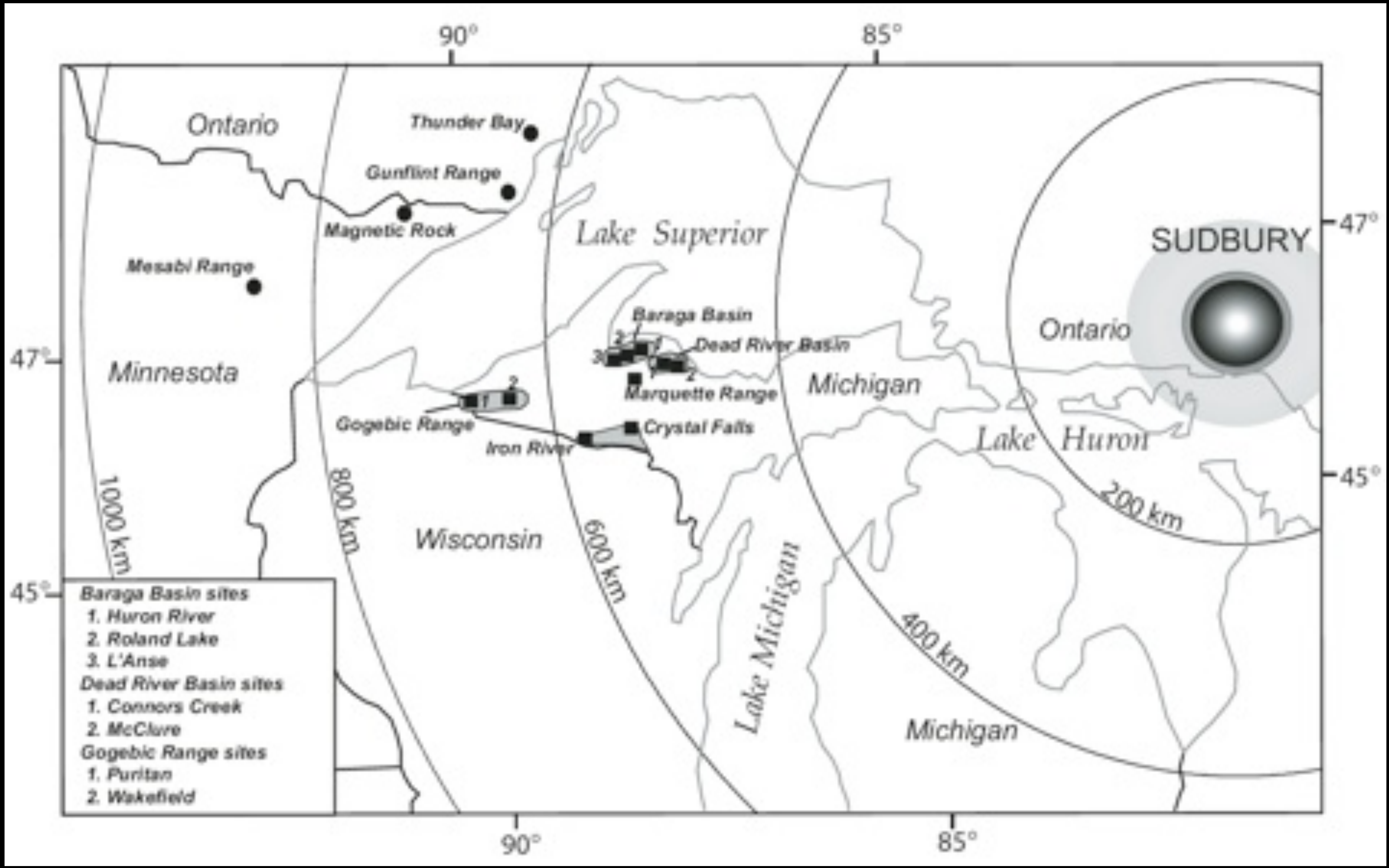
Formed in sea water from dissolved ferrous iron because of oxygen

