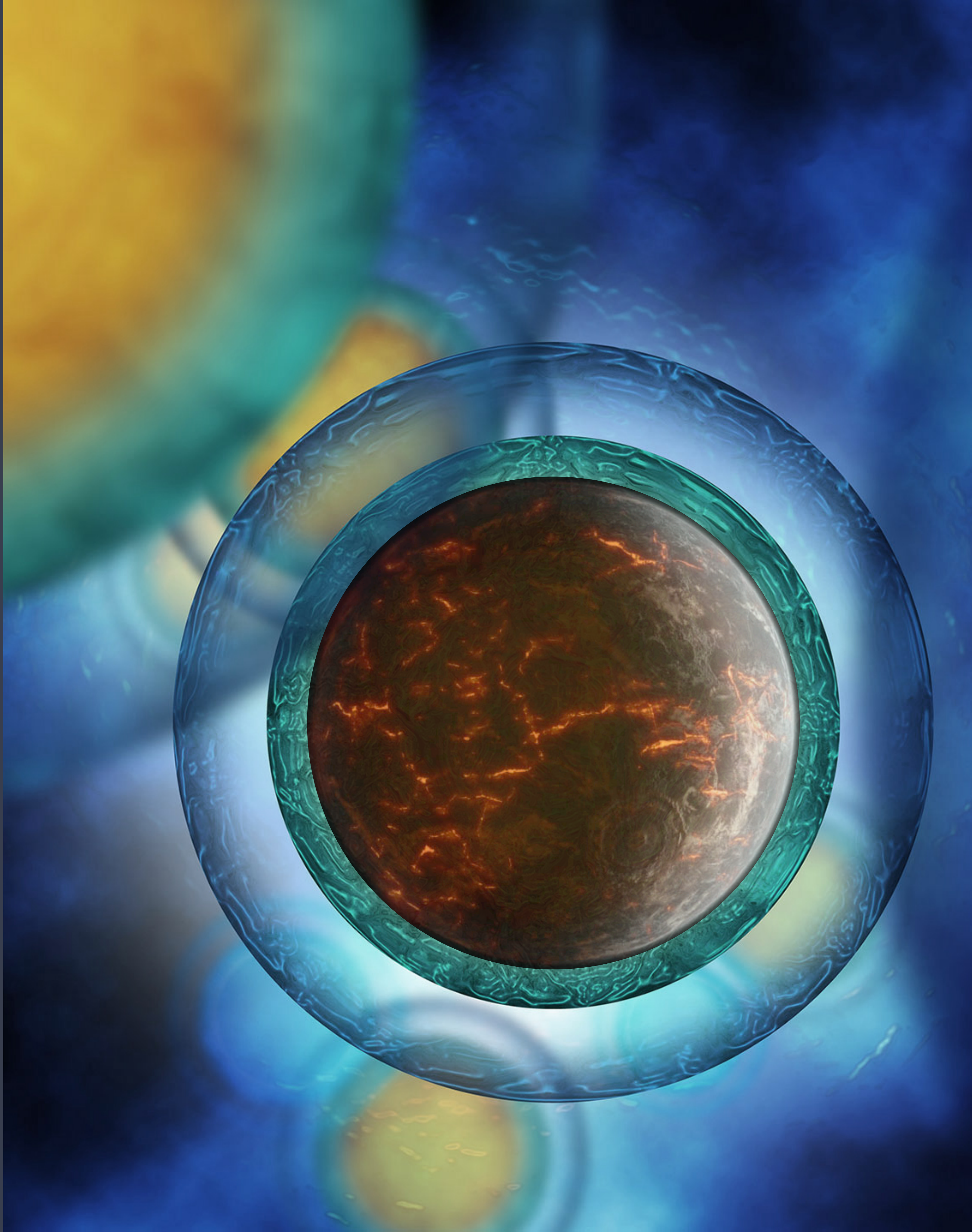
Patrice F Rey

EARLY EARTH
GEOLOGY-BIOLOGY
NEXUS

v.0.92 - 21 October 2024 -



FOREWORD

- Charles Lyell's famous statement - "*The present is the key to the past*" - is at once right and wrong. It is right because the present-day Earth preserves clues about an ancient Earth in its geological record and biological record at the cellular level. It is wrong because the modern Earth, including its biosphere, mineralogy, and geodynamics, bears little resemblance to the Archean and Hadean Earth. Here, we briefly review key informations about the first two billion years of Earth's history.

- First, we consider the formation of the Earth in the Hadean eon, which concludes with the formation of the oldest preserved rock, and briefly review the four eras of the Archean eon, focusing on fundamental geochemical shifts.

- In the second second, we review what we know about the primitive Earth's environment, its atmosphere, oceans, and continents. This section presents arguments in favour of a "waterworld" and a "flatter Earth".

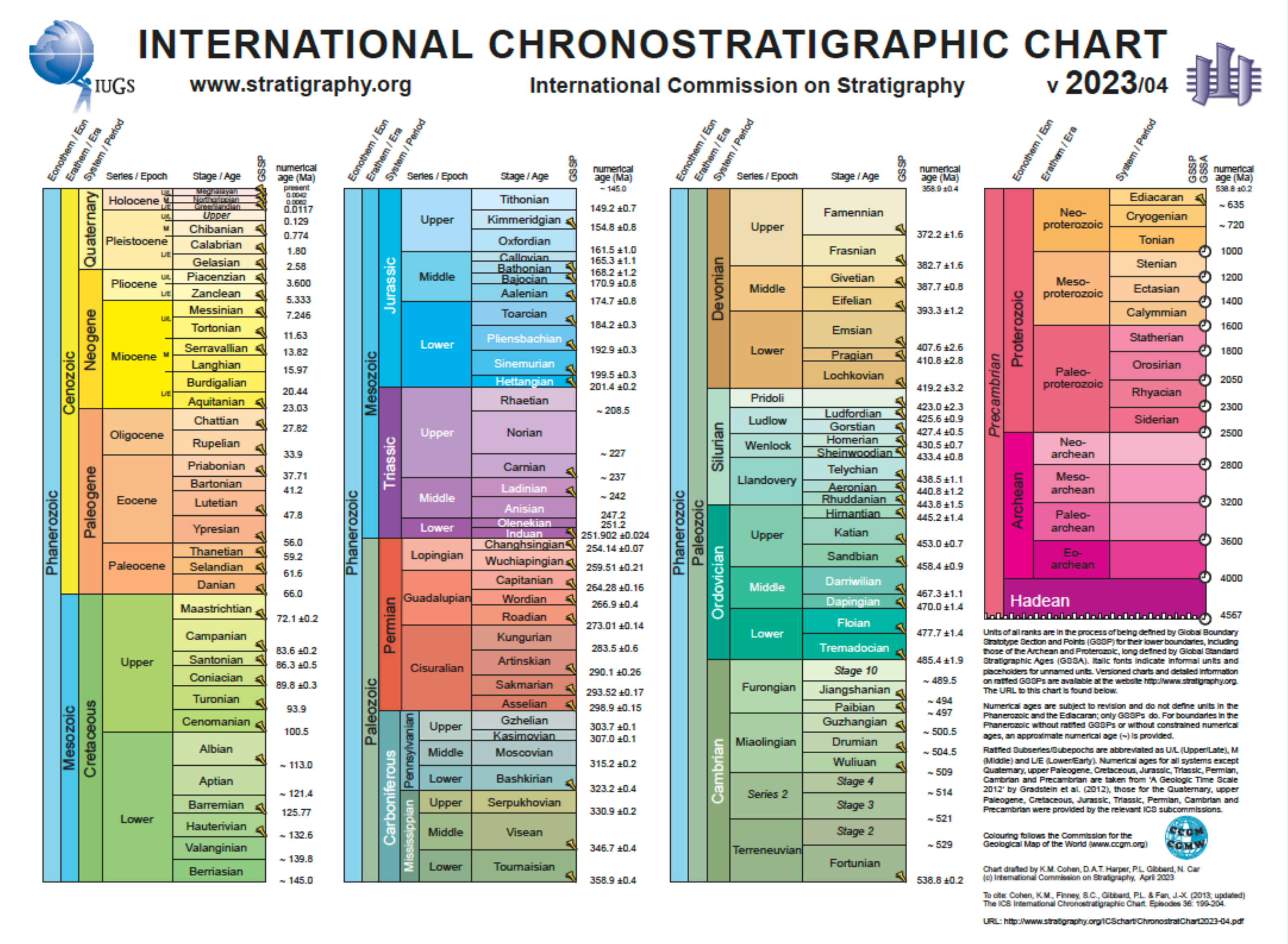
- The early Earth geodynamics is discussed in the third section. This section addresses the question relevant to tectonic processes in the Archean, from plume tectonics, to sagduction, and to transient subduction.

- Finally, we turn our attention to the early life record. Environments that are "extreme" on present-day Earth were the norm on the primitive Earth. These extreme environments and the primitive forms of life they hosted help decode the ancient biological record.

BACK THEN WHEN ALL BEGAN …

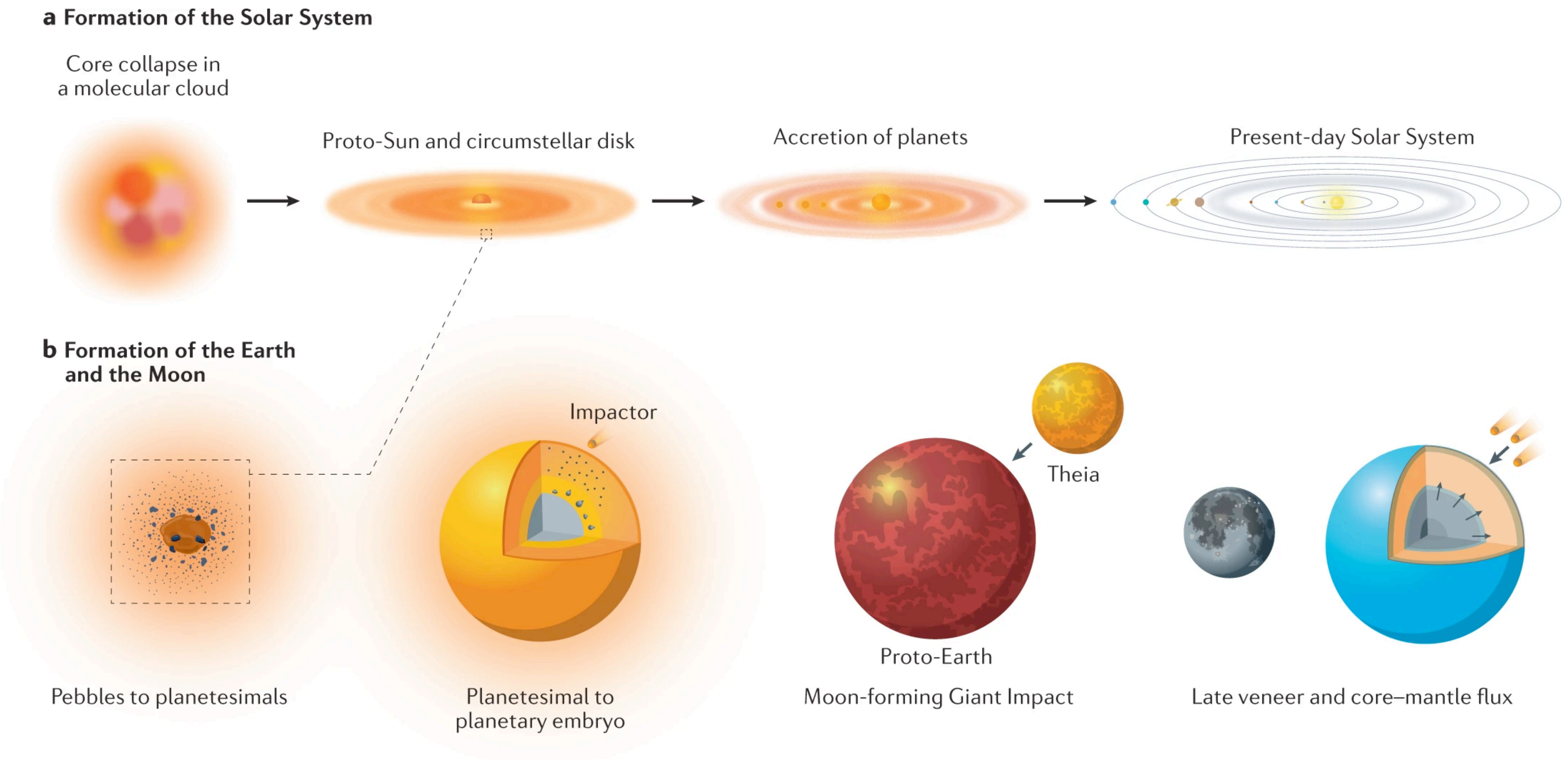
- Earth's formation and the Hadean Eon (~4.567 to 4.031 Ga).
- Archean geological shifts (4.031 Ga to ~2.5 Ga)

In great contrast to what the International Chronostratigraphic Chart suggests, the Hadean and Archean Eons account for 45% of Earth's history. It is during this time that Earth developed its modern geodynamics, and the tree of life developed its main branches. Although there are many unknowns about how our planet and its biosphere co-evolved during the Hadean and Archean Eons, one thing that has emerged is that this co-evolution was, and still is, deeply intertwined. Here, we review this epic history.



The Hadean Eon: 4.567 Ga to 4.031 Ga -

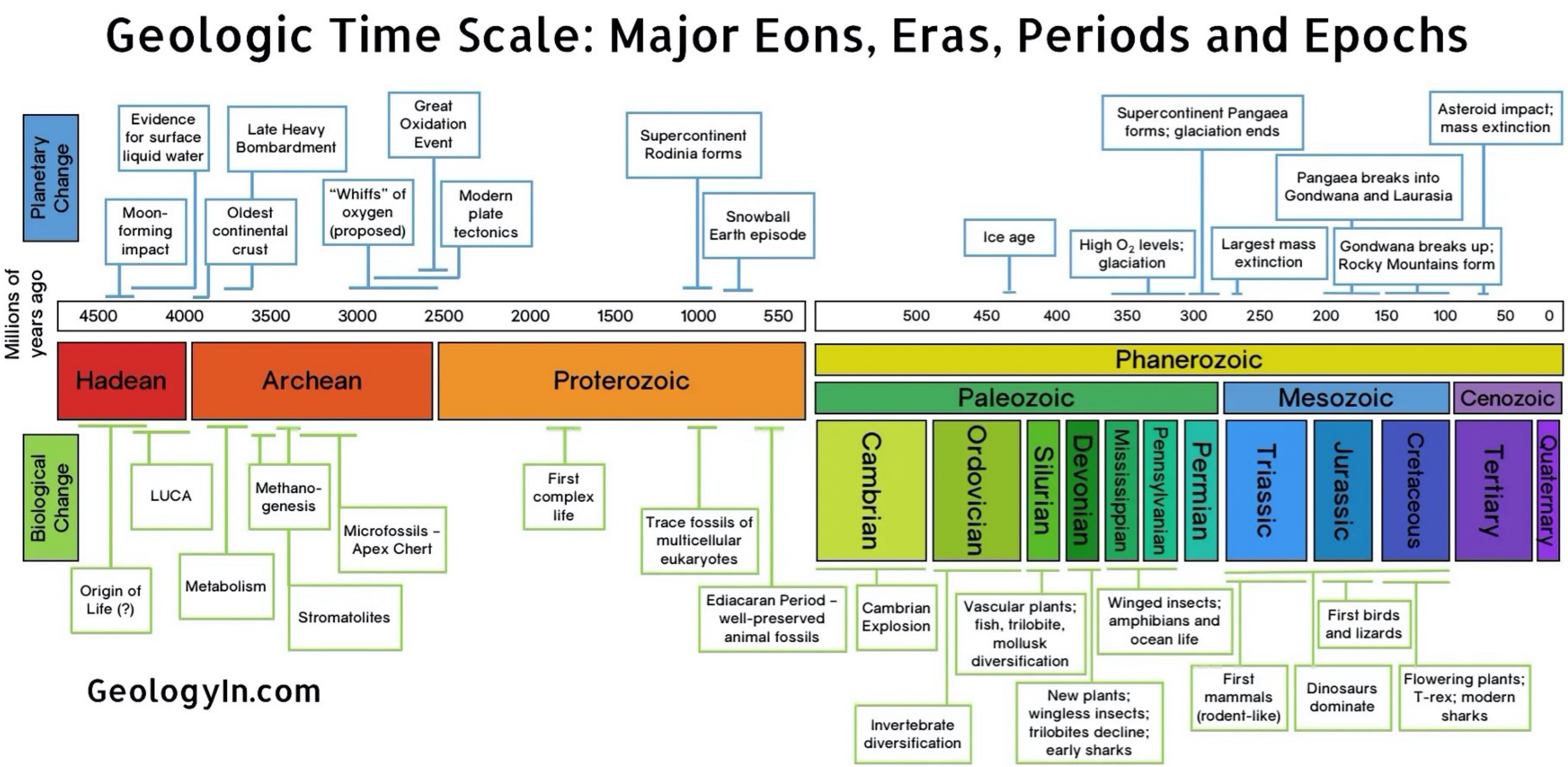
The Hadean, defined as the eon that preceded the formation of the first solid rock, began with the collapse of a molecular cloud, evolved through the accretion of planets around 4.567 billion years ago (the age of primitive meteorites, Moon rocks, etc.), and ended with the formation of the oldest terrestrial rock 4.031 billion years ago.



Source: Nature Reviews Earth & Environment | Volume 4 | January 2023 | 19–35

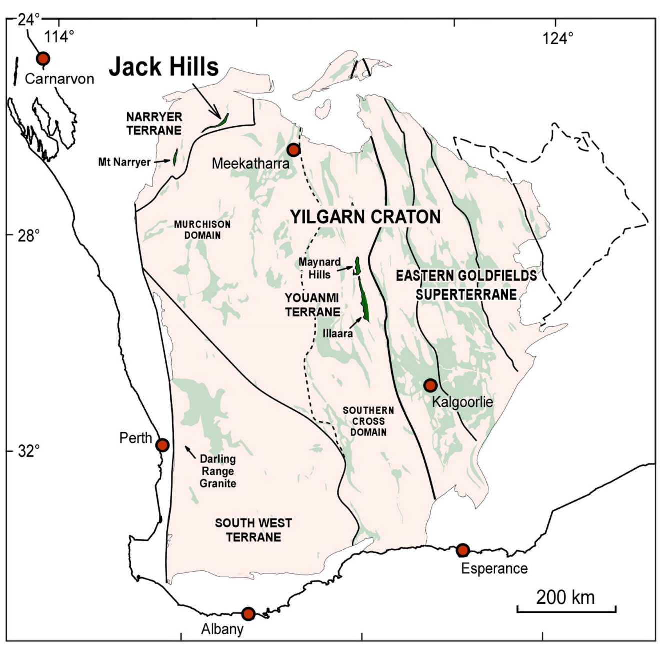
https://www.nature.com/articles/s43017-022-00370-0

The geologic time scale below shows major planetary and biological changes through time. It indicates that the surface of the Hadean Earth was cold enough to support liquid water, and that the Last Universal Common Ancestor (LUCA) of Bacteria, Archaea, and Eukarya—the three main branches of the tree of life—most likely originated in the Hadean Eon.



Key Hadean events

- Planetary accretion progressed from dust (micron), to grains (mm), to pebbles (cm), to rocks (m), to planetesimals (km), and finally to planets (1000 km), including Earth around 4.567 billion years ago.
- Metal-cored meteorites formed within the first million years of the Solar System.
- Mars-sized giant impact produced the Moon around 4.53 billion years ago.
- Intense bombardment by asteroids and comets continued until around 3.8 billion years ago, keeping the Earth's near surface hot.
- The bulk composition of the Earth is similar to that of chondrites, a common type of meteorite. From this bulk composition, the Earth evolved into a differentiated planet with a metallic core (composed of iron, nickel, and a few other heavy metals), a convective mantle, and a surface-cooled lid, which evolved into its present-day lithosphere, and eventually its early ocean-atmosphere system.
- The initiation of the magnetic field occurred through convective currents in the molten outer core, protecting the early Earth from solar winds. The formation of the magnetic field predates the formation of the solid inner core. The magnetic field reached at least 50% of its present strength around 3.7 billion years ago (Nichols et al., JGR, 2024).
- The formation and preservation of Earth's oldest mineral, a zircon (ZrSiO4) from Jack Hills in Western Australia, dated at 4.404 billion years ago (via U-Pb chronometer), with an (^{18}O) signature suggesting the involvement of rocks that interacted with surface water.
- Cooling and formation of the crust, which was recycled by intense bombardment.
- Formation of Earth's oldest rock at 4.031 billion years ago (Bowring et al., 1999), from the Acasta gneiss complex in the Slave Province of northern Canada.