BIF does not form now

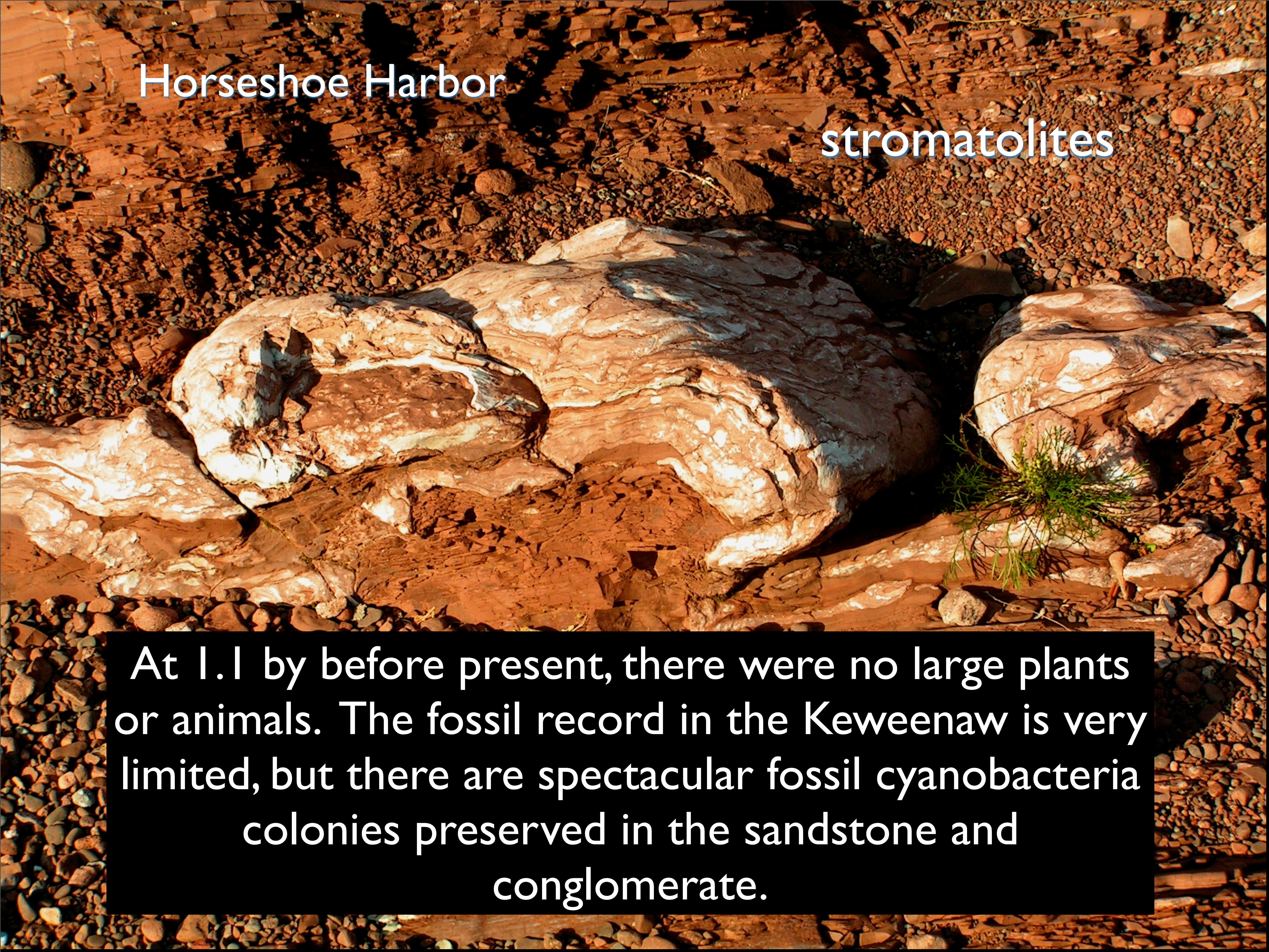
Lunar Maria formation

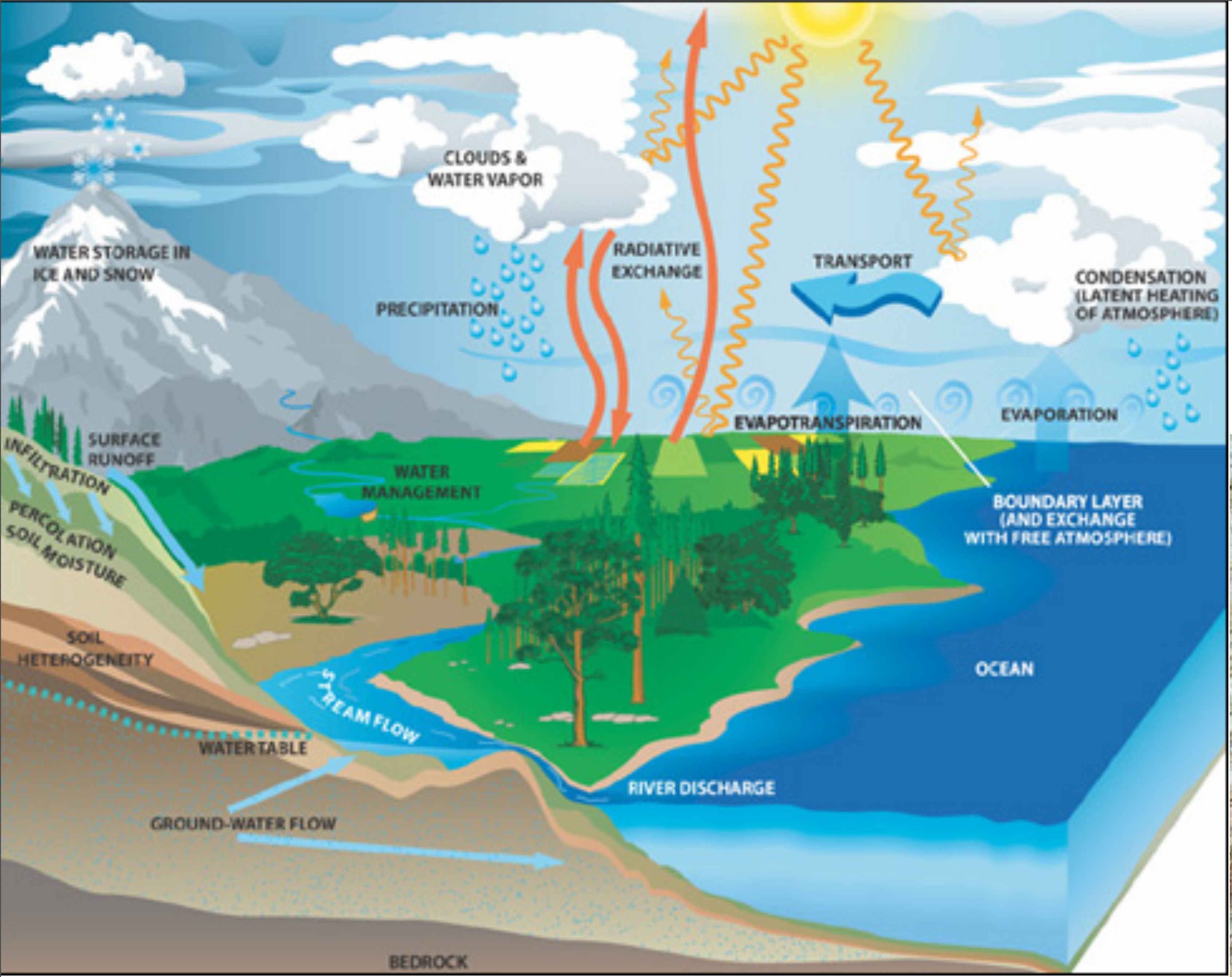
Indicates a period of large impact events which are late, long after the mostly much more energetic Hadean

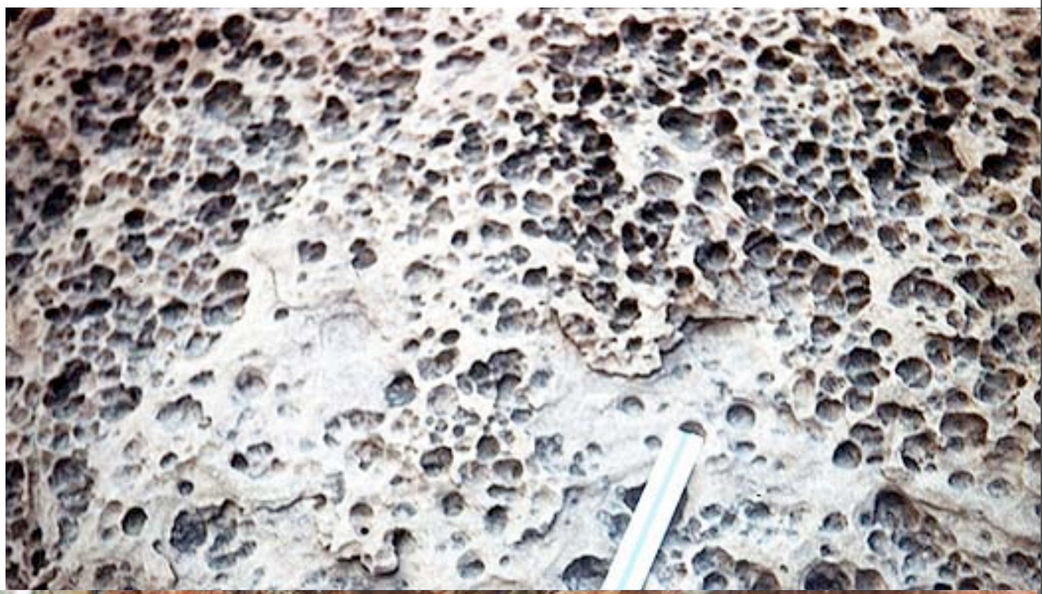
Mostly Archean; between 3 and 3.5 Ba



1.875 Ga was a significant impact event, at Sudbury, Ontario, and this event produced a widespread fall deposit which overlies the major BIF deposits

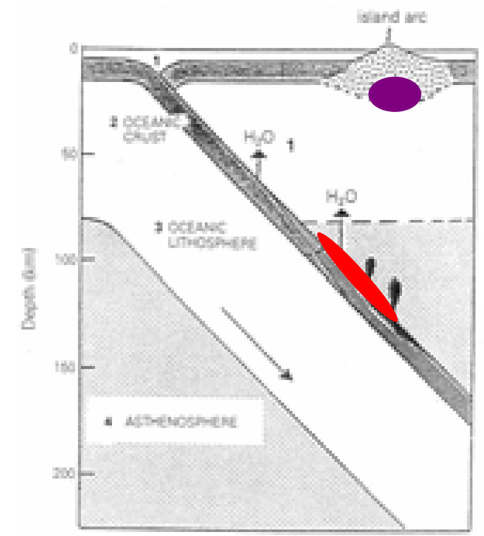

Horseshoe Harbor
stromatolites
At 1.1 by before present, there were no large plants or animals. The fossil record in the Keweenaw is very limited, but there are spectacular fossil cyanobacteria colonies preserved in the sandstone and conglomerate.





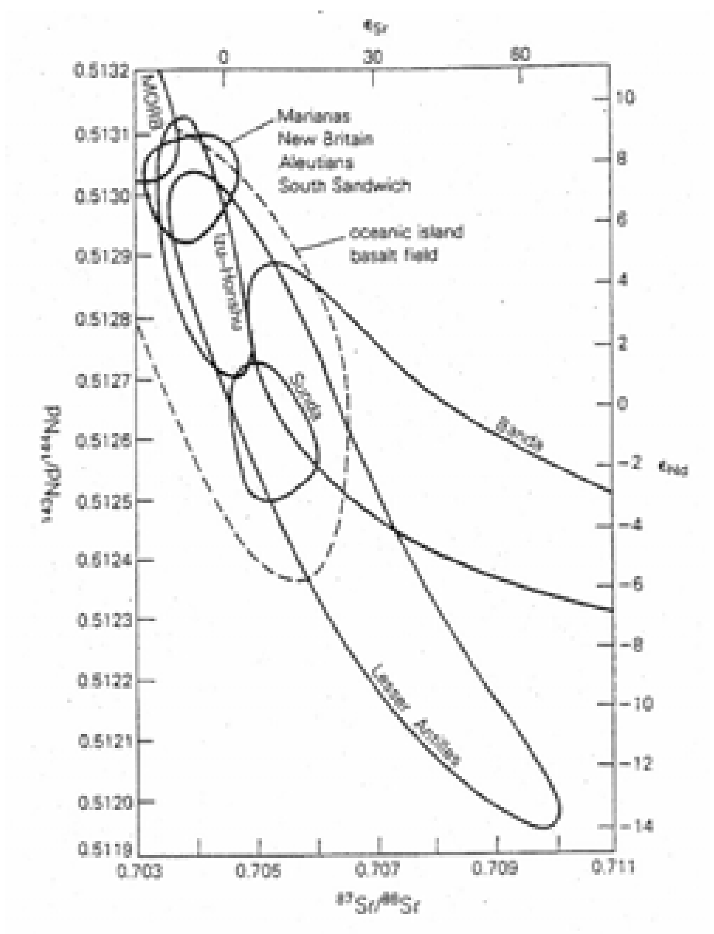
If the early earth developed an ocean from condensation of a part of the residual primordial gas, it would have had a very acid ocean, accumulated quickly. Instead if gas bleeds out of earth gradually, the acid rain falls on the earth and is neutralized during weathering, which brings cations to the sea also and makes change in compositions of the sea more moderate and gradual.

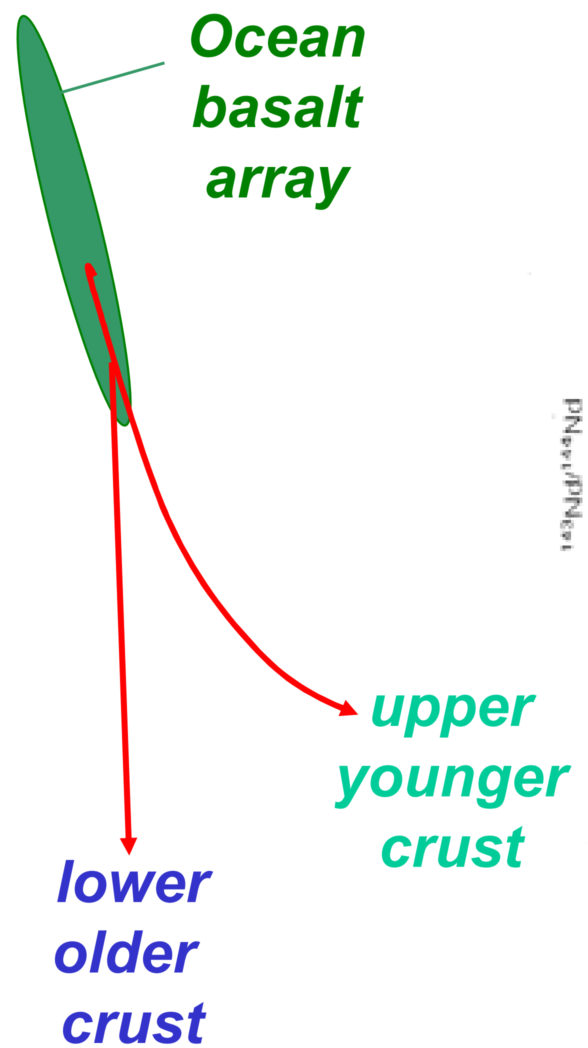
Radiogenic isotopes

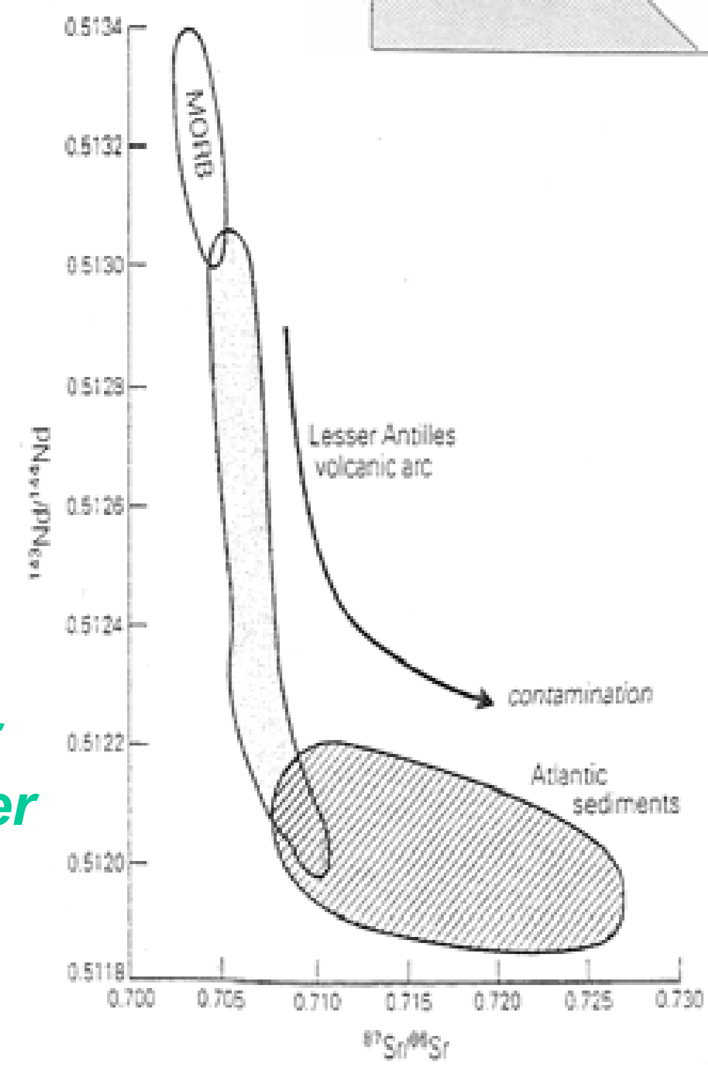


Sr and Nd isotopes

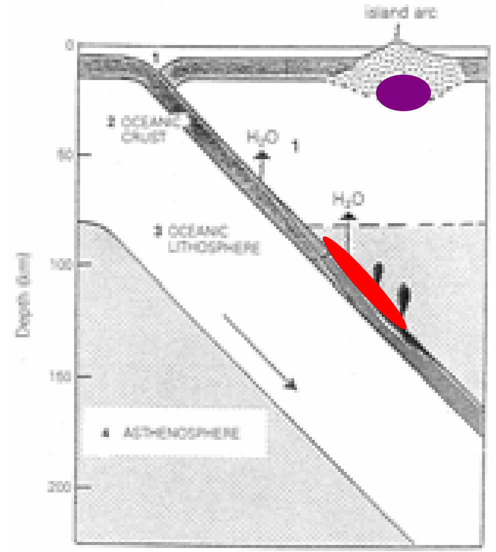
- mixing between mantle & crustal components *(compare to MORB and OIB)*
- mass balance of Sr and Nd: source contamination vs. crustal assimilation
- terriginous sediment in source of Lesser Antilles & Sunda arcs







Radiogenic isotopes



Pb isotopes

Pb contents (>20 ppm) and isotopic ratios of sediments very high

Pb content (< 1 ppm) and isotopic ratios of mantle are low

Thus Pb is a sensitive tracer of sediment involvement in magma source

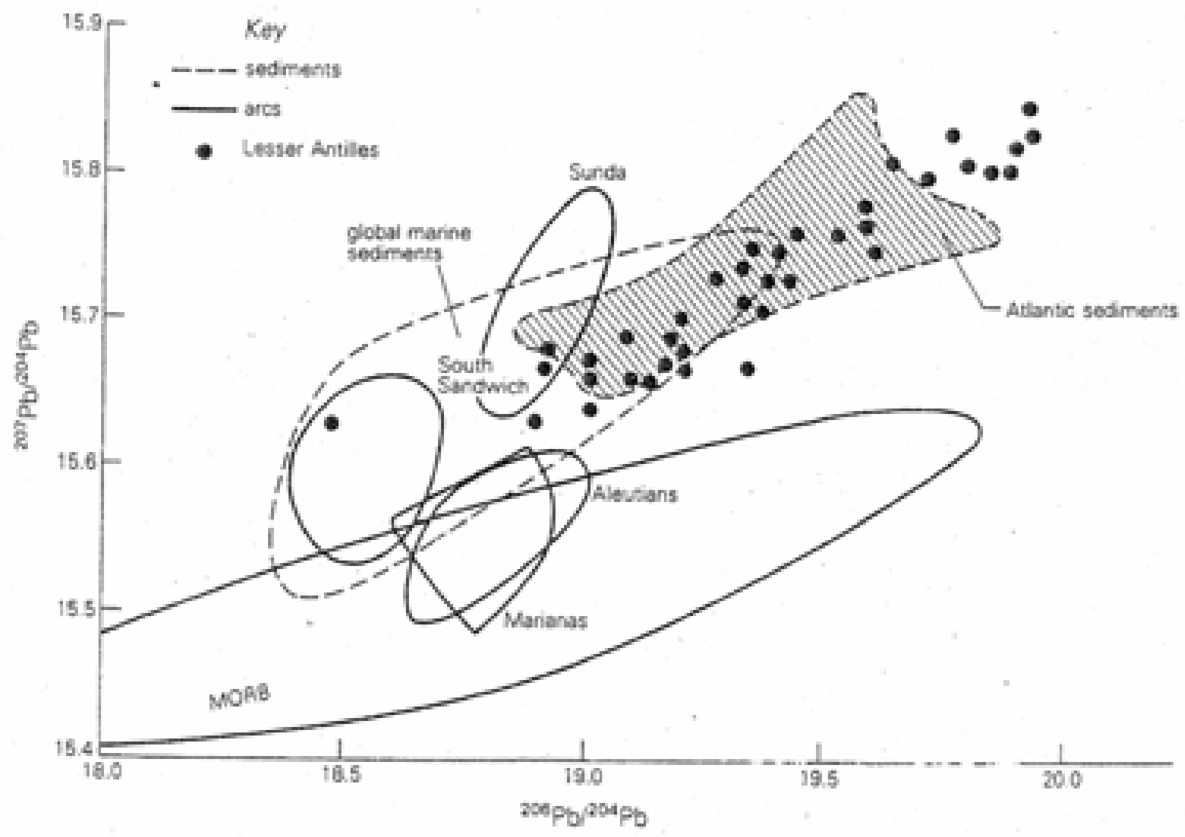


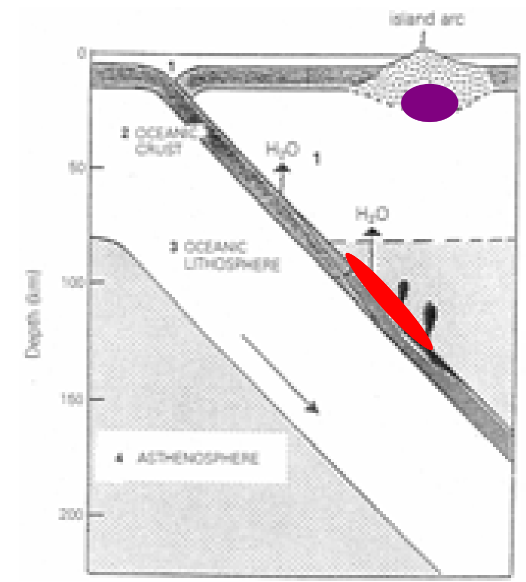
Figure 6.43 Variation of $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ for oceanic island-arc volcanic rocks compared to MORB and oceanic sediments. Fields for global marine sediments, MORB, Atlantic sediments, South Sandwich and Aleutian arcs from White & Dupré (1986); Marianas data from Woodhead & Fraser (1985); Sunda arc data from Whitford & Jezek (1982); data for Lesser Antilles volcanic rocks from Davidson (1986) and White & Dupré (1986).

Lesser Antilles arc lavas

Pb ratios both higher and lower than Atlantic sediments

source contamination *and* crustal assimilation?