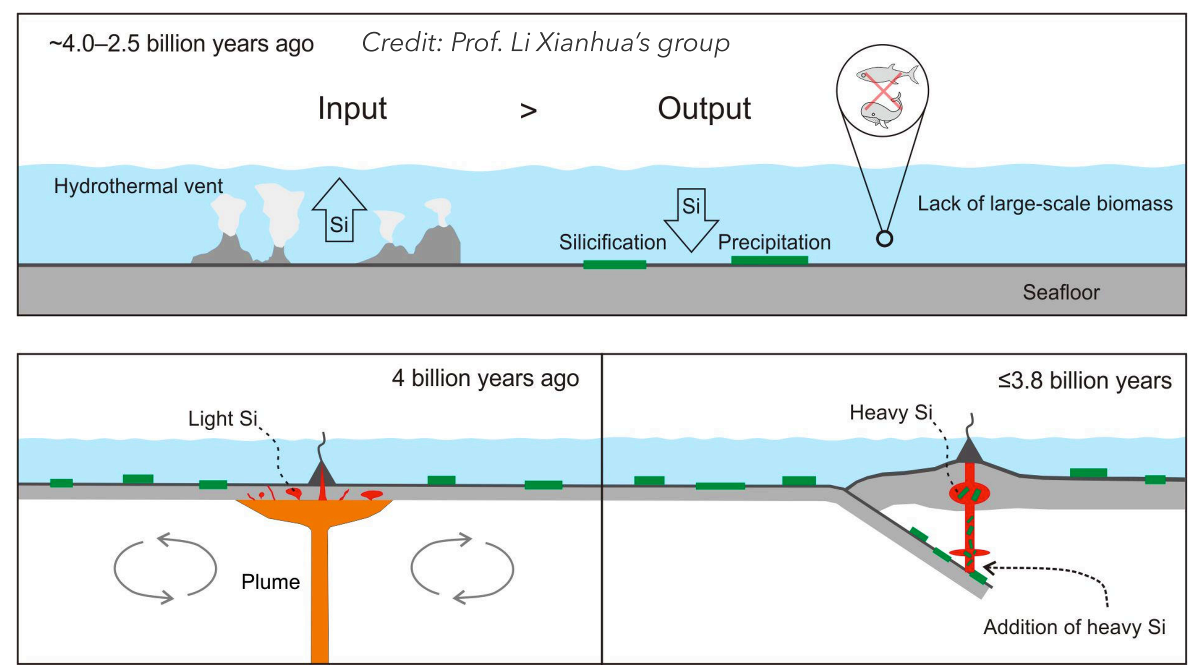


Jack Hills belt in the Narryer Terrane (Pidgeon et al., 2017)

The Archean Eon: 4.031 Ga to 2.5 Ga -

The Archean Eon is make of four eras: Eoarchean, Paleoarchean, Mesoarchean and Neoarchean, defined chronometrically with no reference to specific stratigraphic levels.

Eoarchean 4.031 Ga to 3.6 Ga - Little is left from the Hadean crust, and the crust record until 3.6 Ga is scarce. This record includes the 4.03 Ga Acasta gneiss (Slave Province, Canada), the 3.9 Ga Saglek Gneiss Complex (east coast of northern Labrador, Canada), the 3.8 Ga Isua Greenstone Belt (southwestern Greenland), the 3.8 Ga Anshan region (northeastern North China Craton), and the 3.78 Ga Nuvvuagittuq Greenstone Belt (in Quebec, Canada), the 3.8 Ga Selukwe belt (Zimbabwe), and the 3.64 Ga Ancient Gneiss Complex (Swaziland) . These are the vestiges of a time when the Earth's surface was continuously reworked through relentless heavy bombardment.



- 4.0 - 3.8 Ga: Shift towards lower εHf(t) in younger magmatic zircon points to closed-system recycling via recurrent partial melting of the crust.

- 3.8 - 3.6 Ga: Shift towards higher εHf(t) in younger magmatic zircon points to increasing contribution of a juvenile basaltic crust in the production of magma. Initiation of subduction and plate tectonics on Earth?

- 3.8 Ga: Shift towards higher δ^{30}Si in arc magma shows first evidence of surface heavy silica recycling. Initiation of subduction and plate tectonics on Earth?

Nb: Silica has three stable isotopes: ^{28}Si, ^{29}Si and ^{30}Si. The heavy silica ^{30}Si precipitates very slightly more readily, so silicified sediments at the sea floor is slightly enriched in ^{30}Si.

Mini lesson #1: Age determination of Hadean and Archean events

Radioactive parent (P) -> Daughter (D)

$^{176}Lu \rightarrow {}^{176}Hf$ half-life 37.2 Ga

$^{147}Sm \rightarrow {}^{143}Nd$ half-life 147 Ga

$^{146}Sm \rightarrow {}^{142}Nd$ half-life 0.103Ga

$^{238}U \rightarrow {}^{206}Pb$ half-life 4.468Ga

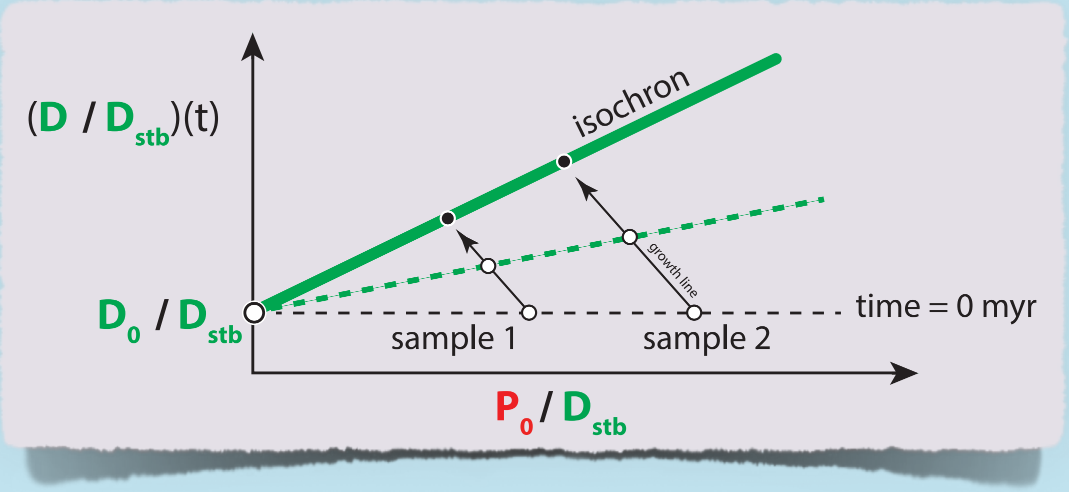
$^{235}U \rightarrow {}^{207}Pb$ half-life 0.704Ga

$D = D_0 + P_0\,(1-e^{-\lambda t})$ **Decay of radioactive Parent into stable Daughter**

Subscript naught refers to initial concentration, "t" is the unknown age of the sample, λ is the half-life.

We rewrite the decay equation using abundance relative to a stable daughter isotope:

$$\left(\frac{D}{D_{stb}}\right)(t) = \frac{D_0}{D_{stb}} + \frac{P_0}{D_{stb}}\,(1-e^{-\lambda t})$$

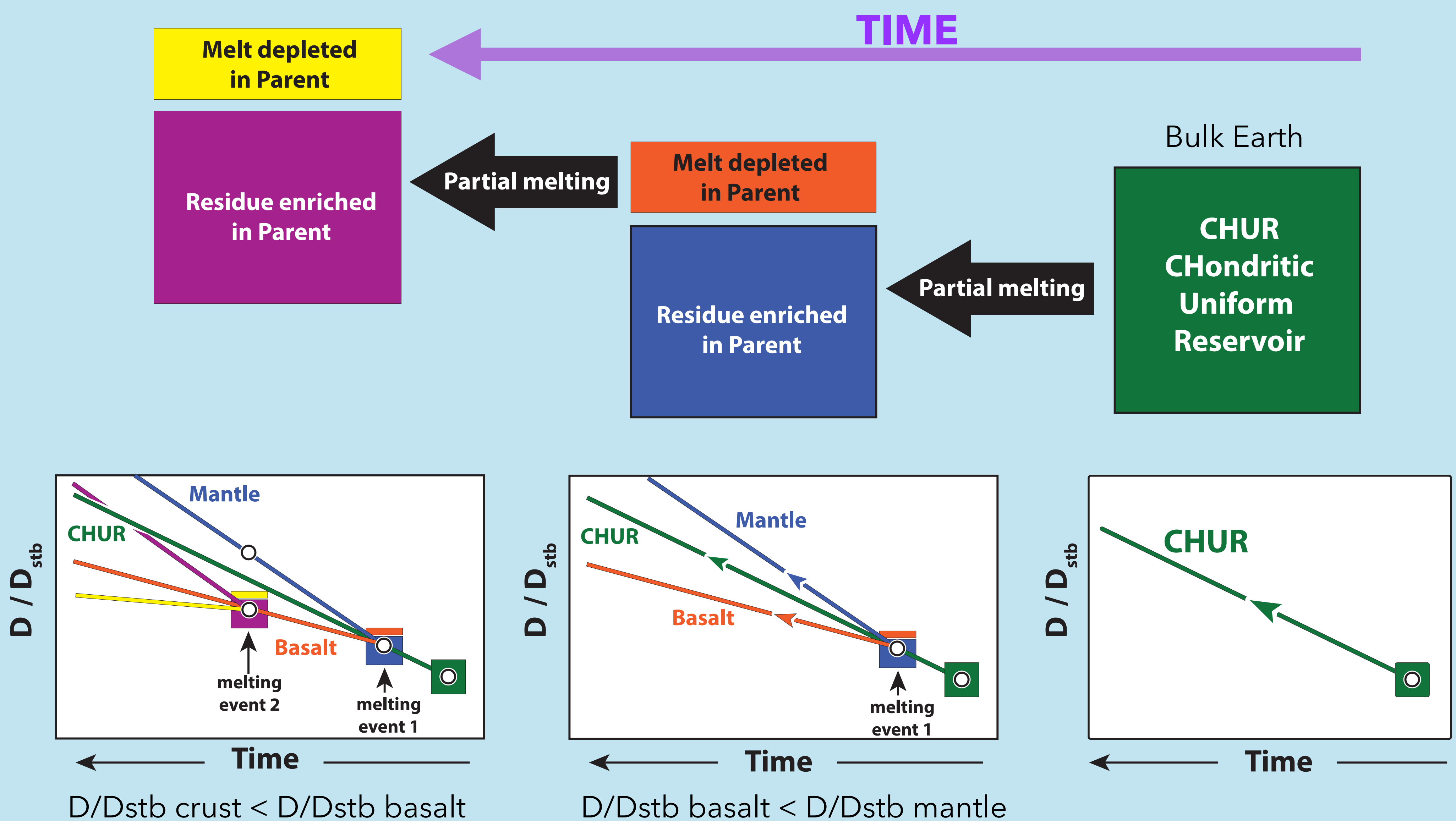


Igneous rocks form through partial melting.

At time of formation (i.e., t=0myr): $\frac{D}{D_{stb}} = \frac{D_0}{D_{stb}}$

Mini lesson #2A: Tracing the origin of partial melting sources ...

During partial melting (PM), parent radiogenic isotopes are less mobile than their daughter products. The latter tends to concentrate in the melt, while the former remains in the residue. Any process that changes the relative proportion between two isotopes is called *fractionation*. Here, partial melting changes the proportion between parent (P) and daughter (D), as P content increases in the melt residue and D content increases in the melt. Hence, partial melting changes the slope of $(D/D_{stb})(t)$.

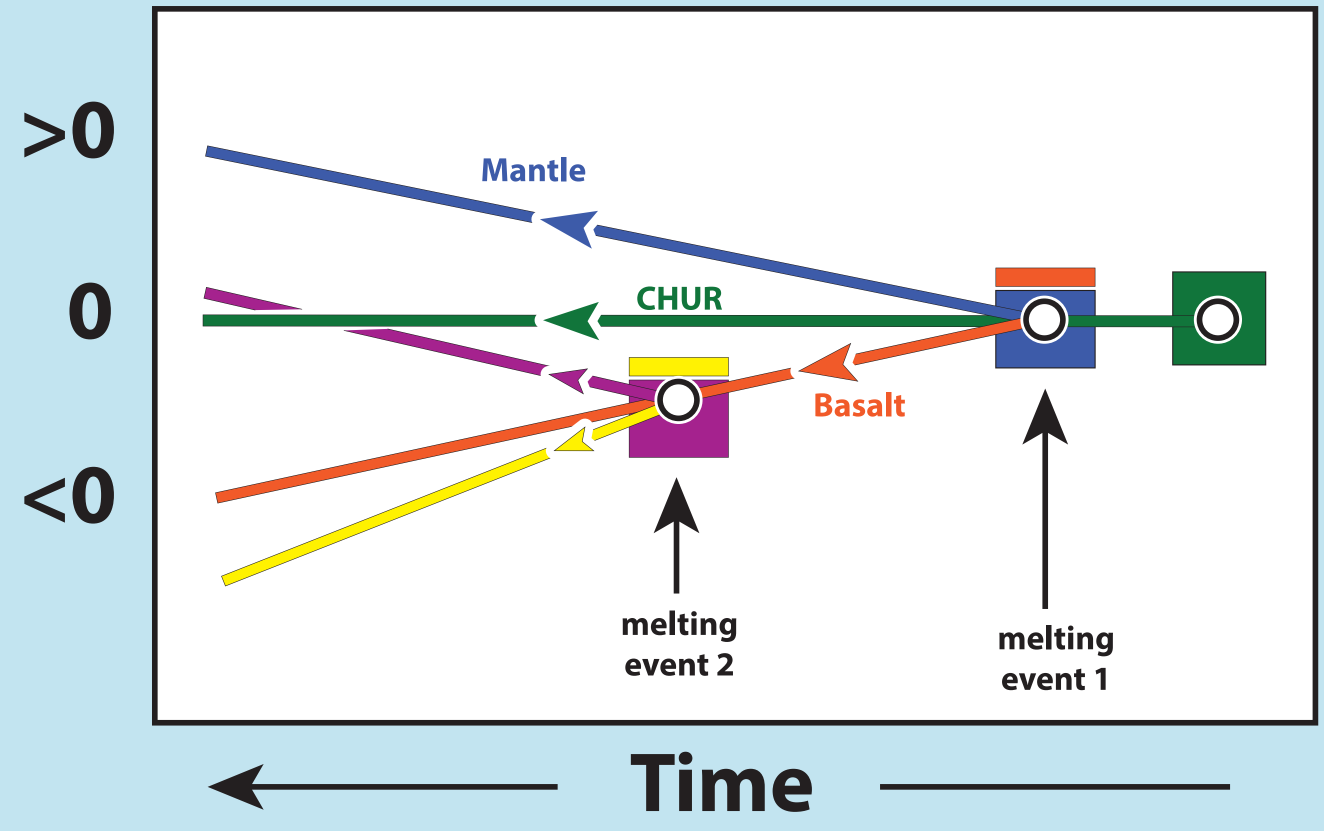


… Tracing the origin of partial melting sources …

To facilitate the reading of the isotopes evolution graph, we normalise isotopic ratios of our samples with respect to a bulk Earth composition model (e.g., chondrite, the Earth's building blocks). We substract 1 to bring the bulk Earth evolution to 0, and then scale the results by multiplying by 10,000. We call these normalised and scaled numbers epsilon (ε) values.

$$\varepsilon Hf(t) = 10^4 \times \left[\left(\frac{(^{176}Hf / ^{177}Hf)_{smpl}}{(^{176}Hf / ^{177}Hf)_{CHUR}} \right) - 1 \right]$$

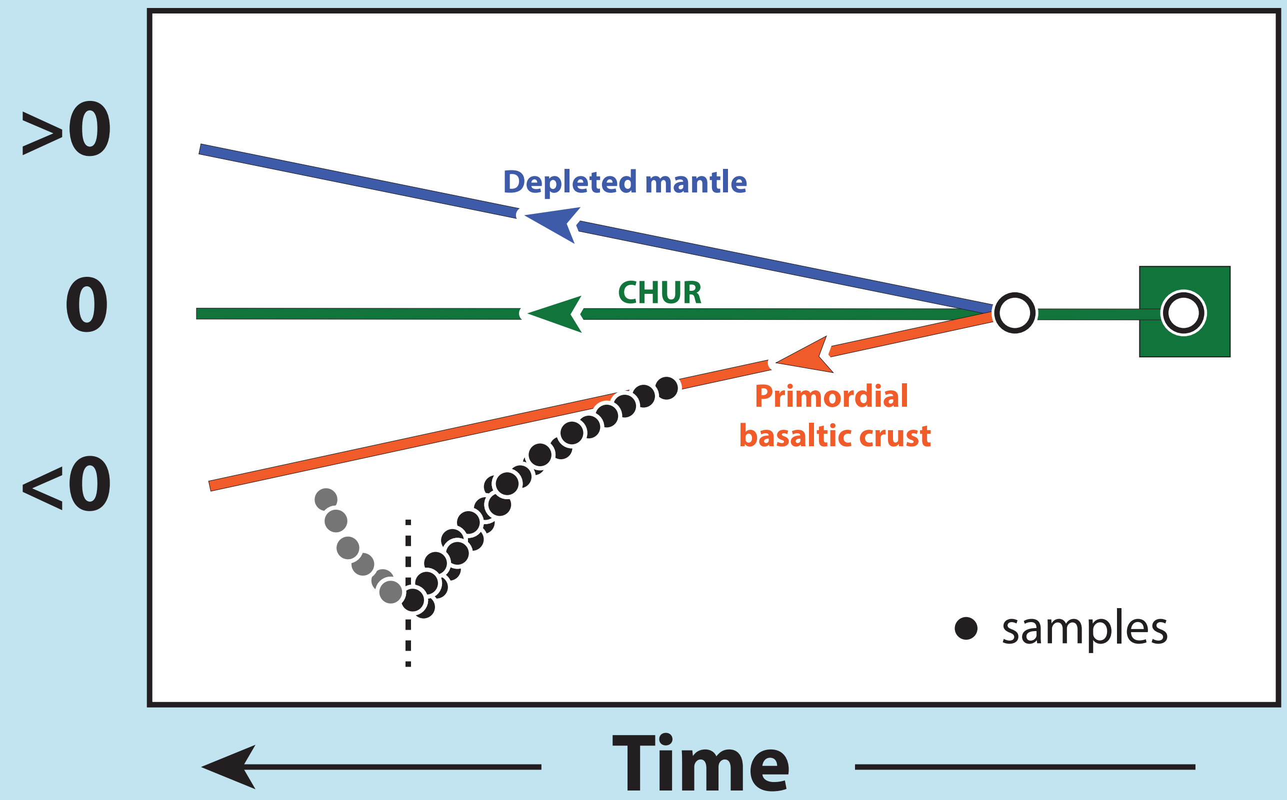
$$\varepsilon^{143}Nd(t) = 10^4 \times \left[\left(\frac{(^{143}Nd / ^{144}Nd)_{smpl}}{(^{143}Nd / ^{144}Nd)_{CHUR}} \right) - 1 \right]$$



We see that the recurrent partial melting of a basaltic crust in a closed system (no contribution from new mantle magma) delivers a trend of decreasing ε (orange to yellow lines).

… Tracing the origin of partial melting sources

$$\varepsilon Hf(t) = 10^4 \times \left[\left(\frac{(^{176}Hf\ /\ ^{177}Hf)_{smpl}}{(^{176}Hf\ /\ ^{177}Hf)_{CHUR}} \right) - 1 \right]$$



The recurrent partial melting of a primordial basaltic crust in a closed system (i.e., with no contribution from new mantle magma) results in a trend of decreasing εHf(t) in progressively younger zircon (black circles). The shift towards higher εHf(t) (grey circles) is explained by the contribution of melt extracted from a depleted mantle source or from a juvenile (recently extracted) basaltic crust, which originates from the depleted mantle (a source of very positive εHf(t)).

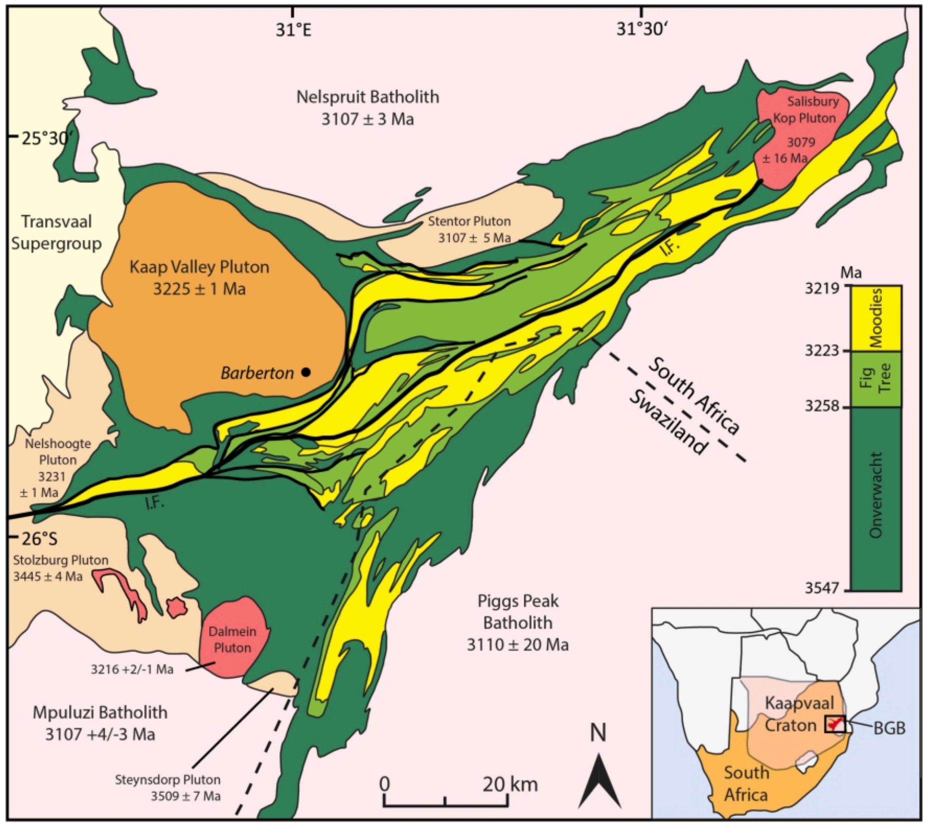
Paleoarchean 3.6 Ga to 3.2 Ga -

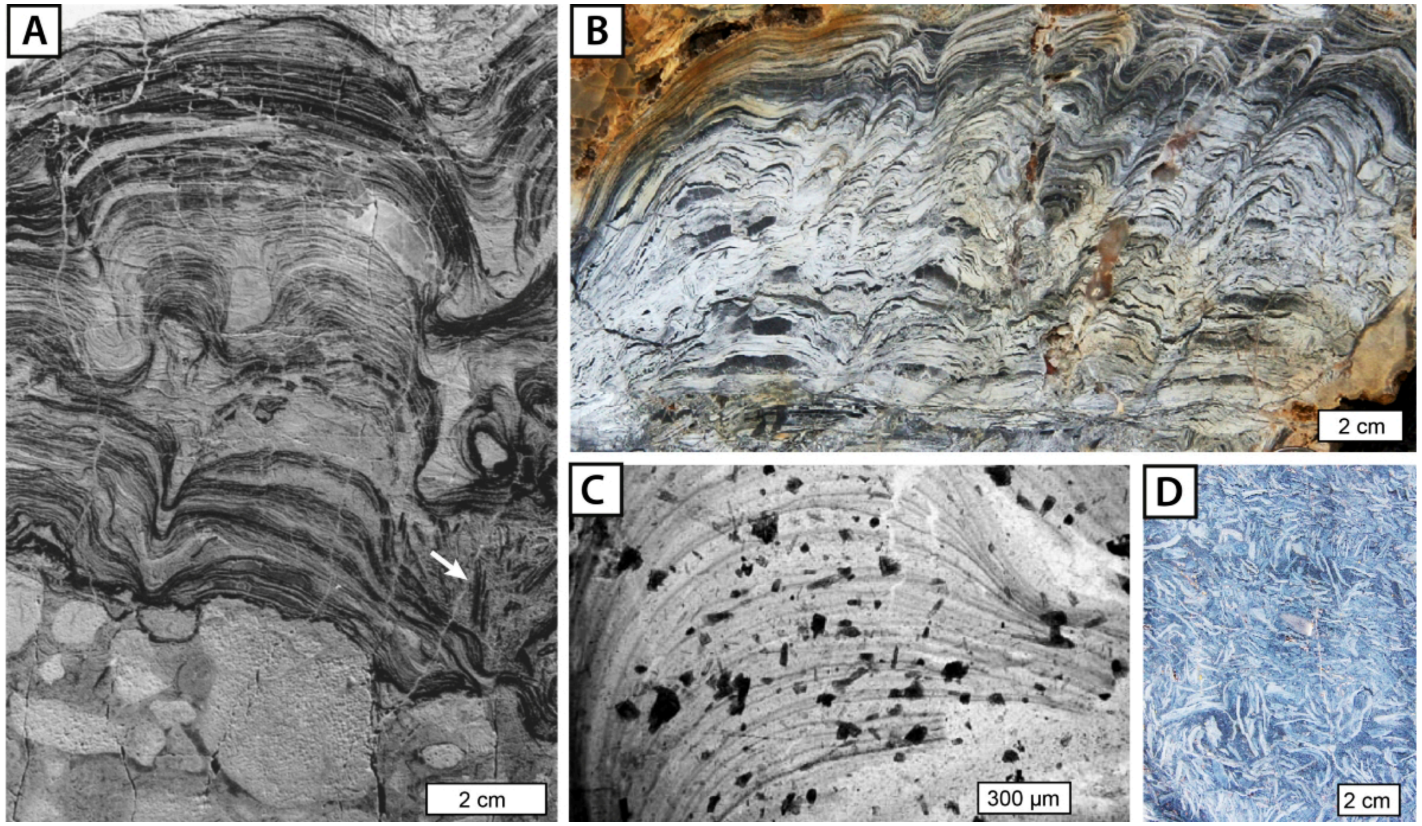
• First solid evidence of early life. The 3.48 Ga Dresser formation and the 3.5 Ga Strelley Pool Chert in the Pilbara (WA) record a diversity of features and geochemical proxies that could be related to microbial mats and stromatolites. However, there is debate as evaporitic precipitation can also lead to stromatolite-looking laminae.

@ Didier Descouens, Strelley Pool Chert

The Paleoarchean Barberton Greenstone Belt (Kaapvaal Craton, South Africa) is known for its numerous occurrence of putative stromatolites.

Homann, 2019, Earth Science Reviews, https://doi.org/10.1016/j.earscirev.2019.102888



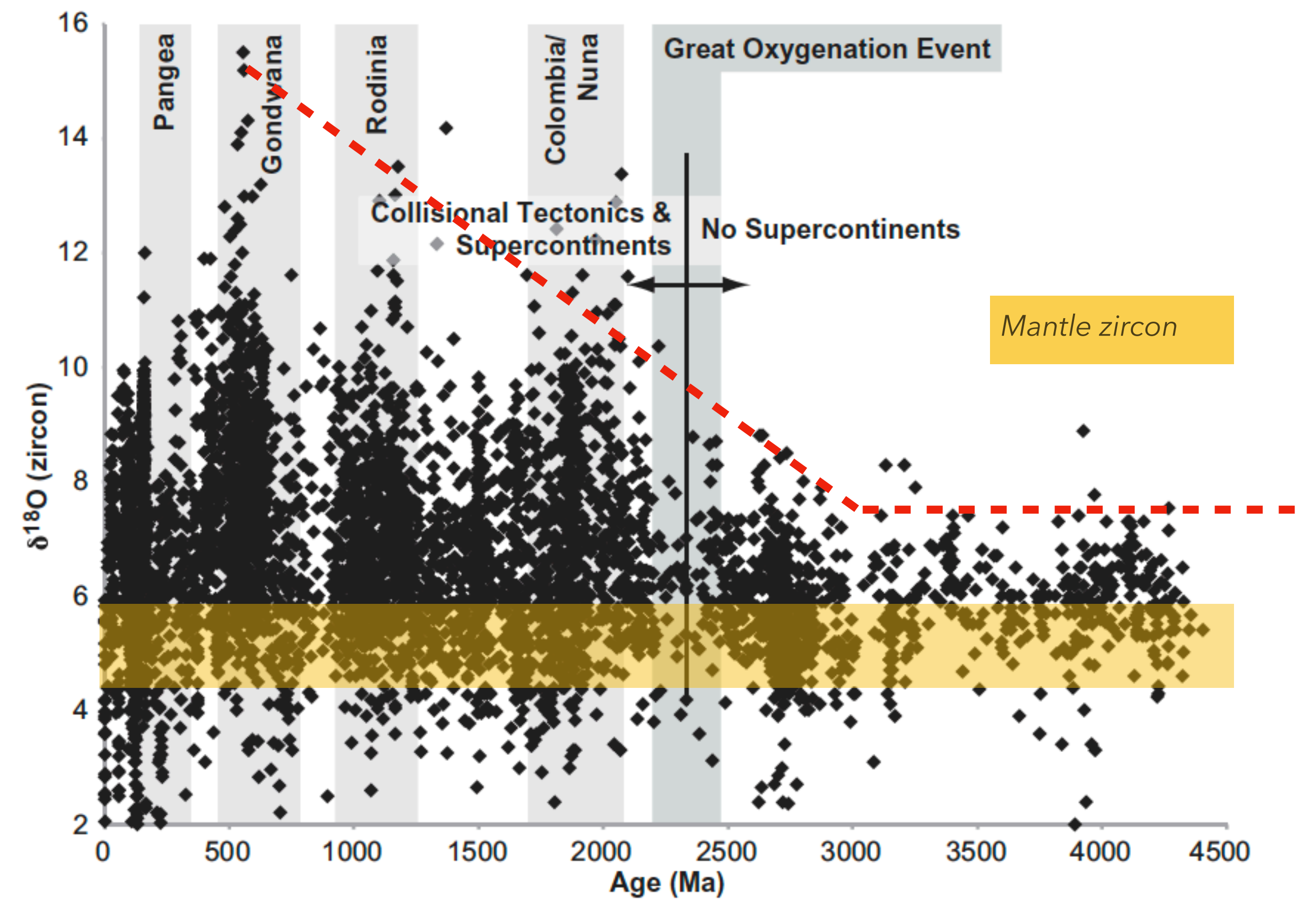


Mesoarchean 3.2 Ga to 2.8 Ga -

- ~3.2 to 2.7Ga Filamentous cyanobacteria and their biomarkers identified in stromatolites.
- ~2.9 Ga Possible first glaciation (Pongola diamectite in the KwaZulu-Natal province of South Africa).
- ~2.9 Ga Oxygen oases (Pongola Supergroup, South Africa). Low concentrations of phosphorus suppressed the growth of oxygenic photosynthesizers delaying oxygenation until the end of the Neoarchean Eon (Ossa Ossa et al., 2019).
- ~2.8 Ga, earliest supercontinent? The similarities between the Kaapvaal Craton (South Africa) and the eastern part of the Pilbara Craton (WA) suggest that both were part of a single craton. The term Vaalbara is sometime used to refer to this craton as the Earth's earliest supercontinent.

Neoarchean 2.8 Ga to 2.5 Ga -

- Recycling sediments in arc magmas. The $\delta^{18}O$ of magmatic zircons shows a change from values that remained stable and ≤ 7.5‰ until ~2.8 Ga, to increasingly higher values since the Neoarchean. Nb: $\delta^{18}O$ in magmatic zircon of 5.5 to 5.9 ‰ points to mantle melt, whereas the melting of sedimentary rocks that have interacted with surface water can reached 12‰. In contrast, melting of rocks that have interacted with water at higher temperature, for instance around hydrothermal cells, have lower $\delta^{18}O$.



Robert & Spencer, 2014. http://dx.doi.org/10.1144/SP389.14

Mini lesson #2B: Oxygen isotopes as tracer of magmatic processes …

$$\delta^{18}O = 10^3 \times \left[\left(\frac{(^{18}O\ /\ ^{16}O)_{Sample}}{(^{18}O\ /\ ^{16}O)_{Standard}}\right) - 1\right]$$

Isotopes of the same element have the same atomic number (number of proton), but differ by their respective number of neutron. For example oxygen has three stable isotopes with atomic mass (sum of proton and neutron) of 16, 17 and 18. Their relative proportion (99.76%, 0.04% and 0.2%) differs greatly.

Fractionation is the process of changing the relative proportion of isotopes during a physico-chemical reaction. For instance, during evaporation the lighter ^{16}O is preferentially partitioned in the gas phase. Fractionation is generally less efficient at higher temperature. Fractionation is expressed by the $\delta^{18}O$, which measure the deviation of the ratio $^{18}O/^{16}O$ of a sample with respect to a reference (standard, e.g., Vienna Standard Mean Ocean Water).

MORB have a $\delta^{18}O$ ranging between 5.4 ‰ and 5.9 ‰. Recurrent remelting of these basalts in a closed system delivers magma with $\delta^{18}O$ ranging between 5.8 ‰ and 7.5 ‰. Yet, the $\delta^{18}O$ of crustal rocks varies between -10 ‰ and +32 ‰. High $\delta^{18}O$ values can be explained by the assimilation of sedimentary rocks of carbonates rocks (+20 ‰ to +35 ‰), which have interacted with surface waters. As zircons inherit the $\delta^{18}O$ of the magma in which they crystallise, and since they can be accurately dated, and since they are immune to alteration and metamorphism, they can be used as a tracers of tectono-magmatic history.

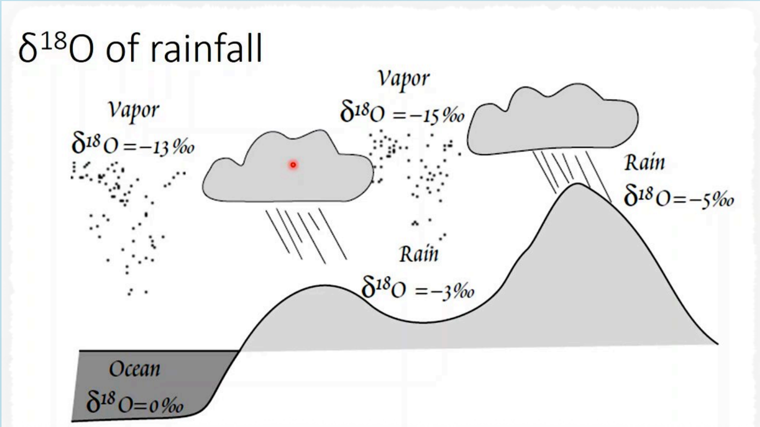
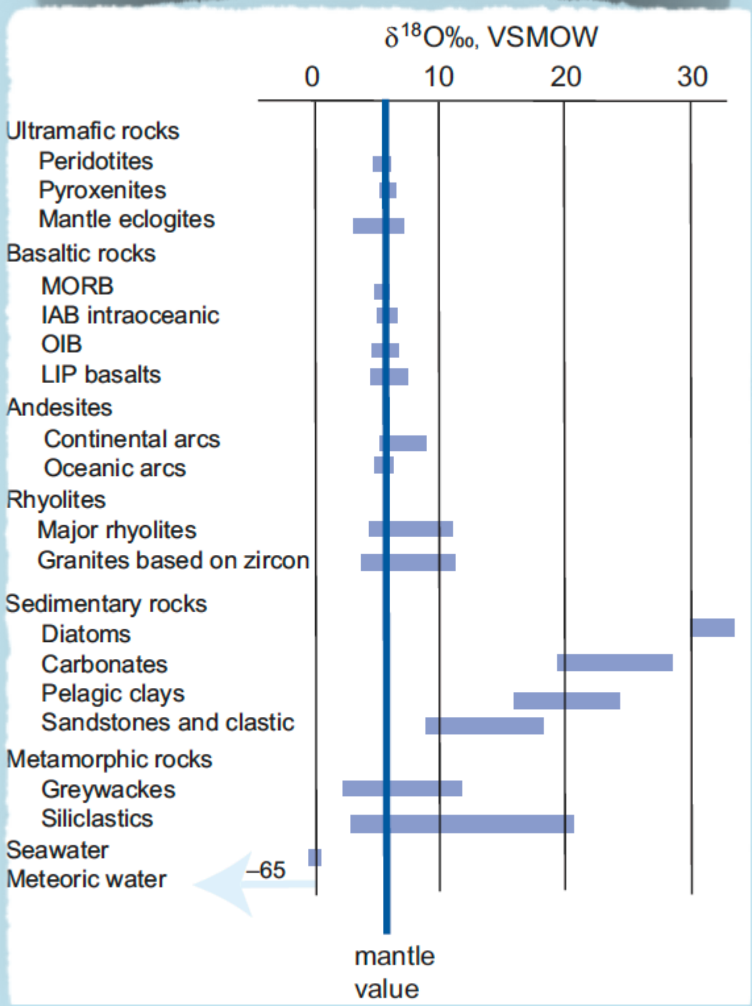


Figure 9.9. Cartoon illustrating the process of Rayleigh fractionation



Mini lesson #2B: Oxygen isotopes as tracer of magmatic processes …

Due to mineral-melt fractionation, isotopic composition of igneous rocks usually differs from that of their original source. At fundamental level, this is due to the different isotopic substitution due to the difference in strength of various bond-types (Si-O-Si, Si-O-Al, Si-O-Mg, …). The degree of ^{18}O enrichment in a mineral is characterised by its oxygen isotope index (I-^{18}O) relative to a reference mineral. The greater the I-^{18}O index the richer the mineral in ^{18}O. The I-^{18}O index of an igneous rock depends primarily on the proportion of mineral phases (CIPW normative minerals), and therefore its chemical composition. For instance, the I-^{18}O index of a rock based on its normalised chemical composition is given by:

$$\text{I-}^{18}\text{O}_{\text{rock}} = \sum X_{\text{oxide}} \times \text{I-}^{18}\text{O}_{\text{oxide}}$$

Using the I-^{18}O of common oxides.

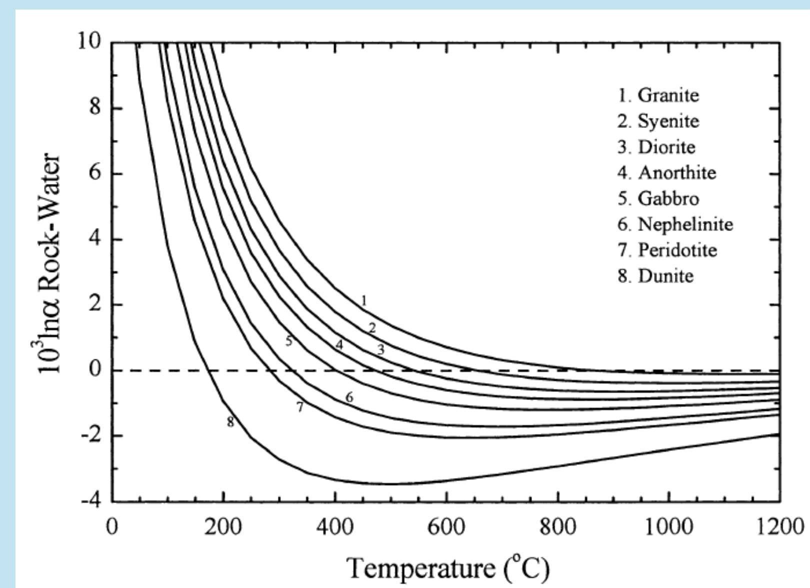
Oxygen isotopic indices of oxides (revised after Zheng, 1991)

Zhao & Zheng, 2003, Chemical Geology.