Beryllium isotope data



The isotope ^{10}Be

- produced by cosmic ray induced rxns in atmosphere
- transported to surface pelagic sediments via rain & snow
- half-life is 1.5 x 10^6 yr
- tracer for young marine sediment in arc magma source

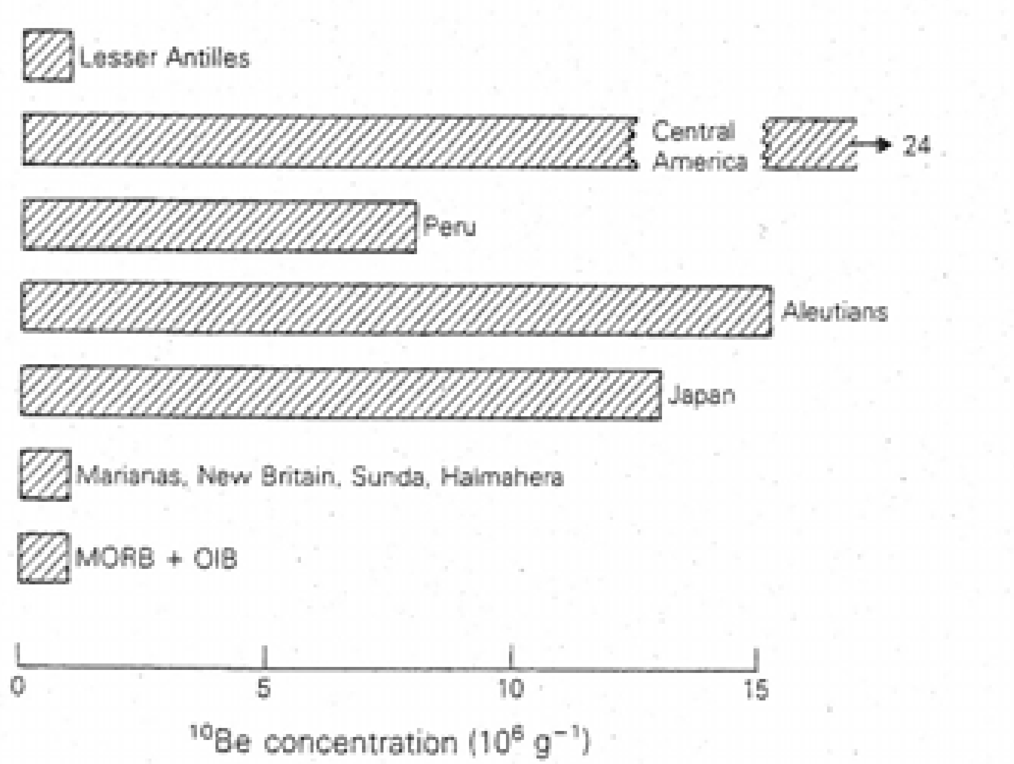


Figure 6.45 ^{10}Be concentrations in subduction-related magmas compared to MORB and OIB. (Lesser Antilles data from White & Dupré 1986; remaining data from Tera *et al.* 1986.)

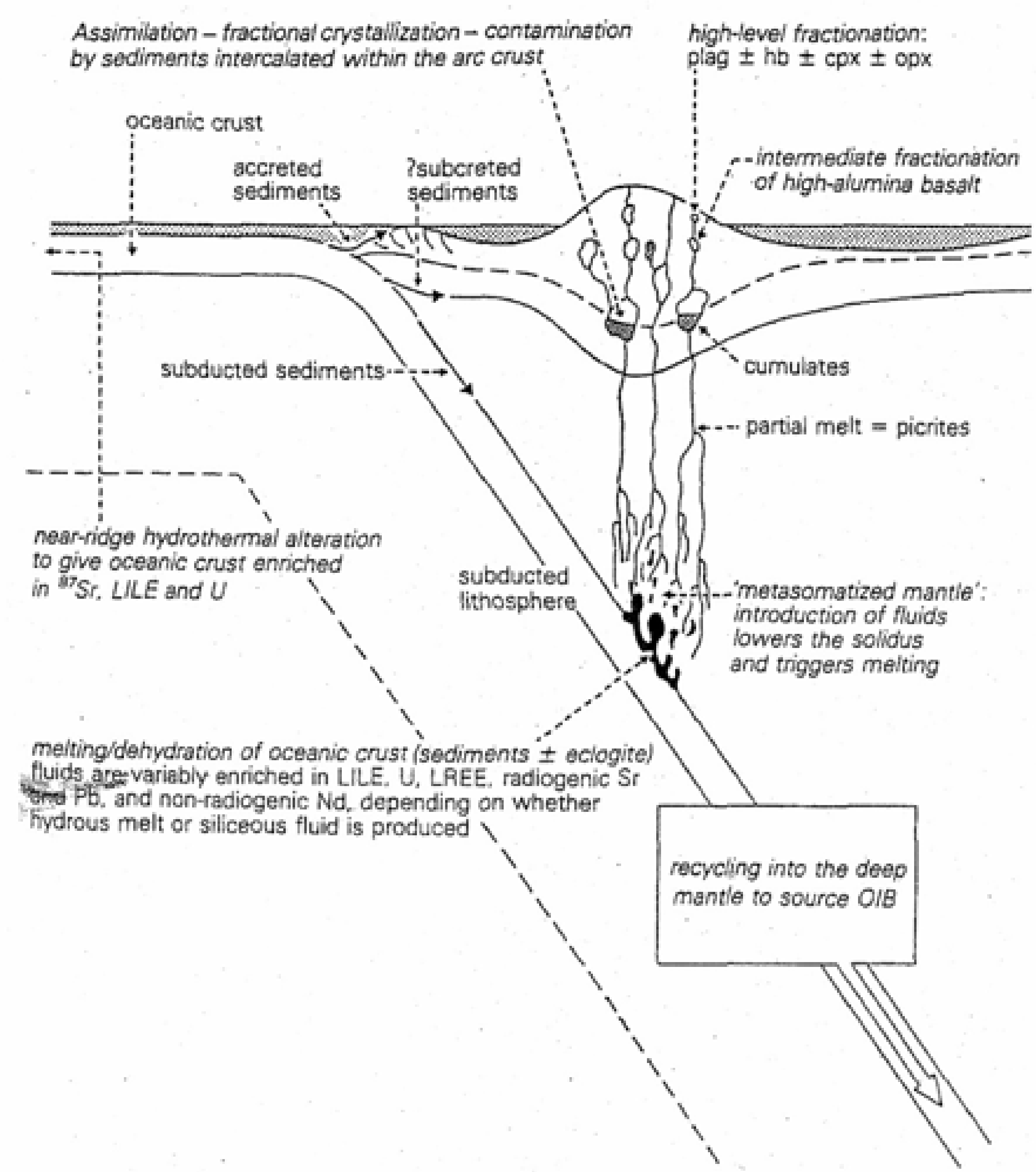
^{10}Be contents of basalts

- below detection in MORB, OIB
- high in basalt from some arcs

thus in some arcs:

uppermost, young sediments are not accreted, they subduct and either melt or release ^{10}Be rich fluid to the mantle in < 10 myr

General model of island arc magmatism



Major element, trace element and isotopic ratios indicate that at most a very small weight %of arc magma comprises subducted crustal elements.

Thus most of the subducted crust bypasses the arc and descends into the deeper mantle.

Perhaps in cases like the Farallon plate crust travels all the way to the core-mantle boundary