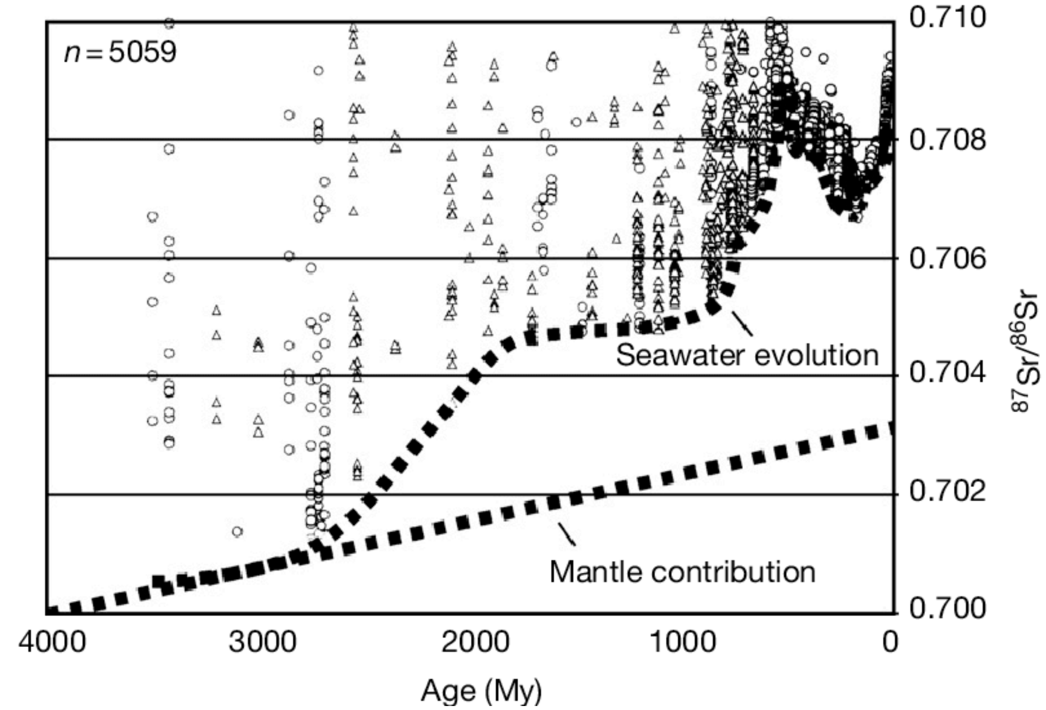
Oxide	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O
I-^{18}O	1.0000	0.6322	0.8697	0.4809	0.4140	0.4066	0.3555	0.2374	0.0701	0.0578

^{18}O enrichment in common igneous rocks is such that: granite > diorite > tonalite > gabbros > basalts > peridotite > dunite

Oxygen isotopes can constrain the origin of aqueous fluids involved in the formation of felsic magmas because low-$\delta^{18}O$ surface waters impact the most on the isotopic exchange during melting processes. A correction factor (thermodynamic oxygen isotope factor) is applied to take into account the logarithmic decreases of $\delta^{18}O$ with increasing temperature of fluid-rock interaction. Hence, low-temperature interaction with meteoric water leads to elevated $\delta^{18}O$ values, and high-temperature interaction leads to low $\delta^{18}O$ values.



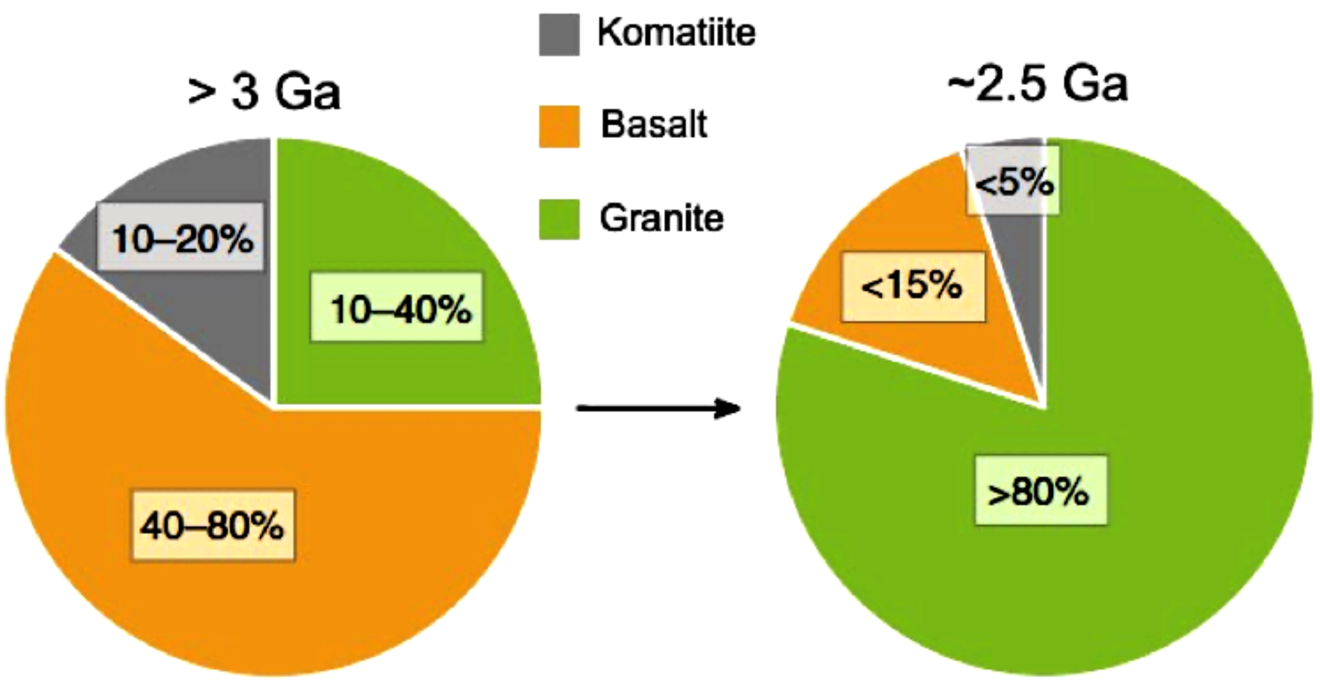
• Shift on the strontium isotopic composition of marine carbonate (Shields and Veizer, 2002) . Sea water inherits the strontium isotopic composition (i.e., $^{87}Sr/^{86}Sr$) of the mantle via volcanic inputs. In turns, carbonates inherit the strontium isotopic composition of the ocean (an homogeneous reservoir) from which they precipitate. At the beginning of the Neoarchean, there is a departure of the strontium isotopic composition of carbonate from the mantle trend, towards higher, more radiogenic values. The continental crust, into which radiogenic ^{87}Rb (parent of ^{87}Sr) is partitioned, is the source of ^{87}Sr. This influx suggests the growth during the Neoarchean of large extent of continental crust exposed to erosion.



2.74 Ga Mopoke member of the Kylena formation in the Meentheena centrocline, with stromatolitic carbonate, Pilbara (WA)

- Shift of the bulk MgO composition of the upper continental crust from highly mafic before 3 Ga to felsic by 2.5 Ga. Fine-grained sediments provide global estimates of the average composition of Earth's emerged surface. It is now well-established that the composition of Archean fine-grained sedimentary rocks suggests that the emerged crust was dominated by mafic-ultramafic rocks during most of the Archean and transitioned to more felsic compositions no earlier than ~3.0 Ga (Taylor and McLennan 1995). This shift is coherent with the Neoarchean shift in $^{87}Sr/^{86}Sr$ of marine carbonates, which identifies fluxes of weathered felsic crust into the oceans. This is also consistent with the lack of prominent pulses before ~3.0 Ga recorded by the distribution of ages in detrital zircon (e.g., Condie et al. 2017). These signals have been interpreted as evidence for a late Archean pulse of crustal growth (see image gallery).

- ~ 2.5 Ga substantial increase in O_2 consumption by oxidative weathering of sulfides, due to either increase in landmass or increase in O_2 production, or both. This pre-dates the 2.4 Ga Great Oxidation Event (GOE) (Johnson et al., 2021, Science Advances, https://www.science.org/doi/10.1126/sciadv.abj0108).



Petolology of the upper crust at >3Ga and ~2.5 Ga (Tang et al., 2016, Science)

@ Graeme Churchard- Dales Gorge, Pilbara (WA)

Nb: Upon hydration, olivine and other Mg-rich minerals in mafic rocks form serpentine minerals, continuously releasing O_2-scavenging molecules such as hydrogen (H_2), hydrogen sulfide (H_2S) and methane (CH_4) to the environment (Smit and Mezger, 2017: https://www.nature.com/articles/ngeo3030).

- Clear evidence of biogenic carbonate stromatolites, displaying metabolic signatures for methanotrophy (the processing of CH_4 as source of carbon and energy), microbial sulphate reduction (i.e., anaerobic oxidation of sulfate into H_2S or FeS_2), and microbial iron reduction (anaerobic oxidation of sulfate of Fe^{3+}), and evidence for evolved and diversified oxygenic photosynthesis cyanobacteria (Lepot, 2020, Earth-Science Review).

- 2.8 - 2.5 Ga - Banded Iron Formations (BIF) are made of chemical sedimentary rocks organised into layers of iron oxides and iron-poor chert. They can be several hundred of meters in thickness, and cover several 100s' km laterally. BIF became prominent in the Neoarchean and formed when soluble ferrous iron (FeO) transported, via anoxic rivers or deep ocean upwelling, into shallow oxygenated sea water, and precipitated as insoluble ferric iron (Fe_3O_4 or Fe_2O_3).

2.78 Ga to 2.42 Ga Hamersely Range (Pilbara, WA, @ Julie Burgher/Flickr, CC BY-NC)

EARLY EARTH ENVIRONMENTAL CONDITIONS

- The faint Sun paradox
- Early atmosphere
- The early Earth ocean
- The rise of continents

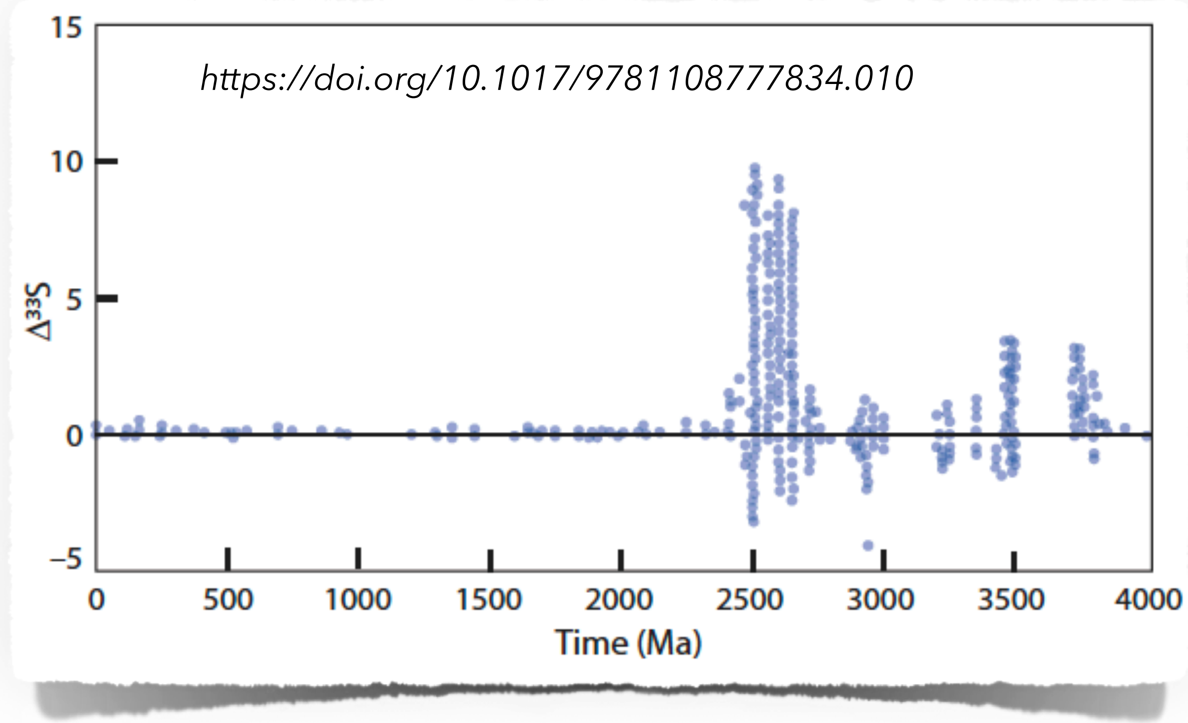
The faint Sun paradox. In the first billion years of the solar system, the Sun's output was ca. 70% of what it is today. Yet, observations suggest that liquid water existed at the Earth's surface before the end of the Hadean Eon. The paradox can be solved by considering high concentrations of greenhouse gases in the Earth's atmosphere at the time.

Early atmosphere - Information about the Archean atmosphere derives from consideration on the composition of the bulk Earth, and how gases affected weathering of rocks and the formation of paleosols, as well as the Th/U ratio in arc igneous rocks which trace the oxidation of the Earth surface and the transfer of soluble oxidised Uranium (U^{6+}) into the ocean.

The highly reducing composition of enstatite chondrite and chondrite meteorites suggests that the early atmosphere and the Earth as a whole were highly reducing. Indeed, the early Earth atmosphere was a mixture of mainly CO_2, N_2, CH_4, and H_2.

The presence of detrital grain of uraninite (UO_2), siderite ($FeCO_3$), and pyrite (FeS_2) and other proxies, suggest a level of oxygen a million times lower than present day. Despite an anoxic atmosphere, local oxygen oases were produced by photosynthesises in lakes and shallow seawater.

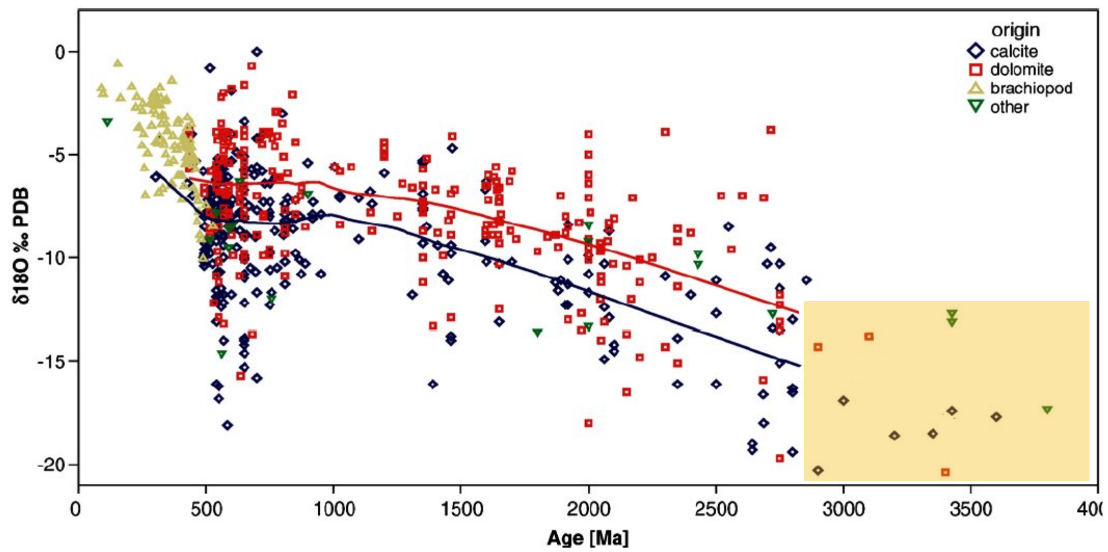
During the GOE, ~2.4 Ga, O_2 level increased to 0.01 Present Atmospheric Level (PAL).

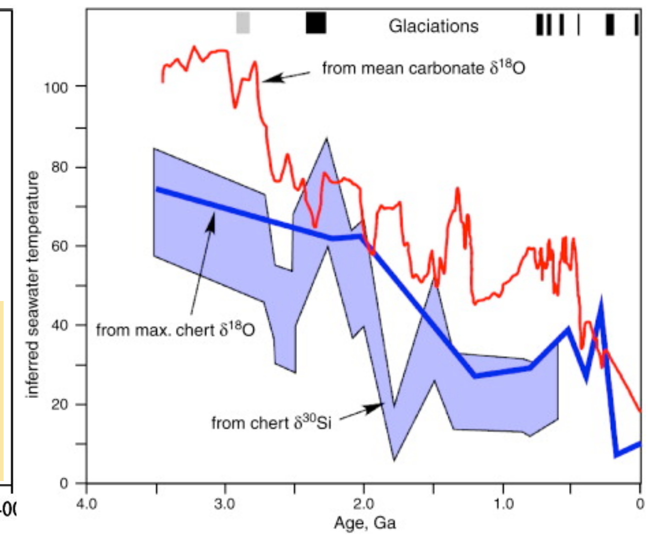


Sulfur isotope Mass Independent Fractionation (MIF) - The fractionation of isotopes is normally proportional on their relative masses. Some photochemical reactions, however, produce Mass Independent Fractionation (MIF). In the absence of a stratospheric ozone (O_3) layer, the interaction between ultraviolet light and volcanic sulfur dioxide (i.e., photolysis) in the troposphere leads to the mass independent fractionation of sulfur (SO_2+UV = SO+O, SO+UV == S + O). Sulfur (S) particles fell to the Earth's surface where they are incorporated into a range of minerals such as pyrite (FeS_2) and barite ($BaSO_4$), while atmospheric sulphate (SO_4) could be transformed into pyrite in microbial mats.

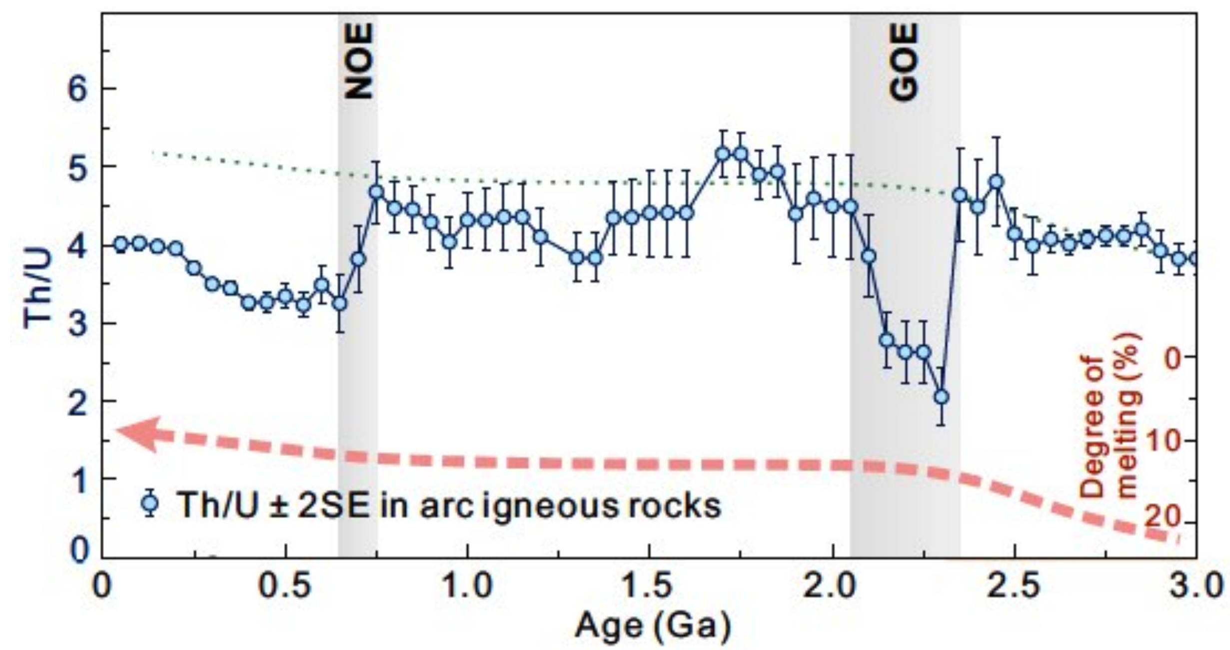
During the Neoarchean, O_2 produced from cyanobacteria was scavenged by the oxidation the Earth surface. Between 2.4 and 2.3 Ga, and since oxidation being a self-limiting process, excess O_2 unused by oxidative weathering was released into the atmosphere where an ozone layer started to form, protecting the Earth from UV light. The sudden disappearance of MIF of sulfur isotopes (expressed as $\Delta^{33}S$) marks the onset of the oxygenation of the Earth's atmosphere.

The early Earth ocean - The first evidence for liquid water comes from the oxygen isotopic composition of ~4.4 Ga magmatic zircon. The chemical, mineralogical, and isotopic compositions of marine chemical sediments deposited on the seafloor of the early Earth's (e.g., iron formation, carbonates, chert) and altered oceanic crust constraint the environmental changes that took place on the evolving Earth. For instance, the strontium isotopic composition of carbonates informs about the relative contribution of the sources (mantle vs continents) of radiogenic strontium ^{87}Sr. The abundance and isotopic composition of Fe(II)-bearing minerals in iron formation inform about the global oxygenation of the atmosphere and the ocean (Konhauser et al., 2017, Earth Science Review). The oxygen isotopic composition of marine chemical sediments and altered oceanic crust (expressed as $\delta^{18}O$) inform about the ocean temperature and the nature of weathering processes. The progressive shift through times towards higher $\delta^{18}O$ in chert and associated carbonaceous matter, as well as carbonates (see graph below) indicates a secular cooling of seawater temperature from 50-60°C from the early Archean to present. This is consistent with the decrease in $\delta^{18}O$ in seawater from >3‰ at 3.8 Ga to -1‰. This secular cooling may be due to increase of continental erosion and weathering through times (e.g., Johnson and Wing, 2020, Nature Geosciences).



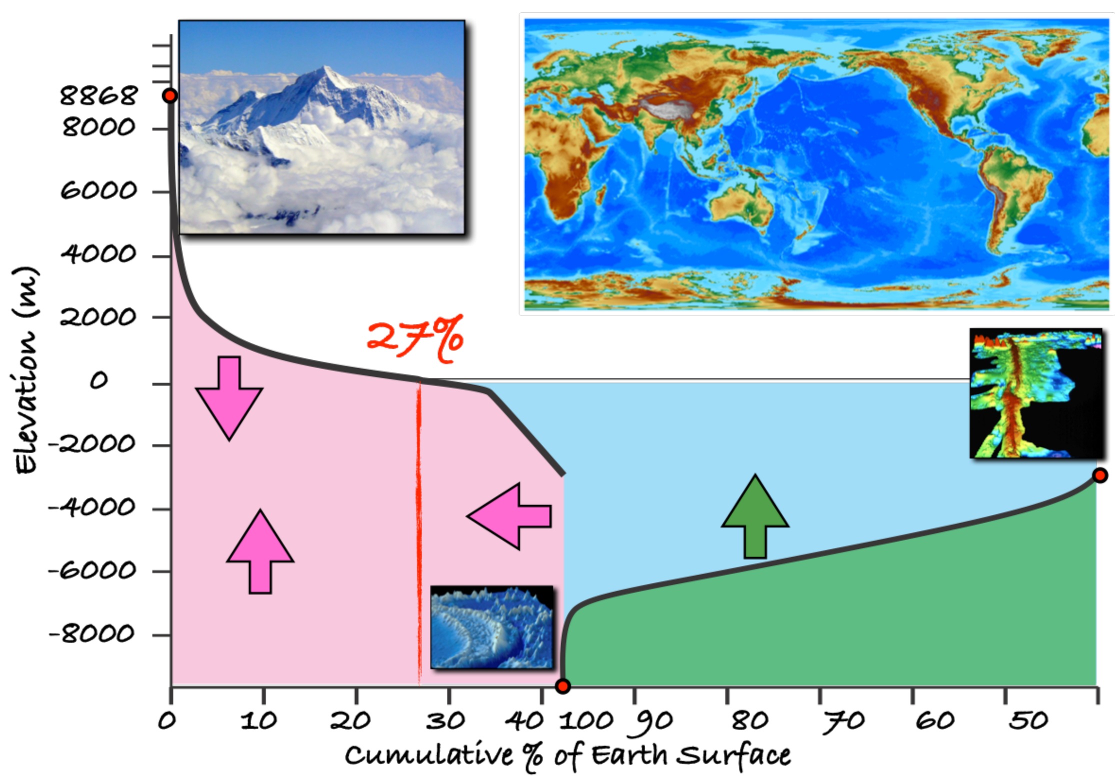


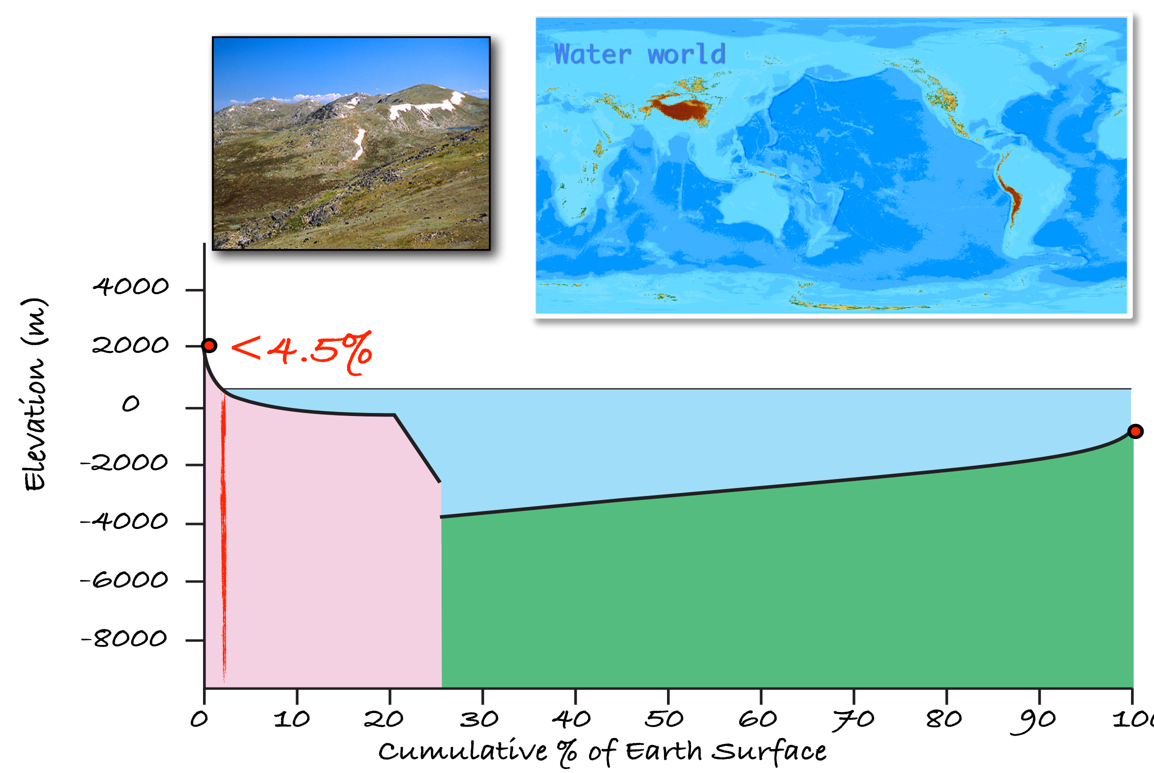
The Th/U ratio in arc igneous rocks reflects the composition of altered oceanic crust, and therefore the flux of Th and U from the continent to the ocean. On an anoxic atmosphere, Th^{4+} and U^{4+} are insoluble and transported into the ocean as suspended particles. In presence of oxygen, U is oxidised into soluble U^{6+} as Th remains tetravalent. This increases the flux of U into the ocean relative to Th. Following seafloor alteration, the oceanic crust inherits a lower Th/U ratio, which is then transferred to arc magmas following subduction (see figure on the right). This explains the Th/U drop during the GOE and the Neoproterozoic Oxygenation Event (NOE) (Graph from Liu et al., 2019, PNAS).



A water world ? On a hotter Earth, a warmer mantle has a reduced water storage capacity (Dong et al. 2021), and it is expected that the volume of the ocean may have been twice what it is today. In addition, it can be shown that on a hotter Earth the ocean seafloor would be shallower. These two predictions, together or separately, imply that the ocean may have overspilled onto continents (Flament et al. 2008). This is the water world hypothesis, according to which the Earth was largely a global ocean until sometime in the Neoarchean. The figures below shows the Earth hypsometry at present (left), and in the Neoarchean (right). The hypsometric curve gives the relative proportion of the Earth surface standing above a given elevation. For instance, on present-day Earth, only 5% of total Earth's surface stands above 2000 m.

The hypsometric curve in the Archean (bottom right) takes into account a reduced volume of continental crust, the limited capacity of hotter and weaker continents to support high orogenic relief and plateaux, and a shallower seafloor. This model is conservative as it doesn't take into account the possibility of a larger volume of water at the Earth's surface.





The Rise of continents - Continents exist for hundreds of millions of years and hold the memory of past tectonic and geodynamic processes. The building blocks of the continental crust (composition: SiO_2,=60.6%, Al_2O_3=15.9%, CaO=6.4%, Na_2O=3.07%, K_2O=1.81%) were extracted from the mantle, leaving their mantle source correlatively depleted in those elements (SiO_2,=44.71%, Al_2O_3=3.98%, CaO=3.17%, Na_2O=0.13%, K_2O=0.006%). Basaltic rocks as old as 3.5 Ga have slightly lower Nb/U ratios (43) than those of modern oceanic basalts (47), suggesting ~75% of the crust was extracted from the upper mantle by 3.5 Ga, which is consistent with the geologic evidence of the existence of pre-3.5 Ga felsic crust.

- Shift in the composition of the upper crust in the Neoarchean - Fine-grained sediments provide global estimates of the average composition of Earth's emerged surface. The composition of Archean fine-grained sedimentary rocks suggests that the emerged crust was dominated by mafic and ultramafic rocks during most of the Archean and transitioned to more felsic compositions no earlier than ~3.0 Ga. This is supported by the $^{87}Sr/^{86}Sr$ of marine carbonates, which identifies fluxes of weathered felsic crust into the oceans. Marine carbonates show a departure at ~3.0 Ga from the mantle trend they inherited from basalts, towards a more radiogenic trend recording an increased contribution of felsic lithologies to continental runoff.

Overall, the sedimentary record suggests no significant volumes of felsic crust at the surface before ~3.0 Ga, despite the well-documented presence of pre-3.0 Ga felsic crust in most cratons. This paradox requires an explanation …

- The flat Earth hypothesis - The paradox can be solved by posing that, until ~3.0 Ga, the early felsic continental crust was buried under thick layers of basalt, and that the surface of continents was below sea level. Therefore, these continents were immune to erosion and unable to influence the composition of detrital sediments. Furthermore, as the strength of rocks is strongly temperature-dependent, the hotter continental lithosphere was much weaker and unable to sustain significant orogenic topography making Archean landscapes flatter, and much less prone to erosion (Rey and Coltice, 2008, Geology). The secular cooling of the Earth, leads to the strengthening of the lithosphere, the deepening of the ocean floor, and the storage of large amount of water into the mantle, all contributing to the emergence of continents, their weathering and erosion, and eventually to the exhumation of the felsic crust to the Earth's surface.

- Here is what David Shiga wrote in 2008 in a Newscientist article titled: *Ancient Earth was a barren Waterworld*


NewScientist

Earth

Ancient Earth was a barren waterworld

By David Shiga

30 December 2008

Dry land may be something of a novelty. Until around 2.5 billion years ago our planet was almost completely covered by water, a model of the early Earth suggests.

Today, some 28 percent of Earth's surface is above sea level. Exactly how the ratio of land to sea has varied through Earth's history is unclear, but it is generally agreed that the amount of continental crust has increased over time.

Now, calculations by Nicolas Flament of the University of Sydney, Australia, and colleagues suggest that Earth was a water-world until about 2.5 billion years ago, with land making up only 2 to 3 percent of its surface (EPSL, DOI: 10.1016/j.epsl.2008.08.029).

The team assumed that back then Earth's mantle was up to 200 °C hotter than it is now, mainly because there was then a larger quantity of radioactive elements decaying and producing heat. A hotter mantle would have made the crust beneath the oceans hotter and thicker than it is today, buoying it up relative to the continents. The resulting shallower ocean basins would have held less water, leading to the flooding of what is now land. In addition, the hotter mantle would cause the continental crust of the time to spread laterally, making it lower-lying and flatter than today, and so more likely to flood.

Then, as the mantle cooled, land would have gradually appeared as the oceans became deeper and regions of high relief on the continental crust formed. The team believes that this transition may help to explain why levels of oxygen in the atmosphere rose around this time. During the water-world period, any oxygen produced by photosynthesizing bacteria would have been quickly used up through reactions with decaying organic matter in the oceans. When the newly emerged land eroded, it produced sediment that, once washed into the oceans, would have buried the organic matter, preventing any further reactions with oxygen, and so allowing it to build up in the atmosphere.

This would have allowed oxygen-breathing organisms to flourish, say the team. The eroded sediment would also have caused an explosion in life by fertilizing the oceans with phosphorus – an important nutrient. And newly formed coastal regions would have provided plenty of shallow habitats for photosynthesis.

Stephen Mojzsis of the University of Colorado, Boulder, agrees that the early continental regions could have been mostly flooded at this time. However, he suspects the land fraction was not quite as low as 2 to 3 percent because many rocks of this age appear to have formed from sediment washed off dry land.

ARTICLE

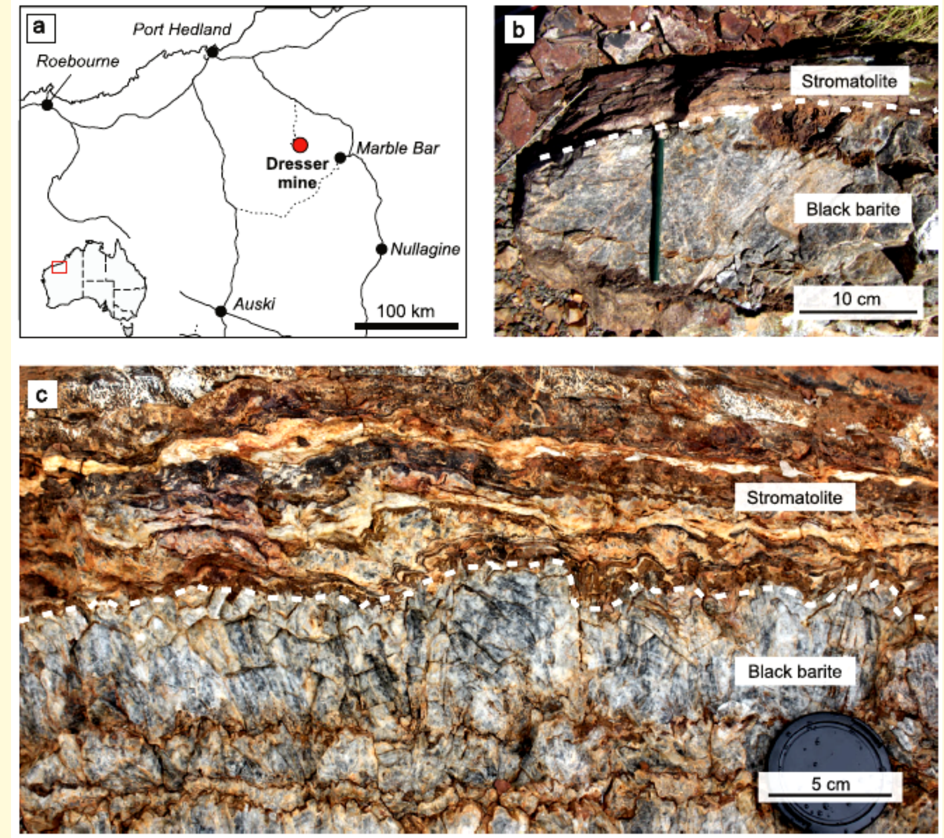
https://doi.org/10.1038/s41467-021-21323-z OPEN

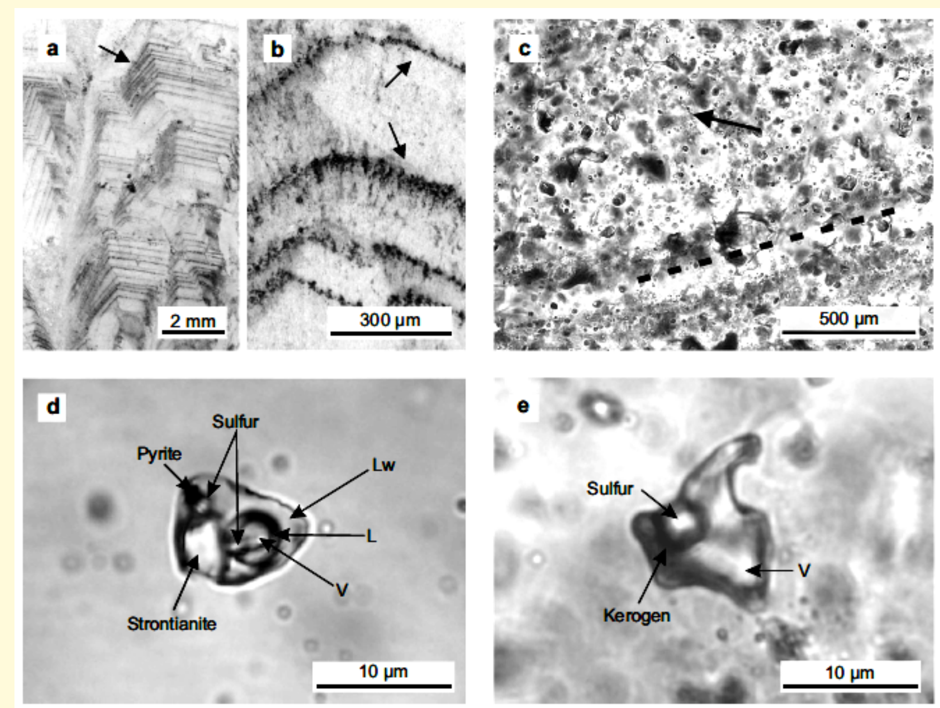
Ingredients for microbial life preserved in 3.5 billion-year-old fluid inclusions

Helge Mißbach[1,6✉], Jan-Peter Duda[1,2,7], Alfons M. van den Kerkhof[3], Volker Lüders[4], Andreas Pack[5], Joachim Reitner[1,2] & Volker Thiel[1]

This paper, published in Nature Communication (2021), reports the existence of indigenous organic molecules and gases in primary fluid inclusions in ca. 3.5-billion year-old barites from the Dresser Formation, in the Pilbara Craton, (Western Australia). The compounds identified include H_2S, carbon mono and disulphide (COS, CS_2), CH_4, acetic acid (CH_3COOH), organic (poly-)sulfanes, and thiols (organsulfur) all important nutrients to sustain sulfur and methanogenic metabolisms. These nutrients may have been delivered by hydrothermal fluids. This paper shows that "*early Archaean hydrothermal fluids contained essential primordial ingredients that provided fertile substrates for earliest life on our planet*".

Black barites from the Dresser mine (top right images) host primary fluid inclusions trails parallel to barite growth bands (black arrows on photo **a**, **b,** and dashed line in **c**). The image **c** shows a minor secondary inclusion trail (black arrow). Thick section image **d** shows an aqueous carbonic-sulfuric fluid inclusion containing three volatile phases (including H_2S), plus pyrite, native sulfur, and strontianite ($SrCO_3$) as solid phases. **e** Thick section image (transmitted light) of a non-aqueous fluid inclusion bearing a vapour phase, native sulfur, and kerogen. These fluid inclusions are usually rich in H_2S. V: vapour/gas, Lw: liquid H_2O, L: other liquid (e.g., CO_2). Organic compounds and gases preserved in these primary fluid inclusions could have provided a substrate to primordial microbial life in the Dresser Formation.





EARLY EARTH GEODYNAMICS

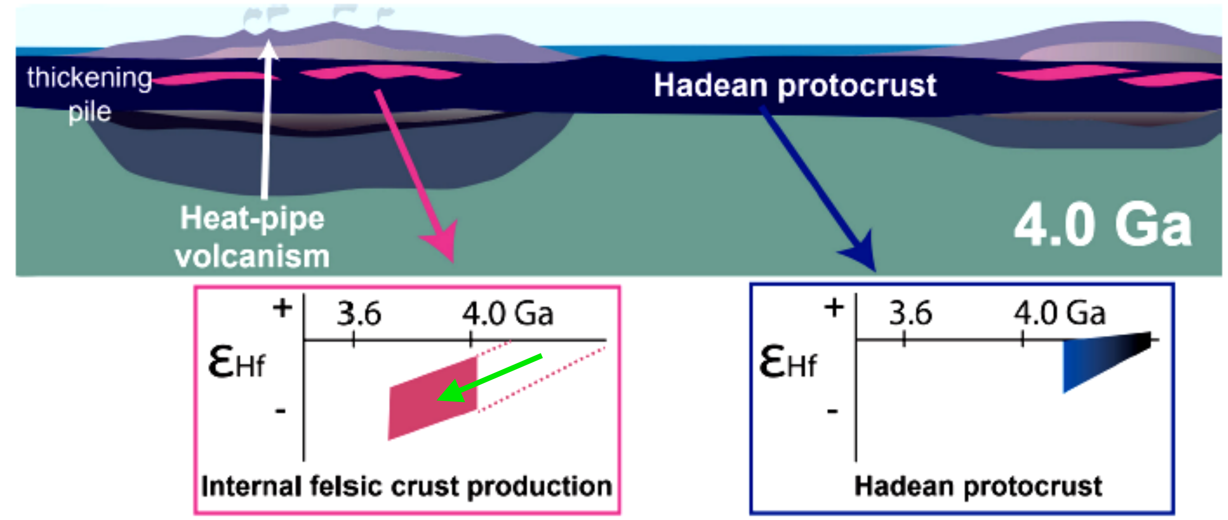
- Intracrustal recycling
- Sagduction
- Geodynamics of the lid
- Plume tectonics
- Protocontinents and subduction
- Dual-mode Archean geodynamics

The present-day Earth geodynamics includes plate tectonics. Active zones of plate tectonics are characterised by subduction zones evidenced by 1/ high-pressure low-temperature metamorphism (i.e., eclogite), 2/ paired low-pressure, high-pressure metamorphic melts, 3/ ophiolites (i.e., oceanic lithosphere transported over a continental margin, or another oceanic lithosphere), and 4/ andesitic magmatism. The fate of these subduction zones is to be dismembered, metamorphosed, and deeply transformed by magmatism during their accretion into collisional orogens, the erosion of which leaves little trace of these subduction zones. Hence, looking for proxies of plate tectonic processes on that remains of the primitive continents is challenging.