Albarede, 2009, Nature 461: 1227

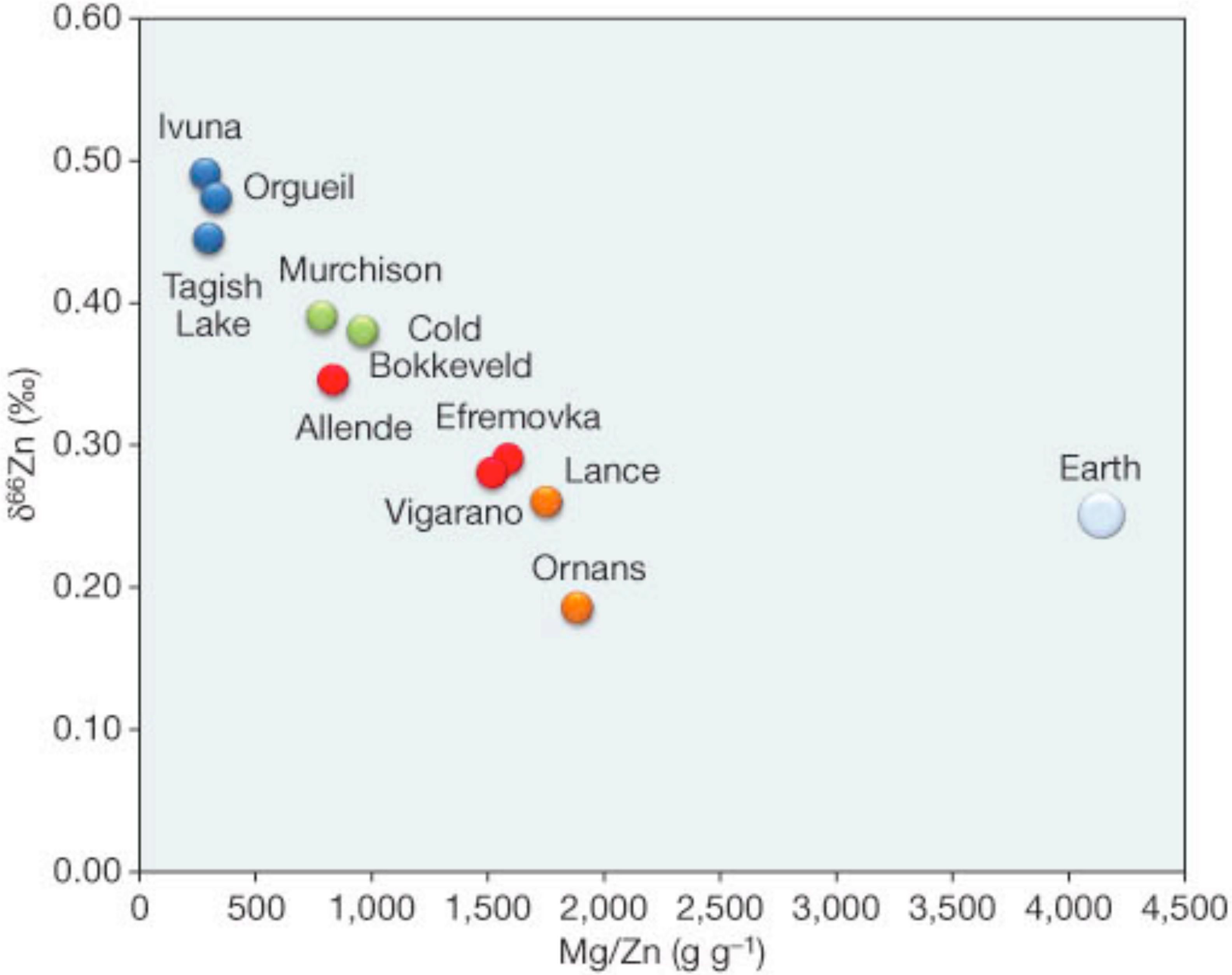


Figure 1 | Fractionation of Zn isotopes is incompatible with volatilization. The data[87] represent the $\delta^{66}Zn$ value, the relative deviation of the $^{66}Zn/^{64}Zn$ ratio in per mil with respect to a terrestrial standard, of each sample. Data for terrestrial samples are shown in pale grey; data for the different classes of carbonaceous chondrites are shown in dark blue (CI), green (CM), red (CV) and orange (CO). In the case of volatilization, preferential loss of the light ^{64}Zn isotope in the residue is expected to accompany the increase of the Mg/Zn ratio, as magnesium (T_{50} = 1,336 K) is much more refractory than zinc (T_{50} = 726 K). Because the opposite is observed, fractionation processes other than volatilization must be sought. T_{50}, at which 50% of the element is condensed[13].

Albarede, 2009, Nature 461: 1227

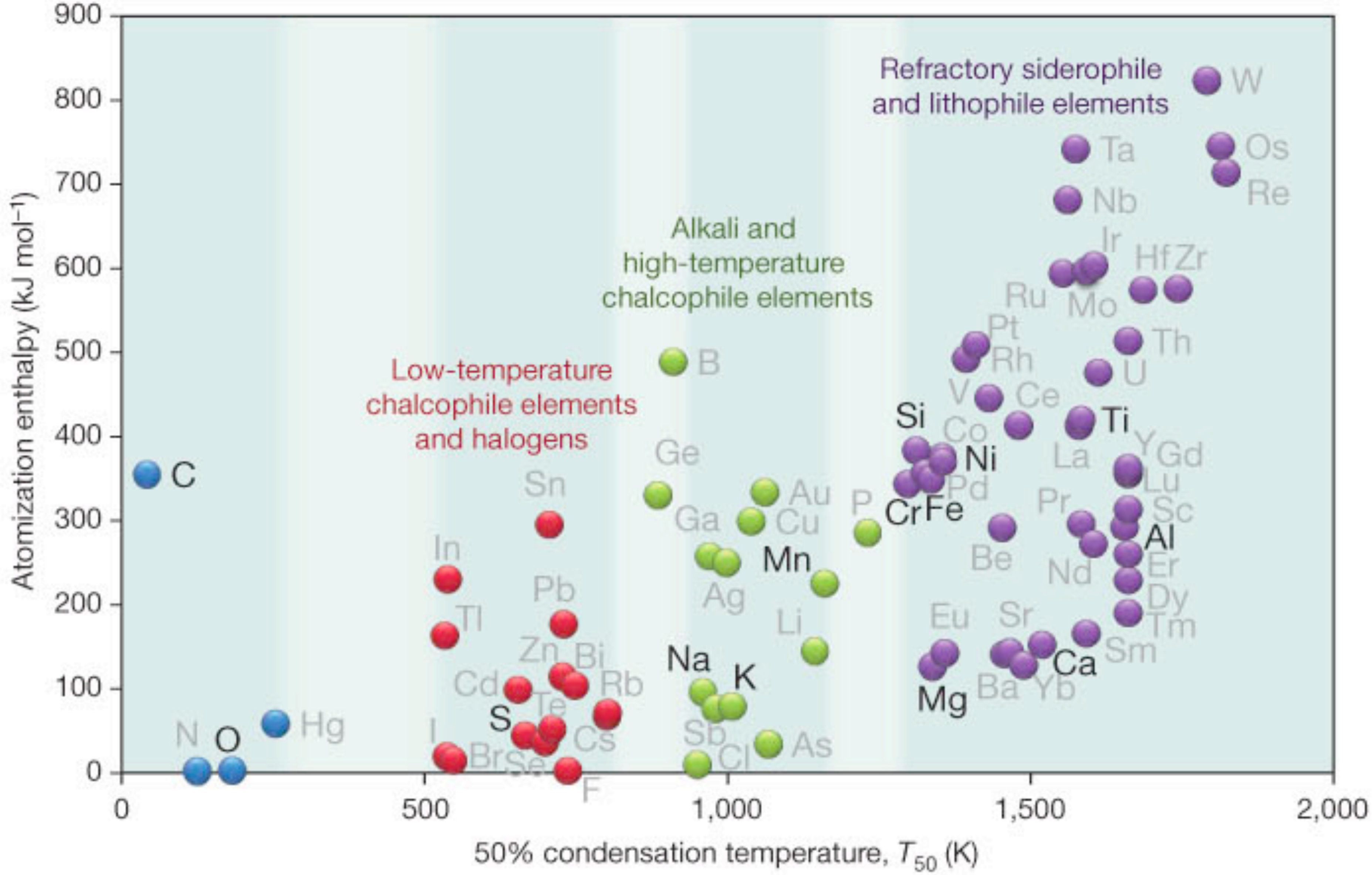


Figure 2 | Stepwise accretion of the elements on cooling of the solar nebula, shown as atomization enthalpy versus T_{50}. The two axes represent two different volatility scales, an intrinsic scale given by the atomization enthalpy[29], which is essentially equivalent to the mean bonding energy per atom in solids, and a scale dependent on the nebular chemistry, T_{50} (see Fig. 1 legend). Black letters, major elements; grey letters, minor and trace elements. The platinum group elements, plus Al, Ti, Zr and W, and most rare-earth elements and actinides, which condense first above 1,600 K, are preferentially found in refractory inclusions. The group of mildly refractory lithophile elements, which comprise the major elements Si, Mg, Fe and Ca, accrete down to 1,300 K as metal, olivine and pyroxenes, and make up the bulk of the planetary mantle and core. These refractory elements are separated from the high-T chalcophile elements (As, Ga, Ge, Cu, Ag), chlorine, and the alkali elements (Li, Na, K, Rb and Cs), which condense between 1,150 and 850 K. From 750 to 530 K, the low-T chalcophile elements (Pb, Bi, Sn, Zn, Cd, S, Te) precipitate, followed by the truly volatile elements (N, C, H) and Hg. Each group appears to be separated from its neighbours by a temperature gap (highlighted in white).