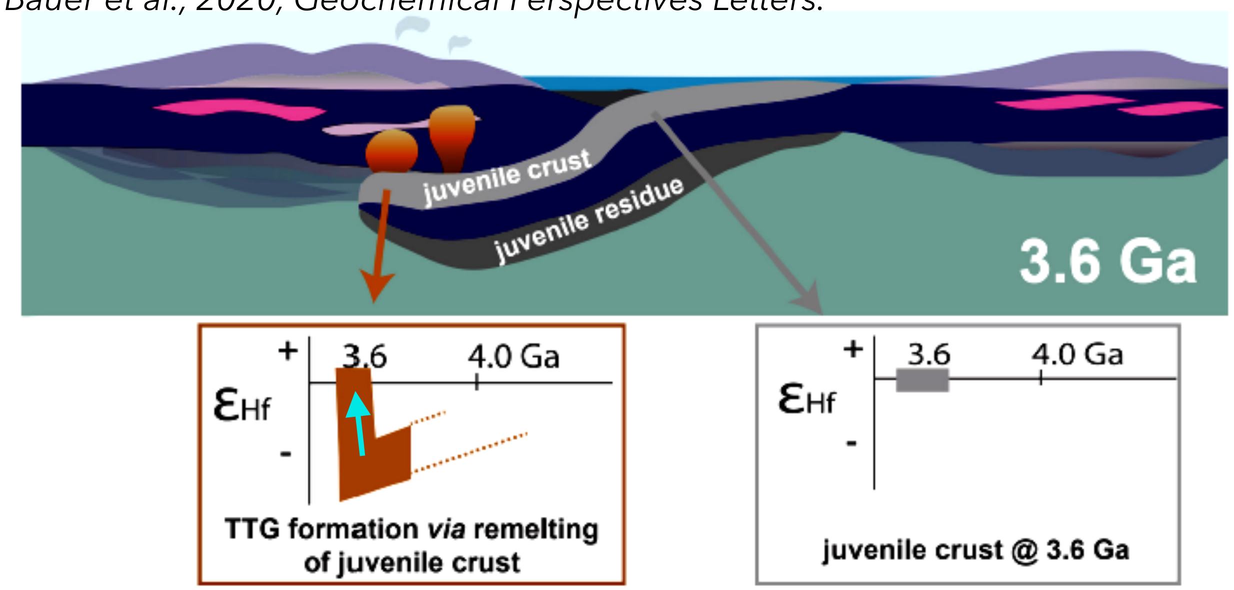
Nevertheless, the geological record of Archean cratons with their unique association of rocks including komatiite-bearing greenstone belts and Tonalite-Trondhjemite-Granodiorite (TTG) suite, and unique architecture of either TTG domes and greenstone basins, or continental scale strike-slip shear zones pointing to a dominant transcurrent tectonic regime, bears little resemblance with that of modern continents. In addition, due to the strong dependence of rock strength to temperature, the hotter lithosphere of the primitive Earth may have deformed differently.

Here we consider a number of global geochemical shifts that point towards possible transition in the geodynamics of the Earth.

- **Intracrustal recycling until 3.8 Ga -** Felsic crust is not directly extracted from the mantle. Partial melting of the mantle leads to the production of basaltic melts, which due to their buoyancy reach the Earth's surface. Felsic crust is produced by the partial melting of these basalts. From 4.4 Ga to 3.8 Ga, the decreasing εHf(t) in zircon from old igneous felsic crust suggests the recurrent partial melting in a closed system of material derived from an ancient basaltic crust (e.g., Bauer et al., 2020). The lack of new contribution from mantle magma suggests that the extraction of the crust before 3.8 Ga left the upper mantle strongly depleted and therefore unlikely to melt, until it was refertilized.

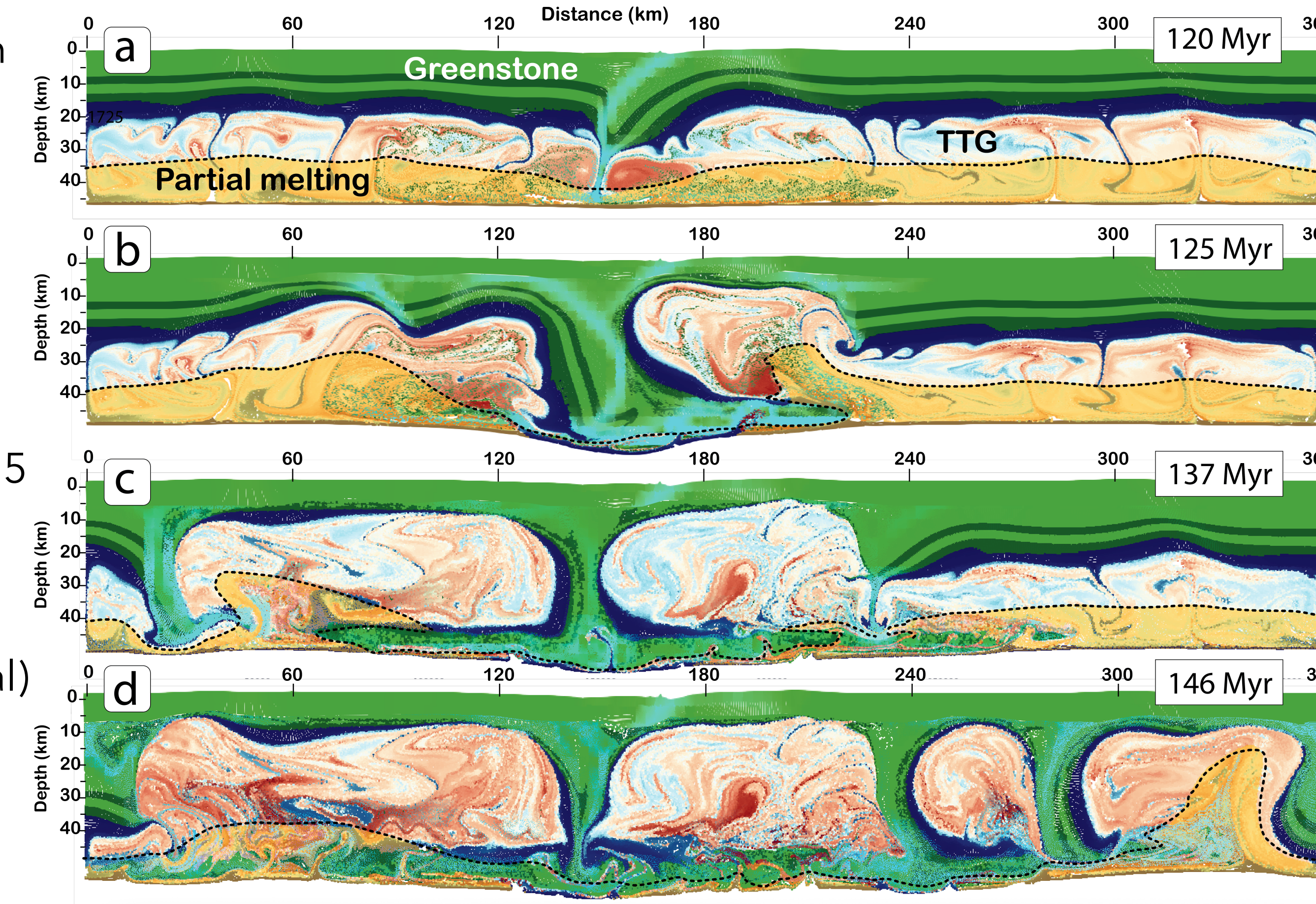


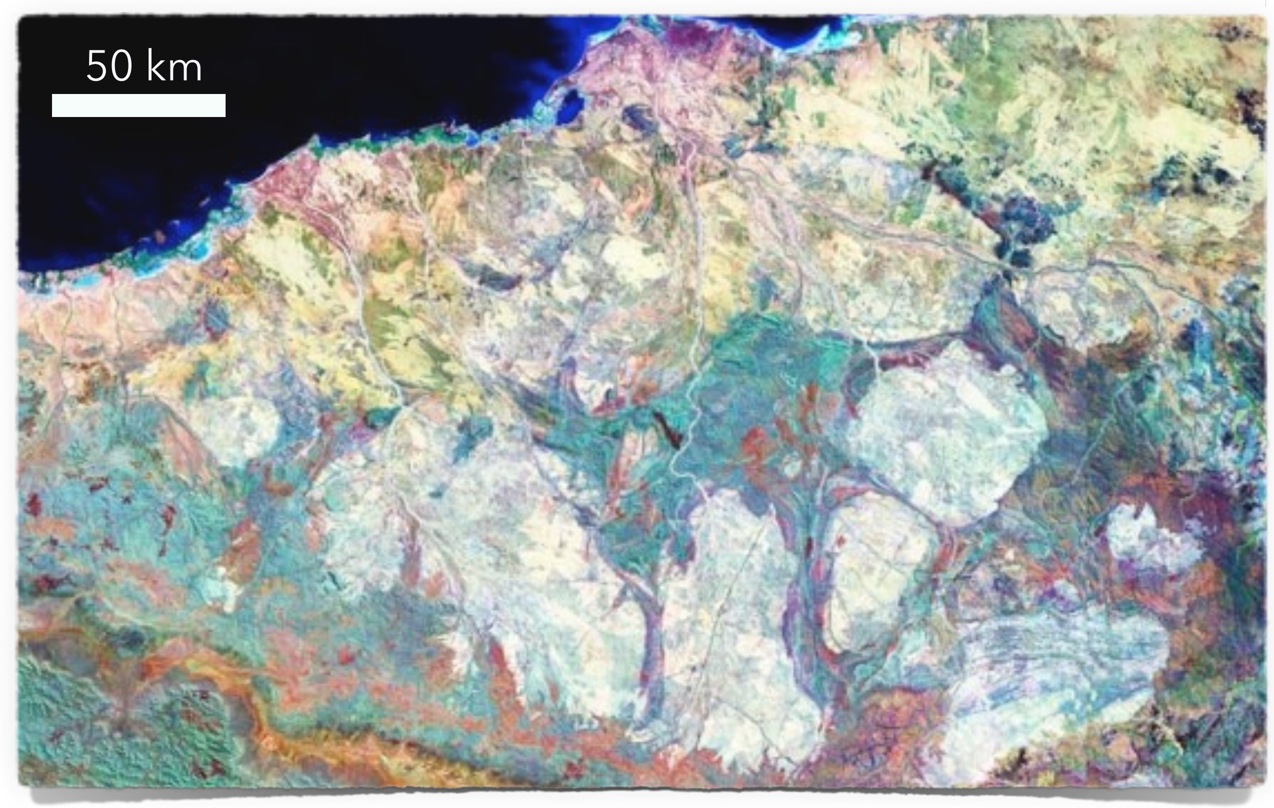
Bauer et al., 2020, Geochemical Perspectives Letters.



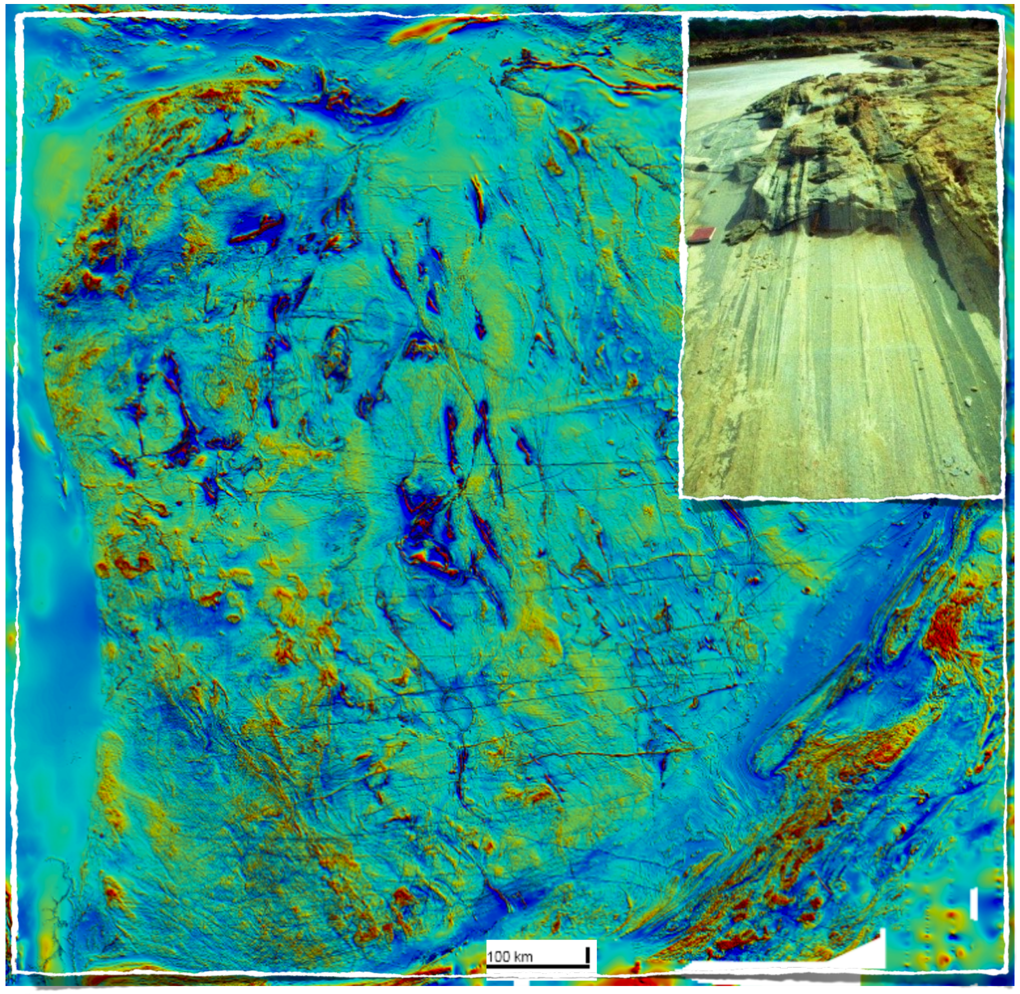
Beginning at 3.8 Ga, the increasing εHf(t) in zircon supports an enhanced contribution of a juvenile basaltic crust - extracted from a depleted mantle - in the production of felsic magmas. The renewal of mantle magmatism at 3.8 Ga could have followed to the progressive convective mixing of the depleted mantle with the deeper, fertile (i.e., undepleted) mantle. To explain this shift, it is tempting to invoke the initiation of a plate tectonic regime involving subduction and melting of the oceanic basaltic crust and sedimentary rocks, as proposed in the sketch above. However, this scenario is in apparent conflict not only with the lack of a corresponding $\delta^{18}O$ shift in zircon, but also with the secular evolution of Archean fine-grained sedimentary rocks showing limited emergent felsic continental crust before ~3.0 Ga. One needs a process that can explain the recycling of basaltic crust without leading to a significant increase in the $\delta^{18}O$ in crustal magmas.

- **Sagduction** - Archean crust consists of an association of volcanic rocks with minor sedimentary rocks called greenstone belts (density 3000 kg.m^{-3}), structurally in contact with underlying felsic rocks from the Tonalite-Trondhjemite-Granodiorite suite (TTG, density 2740 kg.m^{-3}). The geochemistry of TTG suggests that many were formed by melting of hydrated mafic sources at 25 to 50 km depths. Numerical experiments show that small lateral changes in the thickness of greenstone belts can drive their sagduction (i.e., gravitational burial) and the coeval exhumation of partially melted crust into gneiss domes. This process explains well the characteristic dome-and-basin architecture of some Archean cratons such at the Pilbara (WA, bottom right). As intense volcanism renewed around 3.8 Ga, sagduction at the time involved the recycling of juvenile mafic rocks into TTG magmas. This process could explain the shift towards higher εHf(t) in TTG zircon from 3.8 Ga onwards. Compared with modern subduction zones, and in the absence of significant erosion, we can reasonably expect that the volume of buried felsic sediments (a high δ^{18}O reservoir) was limited during sagduction, which could explain the lack of a corresponding shift towards higher δ^{18}O in magmatic zircon.



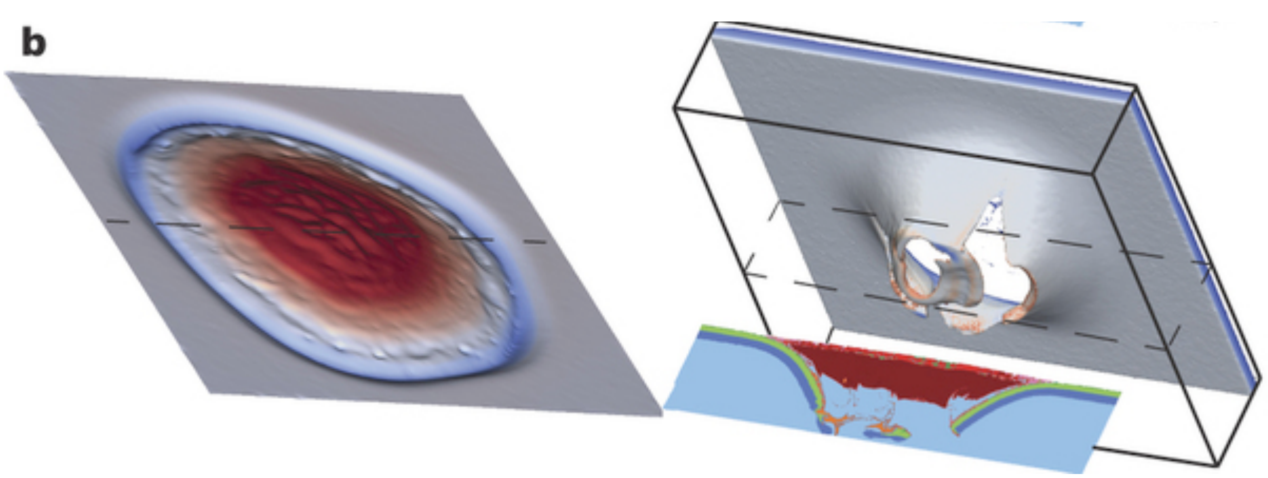


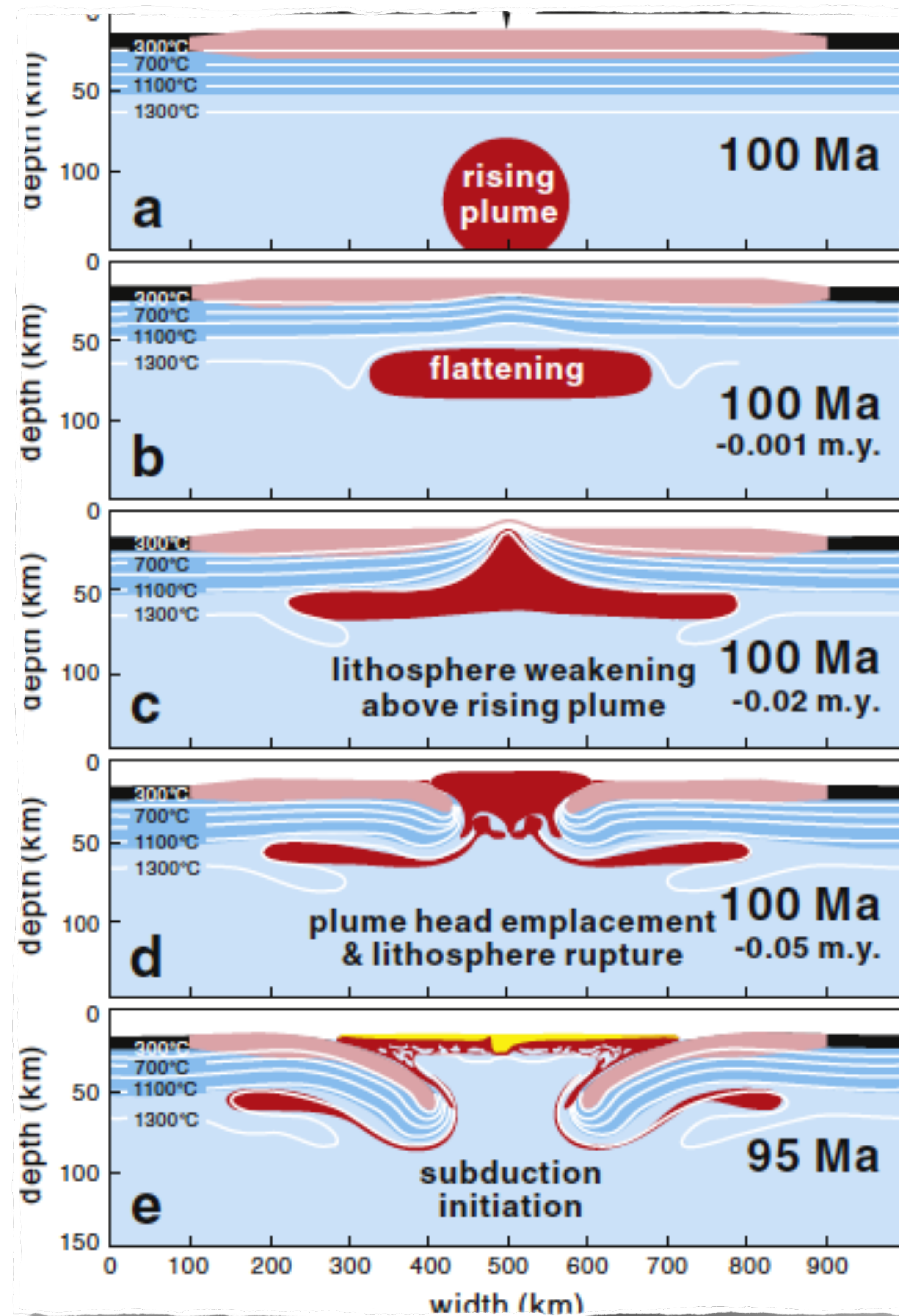
- **Geodynamics of the lid**. Although sagduction can explain Archean crust dominated by TTG domes and greenstone belts (e.g., Pilbara craton), Archean cratons dominated by strike-slip tectonics (e.g., Yilgarn Craton, right) suggests development under conditions of bulk shortening. This requires the existence of horizontal convergence. During Archean times, the presence of komatiites (MgO>18%) suggest that the mantle was 100 to 250 °C hotter than today. On a slowly cooling Earth, the geodynamics of the lithosphere–convective mantle system is expected to go through several regimes due to the strong dependence of rock viscosity with temperature.
  In numerical experiments that consider a mantle >150 °C hotter, the mantle vigorously convects underneath a cooler, rigid, and stable “stagnant lid”. In the stagnant lid geodynamic regime, the lid and the convective mantle are mechanically decoupled. With secular cooling, the lid becomes progressively coupled to the convective mantle, and the stagnant-lid regime transitions to a “mobile-lid” regime, as convective stresses locally overcome the lid’s yield stress (see rheology of rocks below).
  Under a weak mechanical coupling, numerical experiments of mobile-lid systems produce only diffuse surface deformation, and at most, transient episodes of subduction. The transition to a sustained plate tectonic regime, a particular mode of mobile-lid tectonics where deformation is strongly localized at plate boundaries, may have been achieved through further secular cooling and strengthening of the lid, as well as enhanced gravitational forces acting at continent–ocean boundaries in response to the deepening of the seafloor…



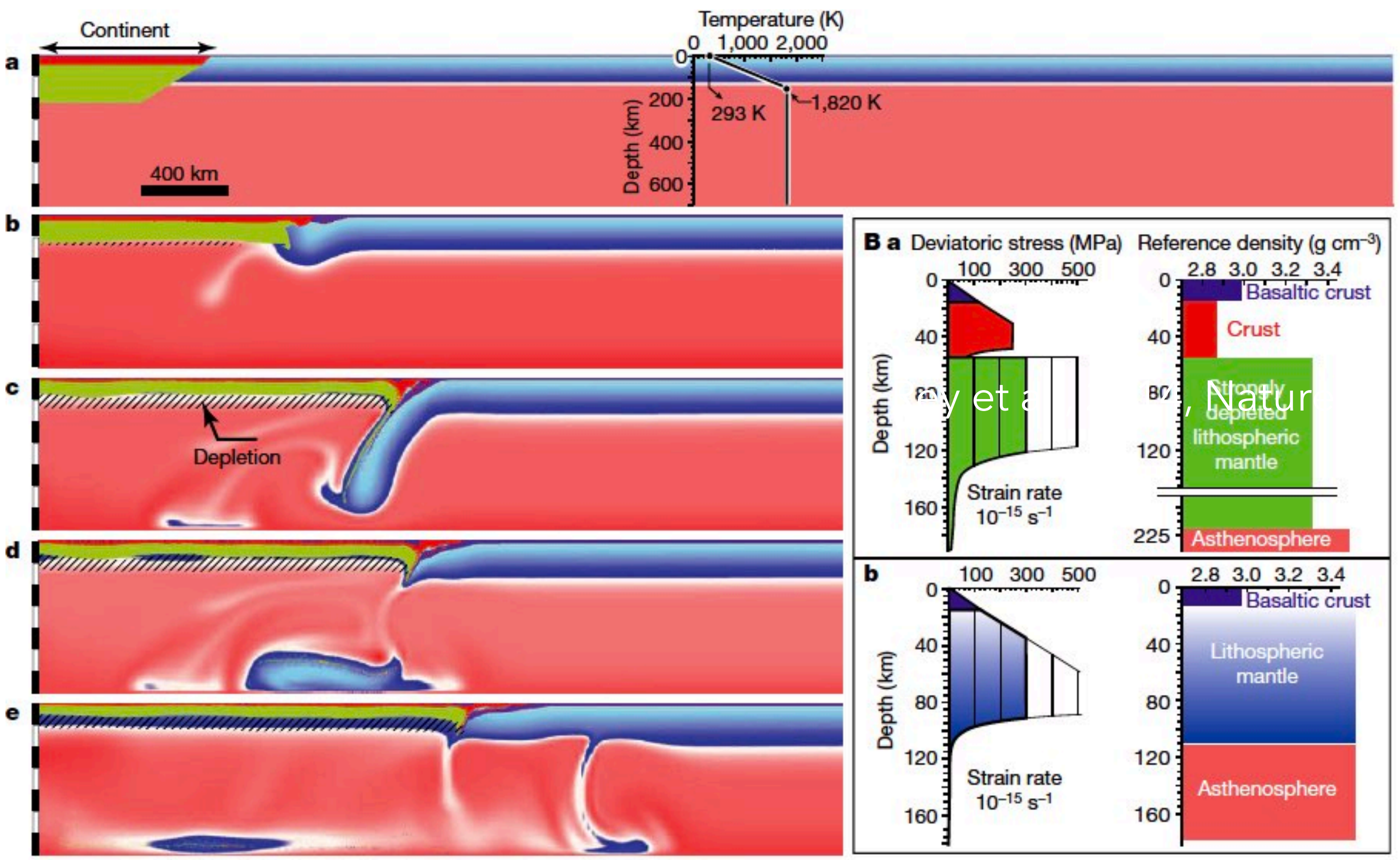
Rheology of rocks: Hot rocks flow under low stresses, while cold rocks remain rigid, only breaking when a stress threshold (the yield stress) is reached. A strong temperature and stress dependence of viscosity with a stress threshold is required to achieve mantle convection coupled with plate tectonics.

- **Plume tectonics -** Numerical experiments show that the initiation of subduction, and the transition from a stagnant lid to a mobile lid regime, can be achieved via impact of a plume head ~200 km in diameter impinging the base of the lid, and eventually piercing through and destabilising the entire lid (Gerya et al. 2015). This process has been called "plume tectonics". The prevalence of plumes in the Archean is supported by the fact that Earth, at the time, was hotter. It is also supported by the presence of komatiites (MgO>18%) and komatiitic basalts (12 % < MgO < 18 %), which requires larger amount of partial melting, typically achieved when the mantle crosses its solidus at depth > 120-150 km.
However, as the plume reaches the Earth's surface, one can calculate that it would produce a 50–60 km thick basaltic plateau in a few million years. Neither of these predictions seem to fit the geological record as greenstone belts are at most 25 km thick and were emplaced over many tens of millions of years.

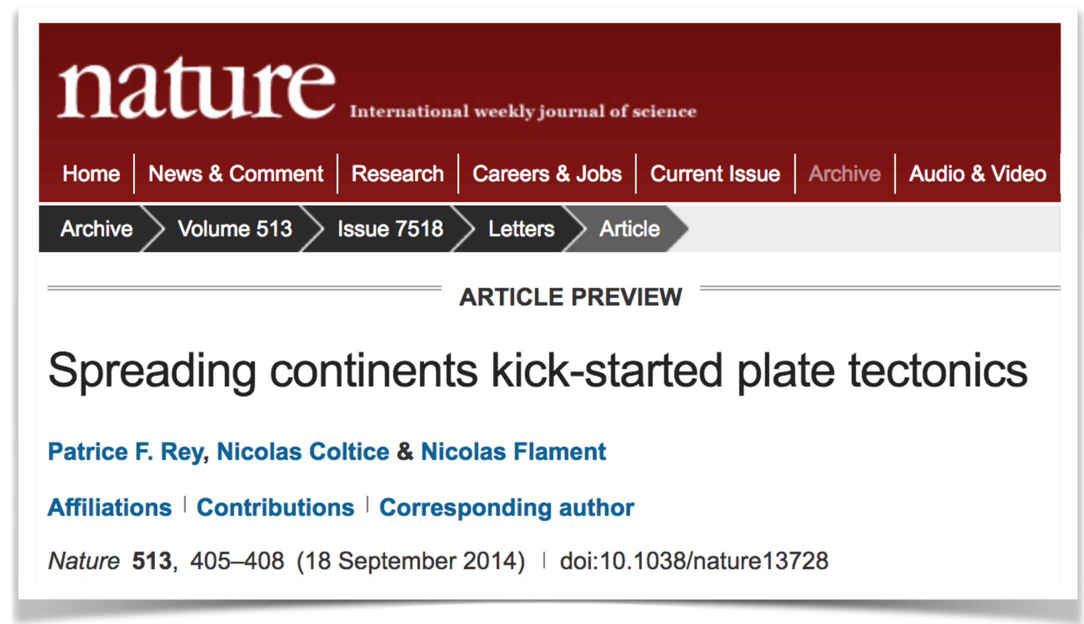




- **Protocontinents and subduction.** In the Archean, the lithospheric lid was compositionally distinct than its modern counterpart. This lid hosted protocontinents that evolved into our present-day cratons. The presence of buoyant protocontinents embedded in the lid is a source of important horizontal gravitational stresses, that needs to be taken into consideration.

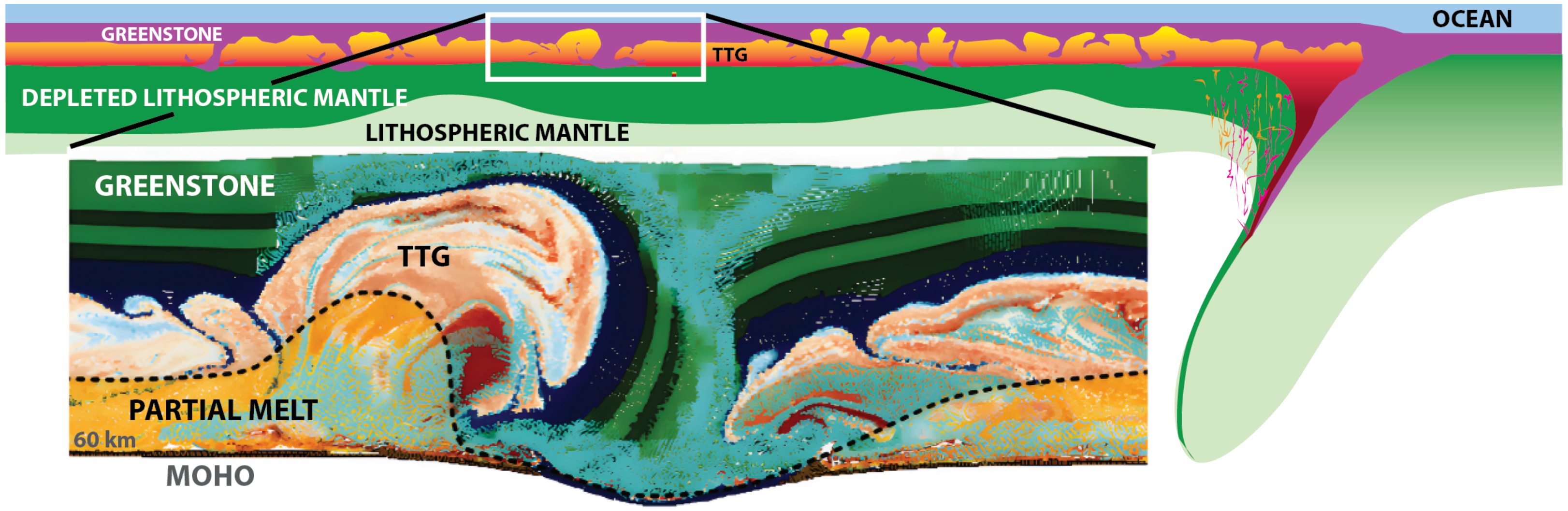


The numerical experiment on the right show that these hot, weak, and buoyant protocontinents (crust in red, depleted lithospheric mantle in green) could have spread under their own weight, forcing the initiation of subduction and the destabilization of the adjacent oceanic lid (in blue). This model predicts that the gravitational spreading and thinning of the protocontinent induces polybaric decompression melting of the underlying fertile mantle (in dark pink). This explains the broad range of MgO content documented in greenstone belts. By varying mechanical parameters within realistic limits, a range of behaviours is obtained from stable spreading of continents in a stable mobile lid regime, through continental rifting accommodated by transient episodes of subduction. These models suggest that protocontinents could have kick-started transient episodes of subduction, until plate tectonics became self-sustained.



- **Dual-mode Archean geodynamics -** In summary, the extraction of a primordial mafic crust, before ~4.3 Ga, left a melt-depleted, Mg-rich, buoyant upper mantle less prone to partial melting. Before 3.8 Ga, this primordial and thick mafic crust (>50 km) evolved into TTG via recurrent partial melting in a largely closed system, explaining decreasing εHf(t) in zircon from 4.4 to 3.8 Ga. The progressive mixing of the depleted and fertile mantle enabled the resumption of volcanism and the accumulation of greenstone basalts from ~3.8 Ga onwards. The shift towards higher εHf(t) of zircon beginning at ~3.8 Ga would record the onset of sagduction, as well as transient subductions at the edges of protocontinents.

These processes did not affect the $\delta^{18}O$ of zircon due to i/ limited sediments involved during sagduction and limited sediments supply at the margins of flat and flooded protocontinents, ii/ short-lived subductions restricting the amount of subducted material, and iii/ fluid– rock interaction at temperatures > 200 °C during sagduction and along hotter subduction zones.



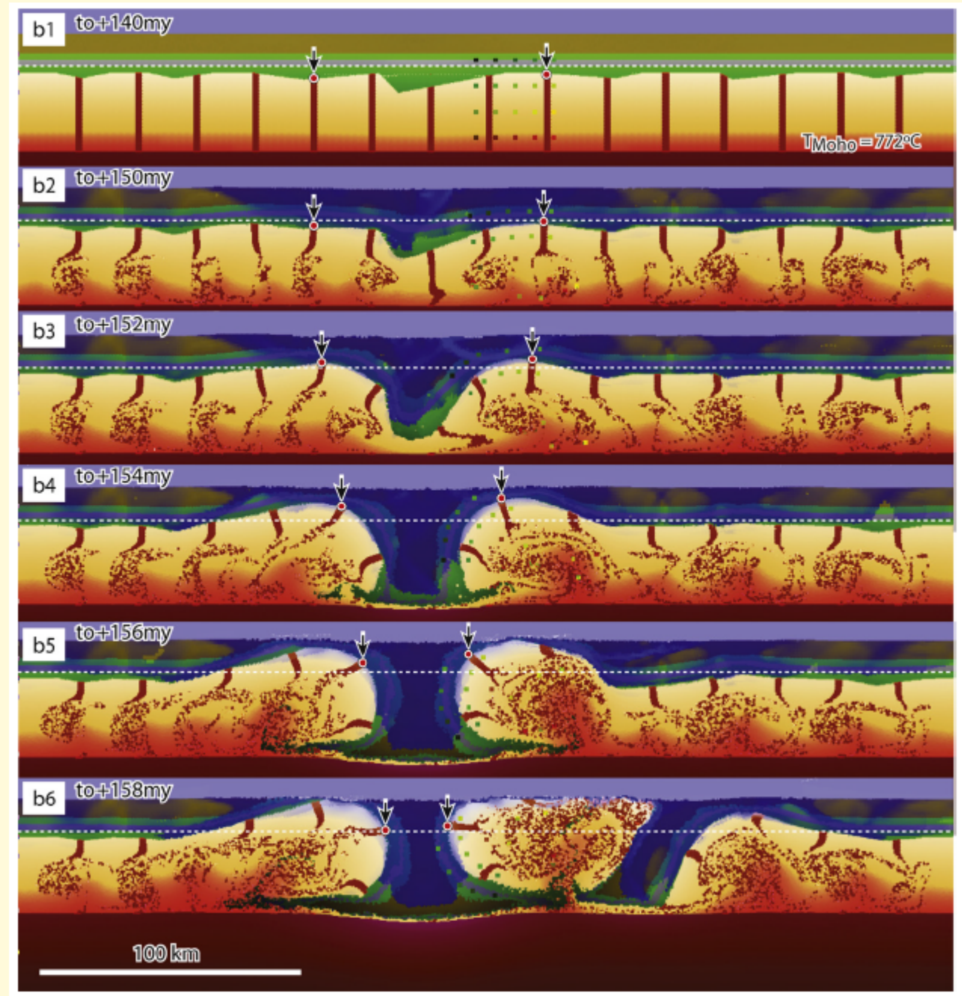
Spreading protocontinents could have triggered polybaric decompression melting, explaining the compositional range of greenstone basalts.

Until ~3.0 Ga, the felsic crust was largely isolated from the surface by ongoing volcanism and a near global ocean. Protocontinents would have slowly emerged from 3.0 Ga onwards due to secular cooling and the resulting deepening of the seafloor. The strengthening of the lithosphere would have enabled the formation of high mountains, enhancing erosion and sediments supply, and allowed for longer episodes of subduction, shifting the $\delta^{18}O$ in arc magmas.

Weathering and erosion would have exhumed the felsic crust from underneath the greenstones, and coupled the newly exposed TTG crust to the Earth's ocean/atmosphere system. Eventually, secular cooling strengthened the crust and inhibited the development of greenstone belts, and sagduction was eliminated from Earth's geodynamic repertoire.