Albarede, 2009, Nature 461: 1227

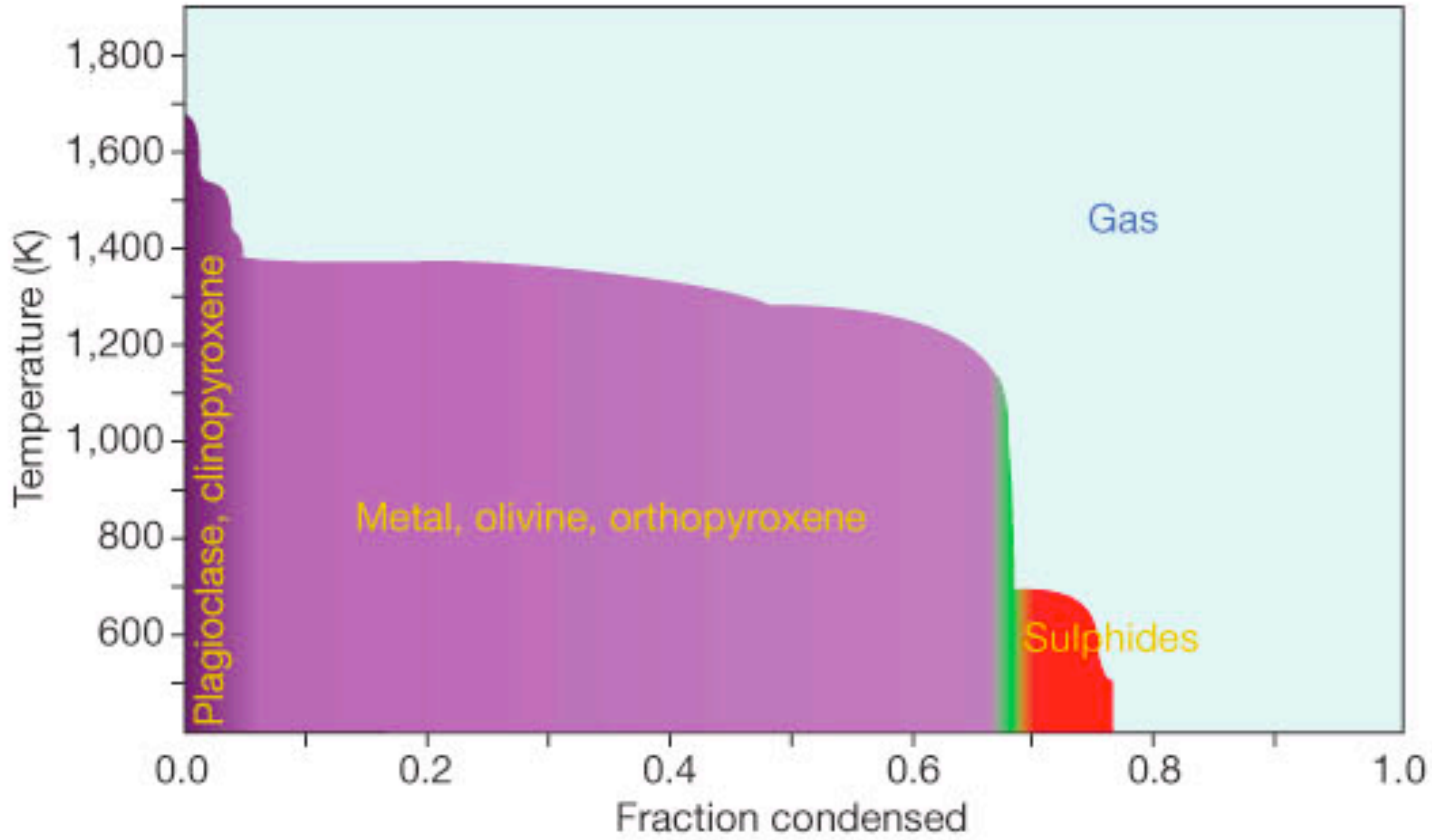


Figure 3 | Stepwise accretion of the elements upon cooling of the solar nebula, shown as fraction condensed versus temperature. Plotted is the fraction of the original condensable matter remaining in the solar nebula at a given temperature (redrawn with changes from ref. 30). The kinks in the accretion rate correspond to the temperature gaps in Fig. 2. After formation of the most abundant refractory phases (plagioclase and clinopyroxene), the bulk of the metallic core and the mantle silicates (olivine and orthopyroxene) is quickly removed from the nebular gas (purple). Alkali elements and high-*T* chalcophile elements precipitate next (green), but do not constitute a large fraction of the planetary material. Low-*T* chalcophile elements, sulphur and halogens come after (red), followed by volatile elements. Most elements accrete over a few tens of degrees, but over 150–250 K for the alkali elements, and Eu and Yb. A planet with a substantial deficit of K or Zn with respect to chondrites therefore cannot have accreted much, if any, water.

Albarede, 2009, Nature 461: 1227

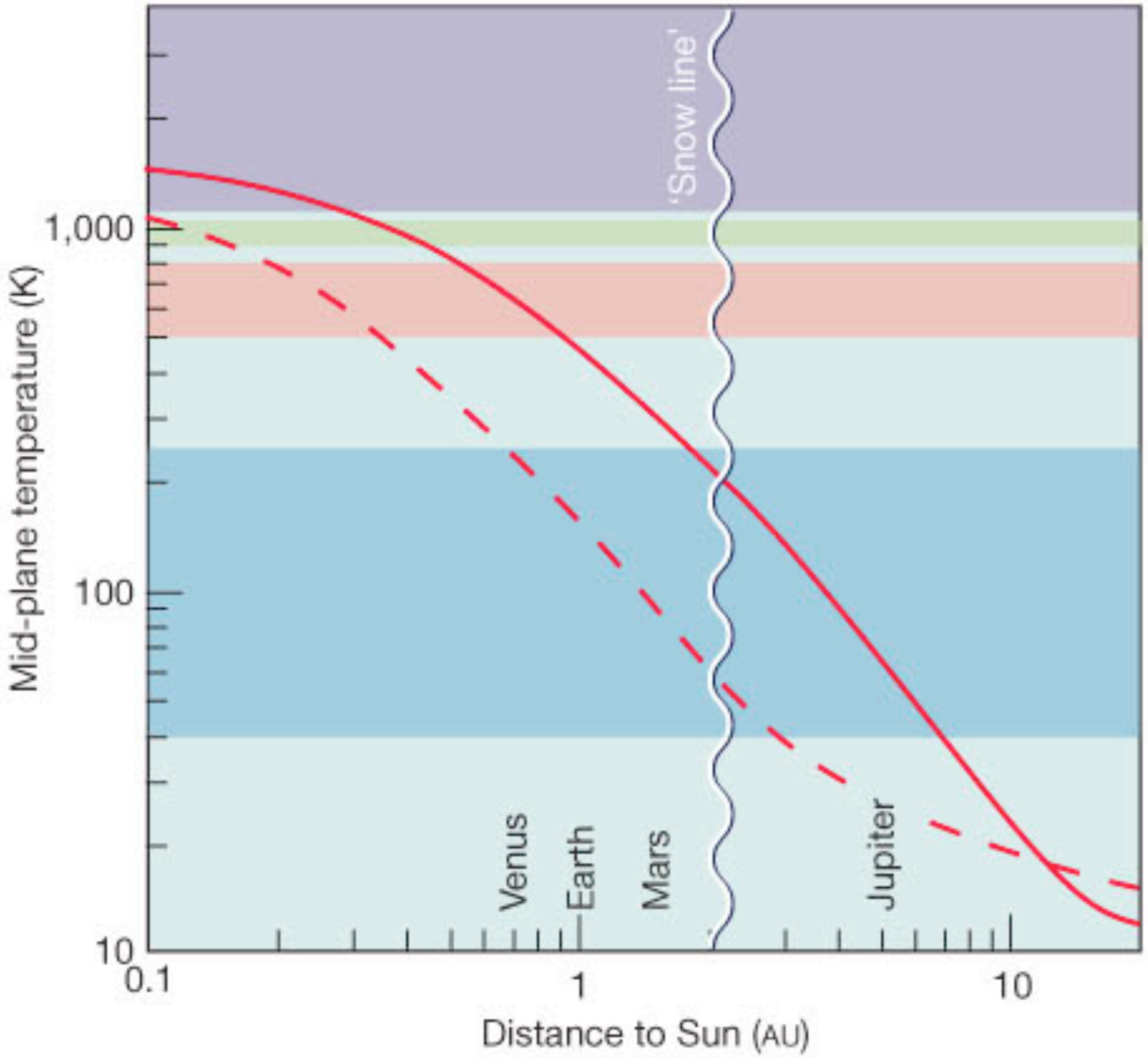


Figure 4 | The thermal structure of the planetary solar nebula: temperature at mid-plane of the nebular disk. Data are taken from ref. 88. Two models of temperature distribution are shown for two different values of the viscous dissipation parameter, α (viscosity × sound velocity at mid-plane × mean elevation above mid-plane) for a rate of solar accretion of 1% per Myr: $\alpha = 10^{-3}$ (solid line) and $\alpha = 10^{-1}$ (dashed line). The position of the wiggly 'snow line', which separates two domains, ice-free inwards and frosty outwards, nearly coincides with that of the asteroid belt[12]. Colour coded areas correspond to the four groups of elements identified by their T_{50} values in Fig. 2. The depletion of volatiles in the inner Solar System is caused by the strong electromagnetic winds emitted by the young Sun, which swept away the nebular gas before accretion was complete.

Albarede, 2009, Nature 461: 1227

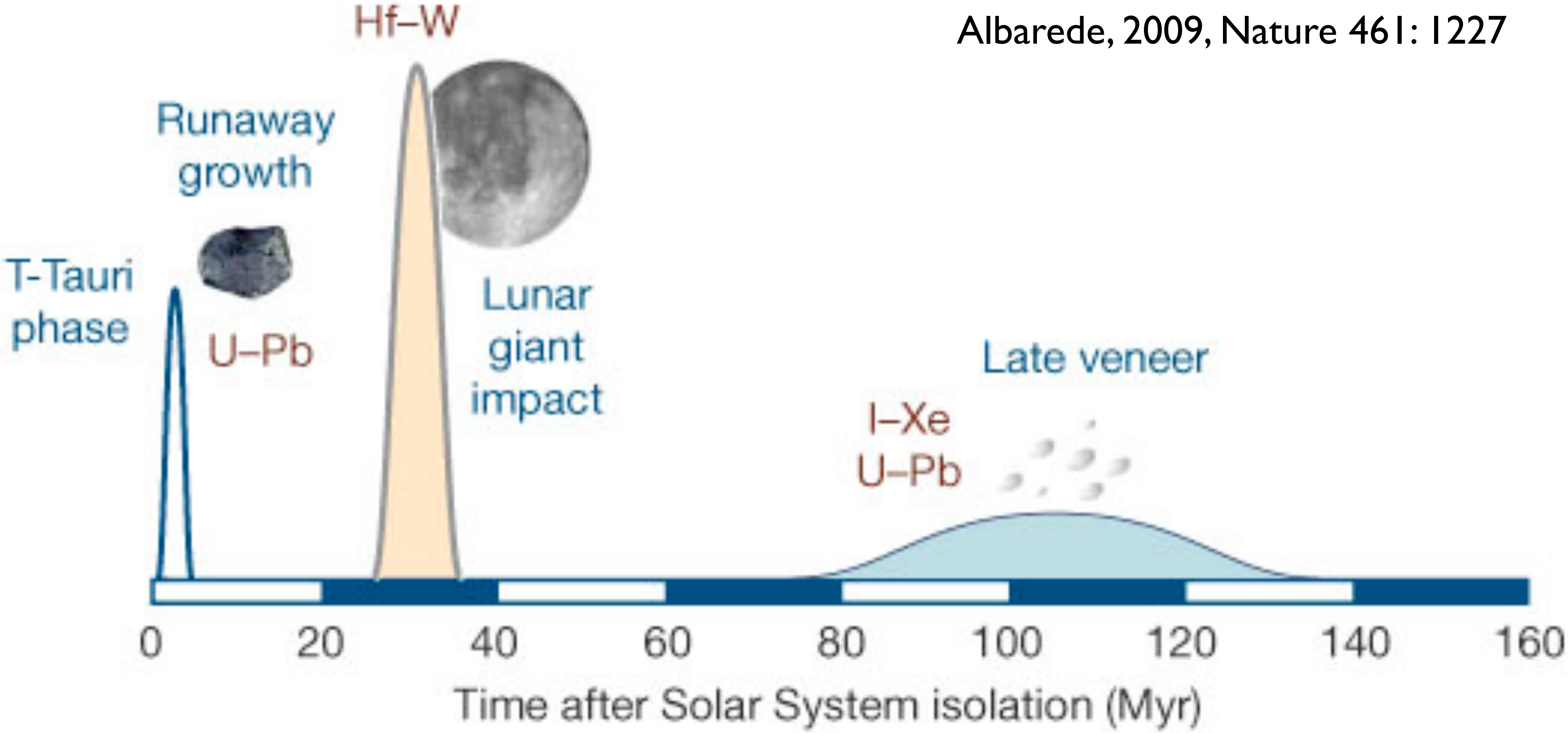
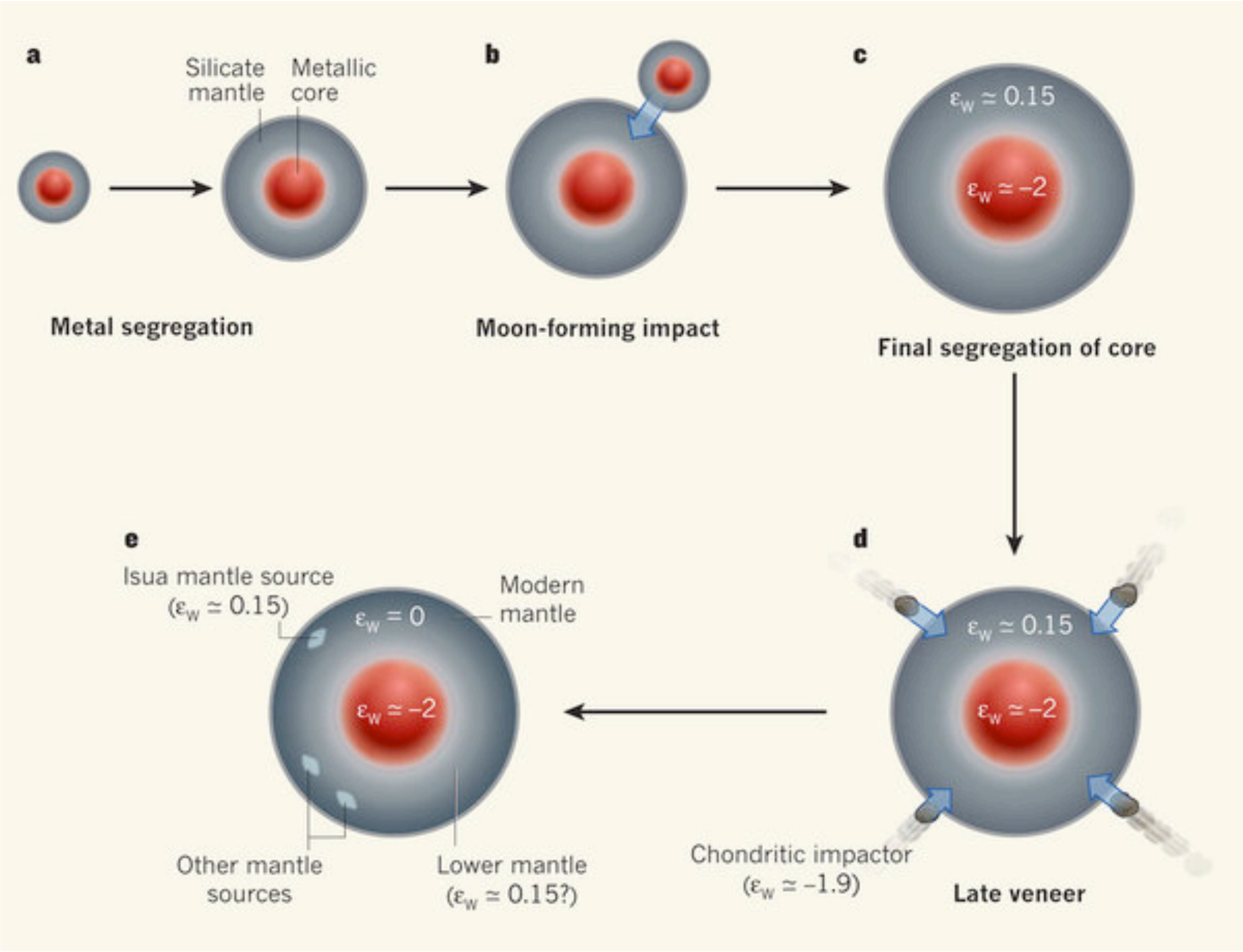


Figure 5 | A tentative chronology of the Earth's accretion. Chronometers shown in brown. Accretion of planetary material was interrupted by energetic electromagnetic radiation (T Tauri phase) sweeping across the disk within a few Myr of the isolation of the solar nebula. Runaway growth of planetesimals produces Mars-sized planetary embryos, which, collision after collision, form the planets with their modern masses. The last of these 'giant' collisions left material orbiting the Earth that later reassembled to form the Moon. The ^{182}Hf–^{182}W chronometer dates metal–silicate separation. The identical abundance of radiogenic ^{182}W between the Earth and the Moon indicates that either the Moon formed after all the short-lived ^{182}Hf had disappeared (>60 Myr) or, rather, the Moon-forming impact and terrestrial core segregation took place simultaneously 30 Myr after isolation of the solar nebula. Addition of a late veneer of chondritic material coming from beyond 2.5 AU provides a strong explanation for the modern abundances of siderophile and volatile elements in the terrestrial mantle. This material also contained water and other volatile elements, which account for the origin of the terrestrial ocean. Such a model indicates that most of the terrestrial Pb and Xe was delivered by the asteroids that constituted the late veneer, and therefore that the young Pb–Pb and I–Xe ages of the Earth date, not the Earth, but events that affected the asteroids. It is suggested here that these events are those of the accretion to the Earth of the late veneer.

T Kleine, 2011, Nature 477: 168-9



A 'late veneer' of meteoritic material, added after Earth's core had formed, may be the source of our noble metals. Its absence from some parts of Earth's mantle will now force a rethink about this late accretion.

a–c, Accretion and core formation (4.567 billion to about 4.5 billion years ago). **a**, Siderophiles are removed from the silicate mantle to the metallic core. **b**, Moon-forming impact and end of Earth's main accretion. **c**, Final segregation of the core: mantle is depleted of highly siderophile elements, now concentrated in the core; εW ($\varepsilon^{182}W$) denotes tungsten-isotope enrichment as parts per 10,000 relative to the modern terrestrial mantle. **d**,**e**, Late accretion (about 4.5 billion to 3.8 billion years ago) following core formation. **d**, Highly siderophile elements are replenished in the mantle by a late veneer of chondritic meteorites. **e**, Addition of the late veneer reduces mantle ^{182}W enrichment to an εW of zero. Willbold et al.2 propose that rocks from Isua in Greenland have the same ^{182}W enrichment (εW ≃ 0.15) as the mantle had before the late veneer formed, indicating that some domains within Earth's mantle may have escaped addition of the late veneer.

Albarede, 2009, Nature 461: 1227

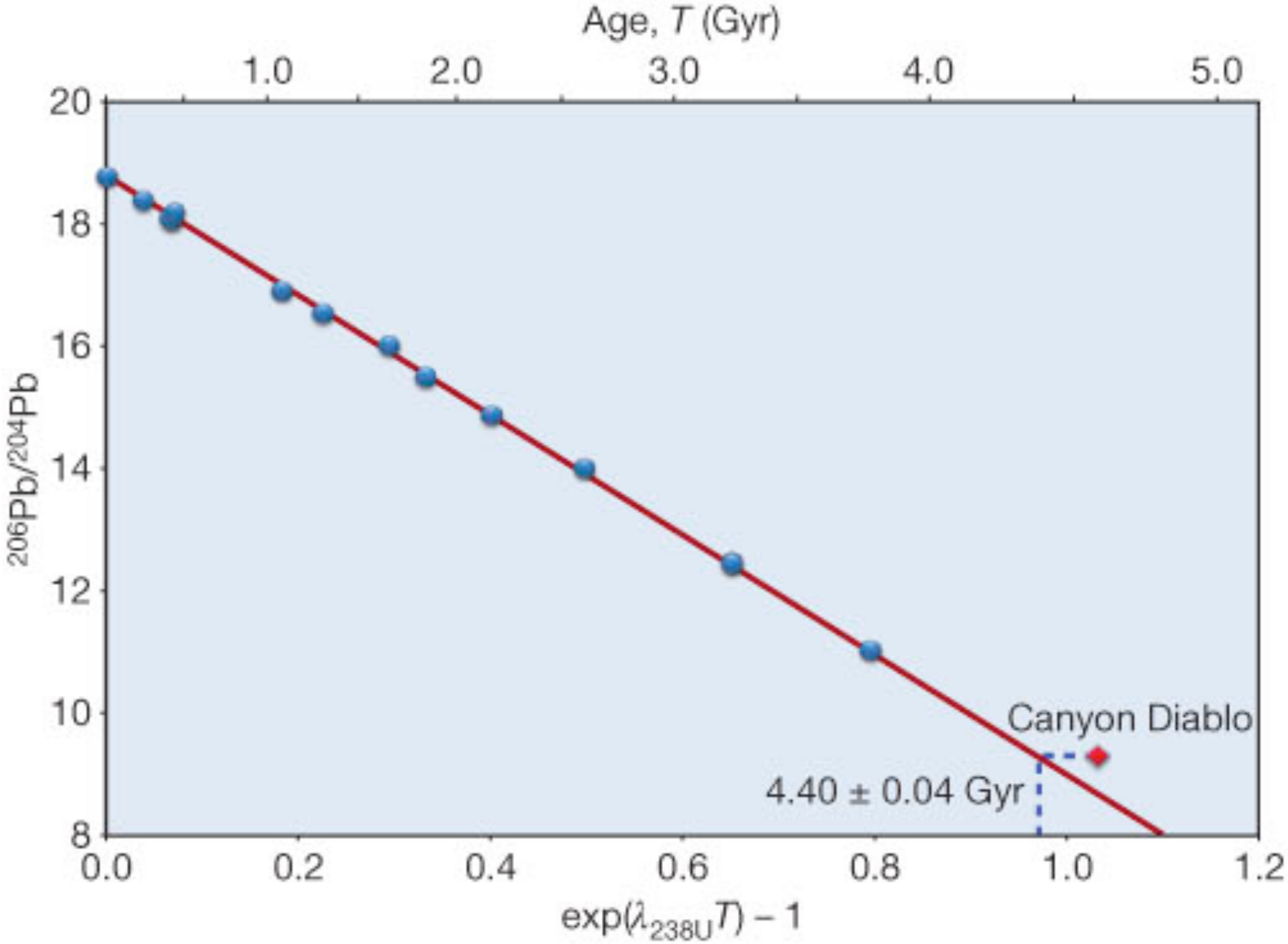
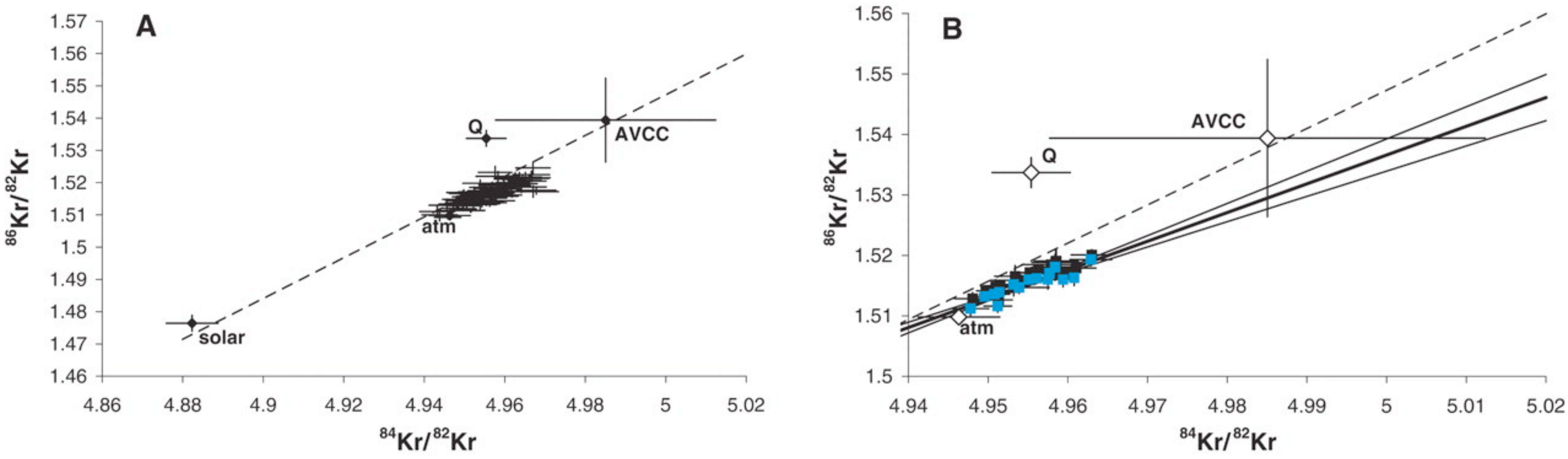


Figure 6 | Galena data and the young age of the Earth. Data are taken from ref. 54. The evolution of $^{206}Pb/^{204}Pb$ in conformable Pb deposits is linear in $\exp(\lambda_{238U}\ T) - 1$, where λ_{238U} is the decay constation of ^{238}U, which indicates that the mantle source of galenas behaved as a closed system since the early geological ages. The primordial Pb of the Solar System, represented by the 4.56-Gyr-old Canyon Diablo troilite[89], is not on the galena trend, which suggests that terrestrial Pb is younger than that of this meteorite. This condition reflects that either Pb segregated into the core at a late stage[89] or, as suggested here, that terrestrial Pb was largely inherited from the late accretion of volatile-rich material (late veneer) to the Earth.

Holland *et al*., 2009, Science 326: 1522



Kr isotope measurements of well gases show a clear, nonsolar primordial component. (**A**) Individual analyses of all sample aliquots (n = 125) are plotted. Uncertainties in well gas data and primordial end-members are 1σ. Data are compared with those from solar-Kr, AVCC-Kr, Kr-Q, and Air-Kr (31). The dashed line represents the solar mass fractionation line. (**B**) Averages of each sample are plotted both as uncorrected data (black) and as crustal fission corrected (blue) (see fig. S4 for corrections involving both U and Pu fission). The bold line is a York fit (32) freely fitted through the data. Thin black lines are 1σ error envelopes to the data. The dashed line represents the solar mass fractionation line. Fission correction is based on crustal U fission determined from ^{136}Xe excesses over air and assumes no Kr/Xe fractionation. Uncorrected data do not pass through air because of a crustal U fission component to Kr as observed previously in Xe isotopes (16); when corrected for fission, extrapolation of the best fit line passes through atmosphere. A summary of primordial end-members is presented in table S4.

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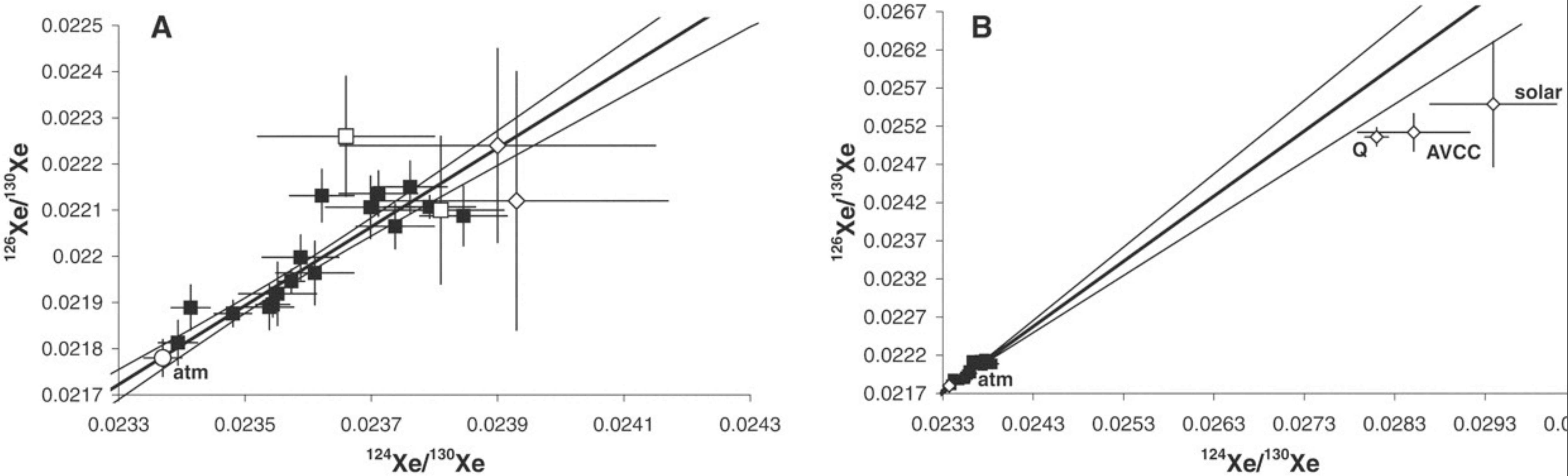

Nonradiogenic Xe isotope measurements of well gases show a primordial component that is completely consistent with Kr data. (**A**) Reduced scale view to show Xe nonradiogenic isotope data, plotted as $^{124}Xe/^{130}Xe$ versus $^{128}Xe/^{130}Xe$ with errors at 1σ uncertainty. The bold line is a York fit (32), freely fitted through the well gas data presented in table S2. Thin black lines are 1σ error envelopes. Open squares are Harding County and Caroline well gases (19). Open diamonds are MORB averages computed from (21). The open circle is modern atmosphere (atm). (**B**) Expanded scale view to incorporate possible end-members, plotted as $^{124}Xe/^{130}Xe$ versus $^{126}Xe/^{130}Xe$. The bold line is the error-weighted best fit, freely fitted through the data. Thin black lines are error envelopes of 1σ. Uncertainties in the primordial end-members are 1σ. Isotopic compositions of solar Xe, AVCC-Xe, Xe-Q, and Air-Xe are tabulated in (31) and table S4.

Why do we care about this idea?

Is volcanism compatible with life?

Earth the water planet is very poor in volatiles. The ocean is only 0.02 % of its mass. Because of the need of life for liquid water, we need to understand how Earth got the way it is.

Many unresolved questions:

Is earth's hydrosphere still receiving significant masses of new volatiles from inside the deep earth, from recycled subduction and from small comets?