NotebookLM “Deep Dive” podcast …

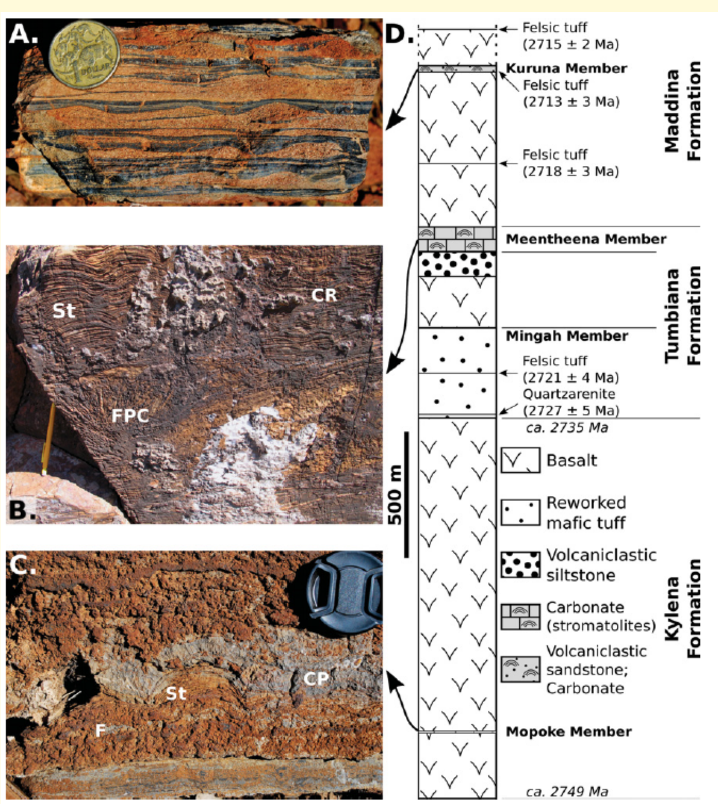
Numerical experiment of sagduction

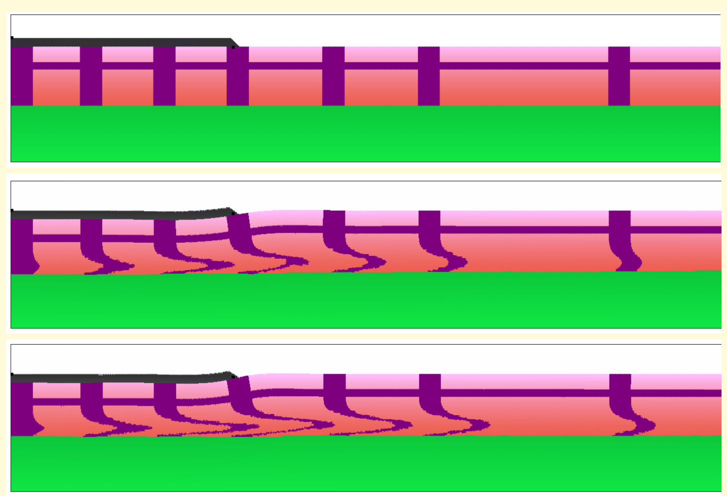


Lower crustal flow kept Archean continental flood basalts at sea level

Nicolas Flament[1,2]*, Patrice F. Rey[2], Nicolas Coltice[1], Gilles Dromart[1], and Nicolas Olivier[1]

GEOLOGY, December 2011



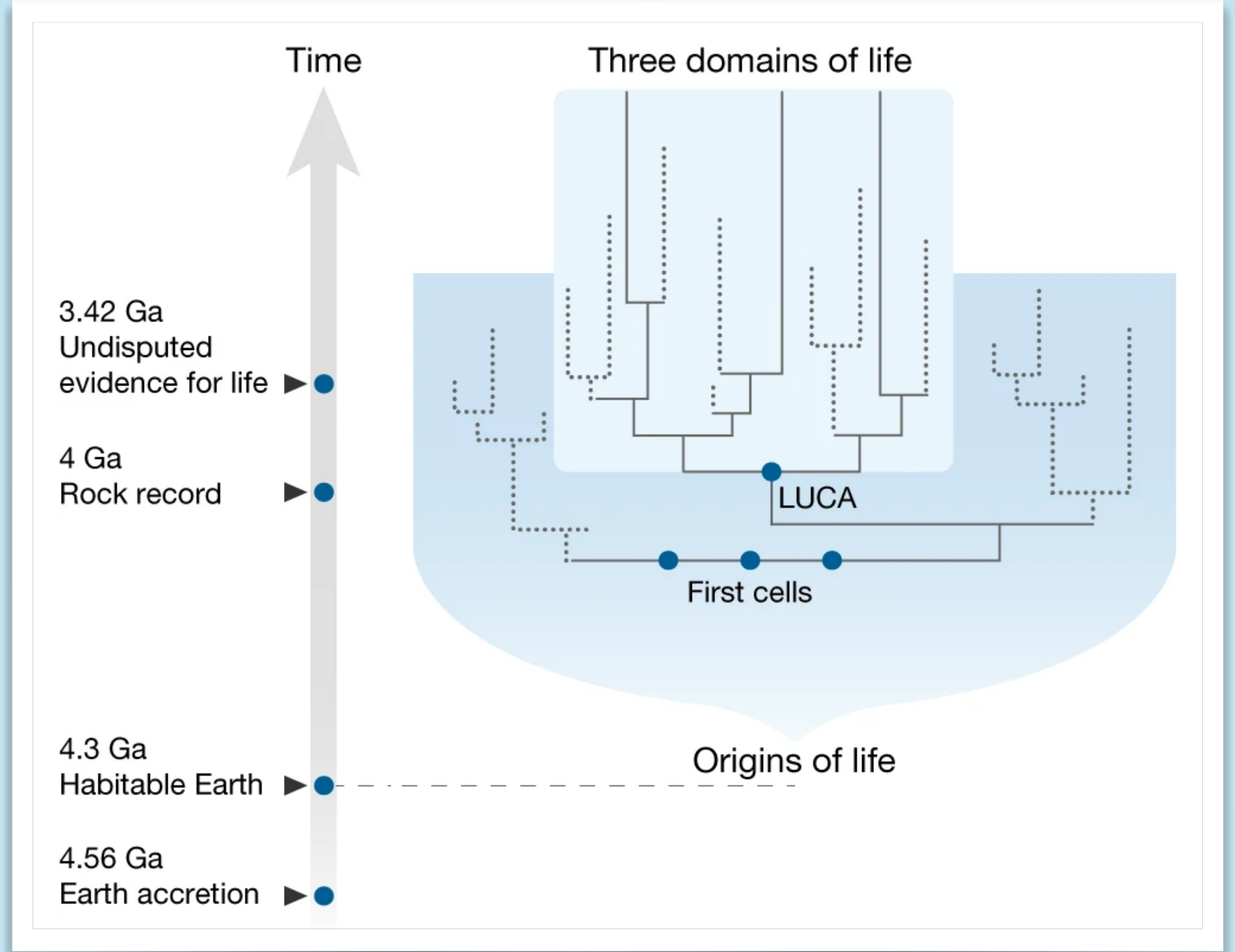


The Meenthena centrocline in the east Pilbara is an example of Neoarchean basin that accumulated kilometres of volcano-sedimentary rocks with regular intervals showing evidence of deposition in a shallow water environment (see photo on the left)., including ripple cross-laminated grainstone (see photo on the right)

EARLY LIFE

- Hadean biogenic carbon
- Hydrothermal vents
- Microbial mats and stromatolites
- Extremophile and early life
- The tree of life
- The rise of eukaryotes

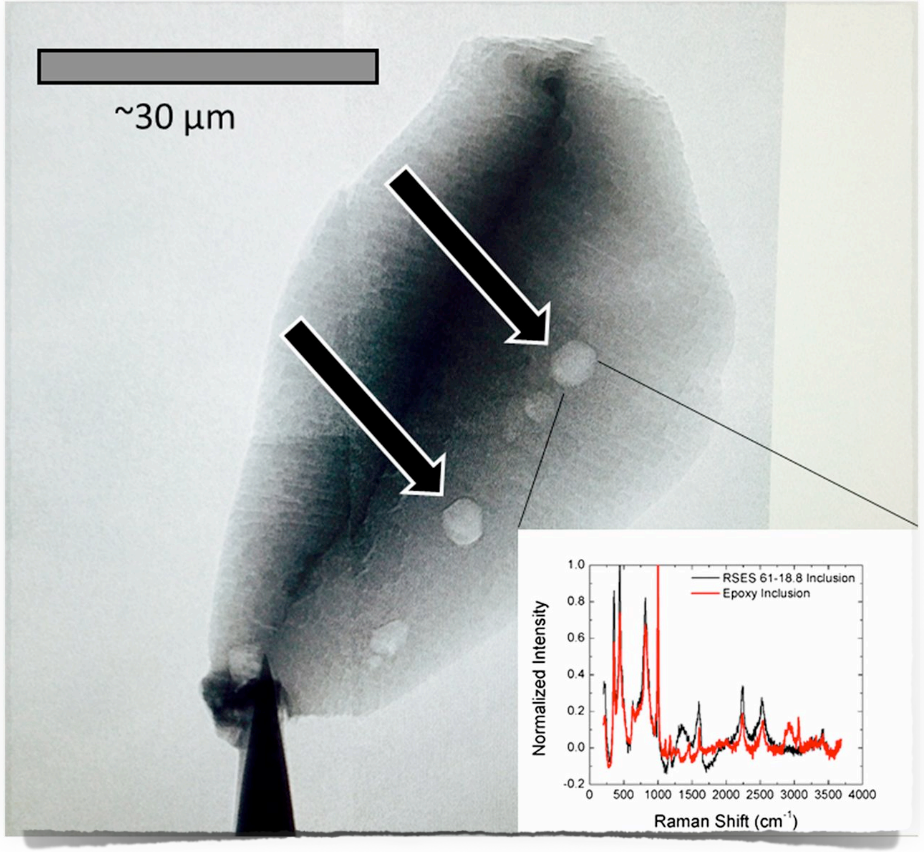
Conditions suitable to life may have developed in the Hadean. Yet, the oldest known fossils are only 3.42 Gyr old, which suggests that heavy bombardment by asteroids and comets, and ongoing volcanic activity may have erased most of the earlier record. In addition, in the absence of ozone layer, UV light were not filtered damaging living cells at molecular level. Although life was slowed down for a billion years, it was part of the early Earth's environment, and didn't go away until more favourable conditions were established.



Javaux, 2020, https://www.nature.com/articles/s41586-019-1436-4

Hadean biogenic carbon ? - In the absence of clear microfossils before 3.7, and most probably before 3.4 Ga, looking for trace of life in the Paleoarchean, Eoarchean and Hadean is based on identifying biomarkers in the form of bio isotopic signals, and biomolecules. The challenge in this quest is to make sure that the material analysed has not been contaminated by younger bio-materials. One of the criteria used to identify a pristine source of material is that it must be included in a non-porous, very resistant material, devoid of evidence of fractures. It helps if the host of the bio-material can be accurately dated.

There is nothing more resistant than zircon, which also can be easily dated. Zircon grows in magma, in which remnant of ancient biogenic carbon can be preserved as tiny inclusions a few micrometers in size. Biogenic carbon (carbon manufactured by biological processes) is characterised by high $^{12}C/^{13}C$ isotopic ratio. This is because light carbon (^{12}C) is preferentially incorporated during carbon fixation. Despite experiencing temperatures in excess to 900°C, these carbon inclusions preserve their original isotopic composition, and therefore the potential fingerprint of ancient life forms. The ages of the famous detrital zircons from Jack Hill (WA) range from 3.3 Ga to 4.4 Ga. One of them, dated at 4.1 Ga, contains graphite inclusions with a $\delta^{13}C_{PDB}$ of -24±5‰, consistent with a biogenic origin which typically range from -15‰ and –35‰ (Bell et al., 2015, Earth, Atmosphere and Planetary Sciences).

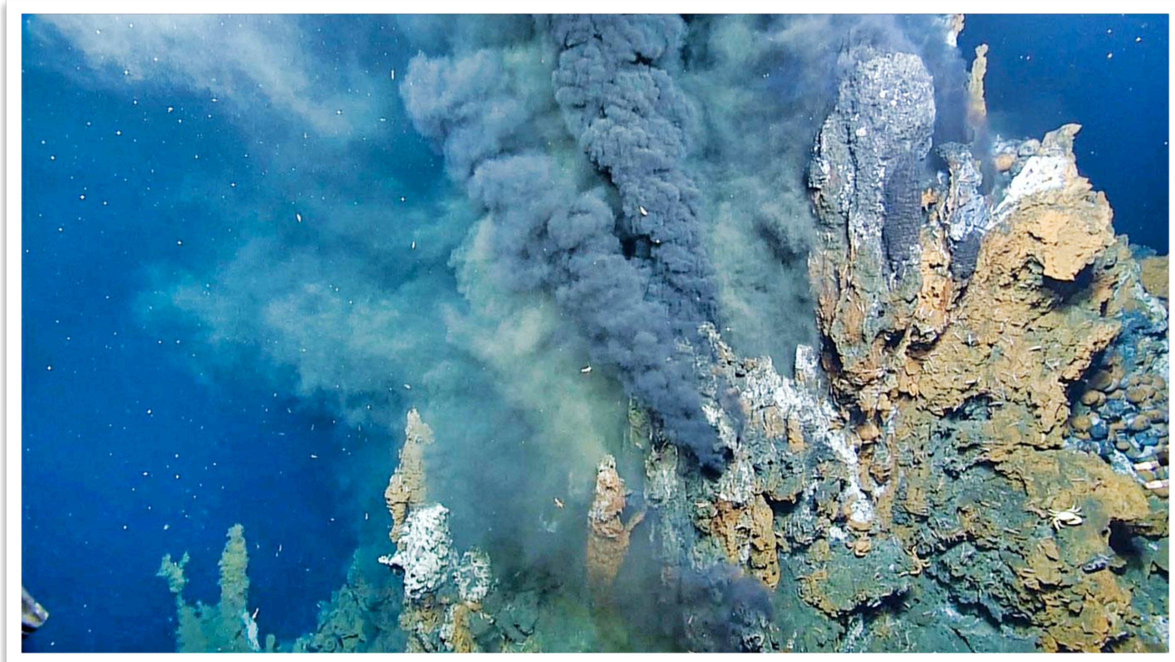


X-ray image of a zircon with graphite inclusion. (Inset) Raman spectra in red (Bell et al., 2025)

Though all biogenic carbon is enriched in light carbon, not all light carbon isotopic signature have a biogenic origin. Light $\delta^{13}C$ signatures can be the outcome of abiogenic processes, including the Fischer-Tropsch mechanisms, or that of the incorporation of meteorites (+68‰ to -60‰ $\delta^{13}C$).

Hydrothermal vents - Until the 2.4 Ga great oxidation event, life could not take hold on ocean's photic zone or on emerged lands. Hot hydrothermal vents on flooded continents or oceanic environments provided nutrients and energy for life to take hold. These environments still exist today in the form of acidic hot springs and deep-sea hydrothermal vents, providing modern analogs to Earth's early ecosystems.

On present-day Earth and away from its photic zone, hydrothermal vents support colonies of chemosynthetic bacteria and archaea that are at the bottom of the food chain supporting a diversity of organisms. These chemosynthetic bacteria and archaea are the outcomes of a chain of physico-chemical processes producing prebiotic molecules, which polymerised into long chains or vesicles, and eventually led to the formation of protocells, and living cells.



Hydrothermal vent on the Niua underwater volcano in the Lau Basin, southwest Pacific Ocean. Copyright: U.S. Geological Survey/Schmidt Ocean Institute

Discovered in 1979 on the East Pasific Rise, black smokers release hot (several 100's °C) acidic (pH 2-3) waters enriched in CO_2 and sulfur-bearing minerals that precipitate in contact with cold water on the ocean floor and forming black chimney-like structures. In contrast, white smokers form at a distance from the main heat source, and release silicon, barium and calcium into cooler (70-90°C) and alkaline (pH 9-11) plumes. They contain little CO_2 or H_2S. The temperature and chemical gradients these hydrothermal vents sustain over a long period of time are critical for a range of physico-chemical reactions. These reactions involve a range of reduced chemicals such as H_2, H_2S, CH_4, Fe^{2+}, and Mn^{2+}, and a long list of metals. Reduced sulfide (H_2S) is critical to archaea and bacteria due to its chemical versatility (eight oxidation states from -2 to +6), and molecular similarity to water. It diffuses easily through cells membranes, and provides a major source of energy powering metabolic pathways. Following the GOE, oxidation of sulfide eliminated H_2S as a major energy source.

Elements important to present-day life include carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and phosphorus (P). Injecting this elements in the form of ammonia (NH_3), methane (CH_4), and water vapour (H_20) in an enclosed glass and passing electrical sparks to simulate lightning, the famous "primitive soup" of Miller and Urey (1952) delivered a range of amino acids, the building blocks of proteins.

In 2020, Japan's Hayabusa mission returned samples from the the asteroid Ryugu. On these samples, a range of amino acids were discovered. The asterod Ryugu, as well as Miller and Urey experiment shows that complex compound important to life can be formed from relatively simple chemical systems, and that some of these compound could have been formed in the Solar system, and transported to Earth via meteorites and comets.

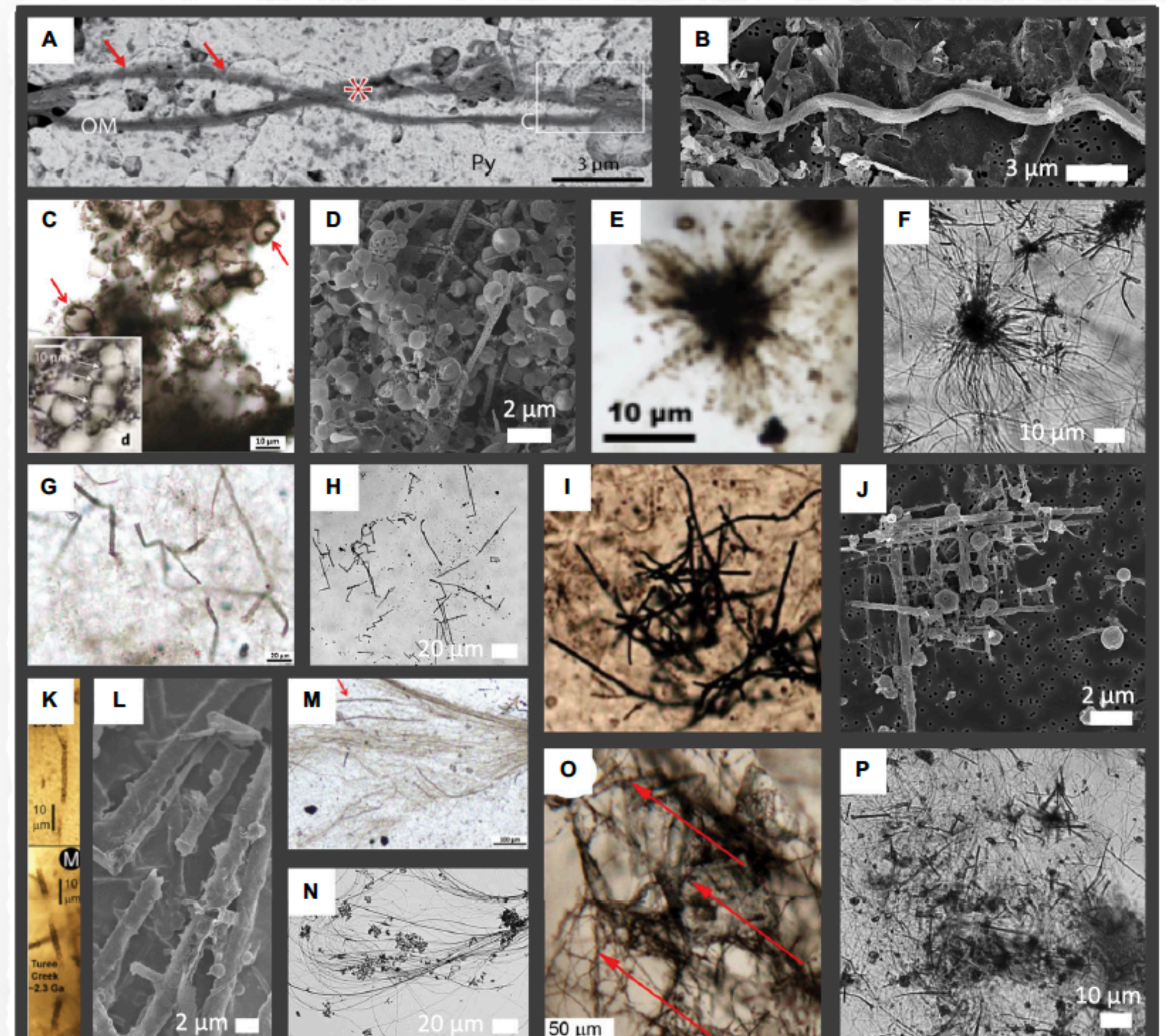


Figure 1. Side-by-side comparison of Precambrian putative organic microfossils and organic biomorphs synthesized in the laboratory. (A) Organic strand from 3.5 Ga Dresser Formation (Western Australia). OM—organic material; Py—pyrite. (C,G) Cluster of spheres (C) and "straw-like" filaments (G) from the 2.4–2.2 Ga Turee Creek Group (Western Australia). Spheres in panel C inset are from the 3.4 Ga Strelley Pool Formation (Western Australia). (E,I) Rosette (E) and cluster of filaments (I) from the 1.9 Ga Gunflint Formation (northeastern North America). (K,M,O) Rigid branching filaments (K), "river" of flexible filaments (M), and cobweb-like network of filaments (O) from the 2.4–2.2 Ga Turee Creek Group. (B,D,F,H,J,L,N,P) Organic biomorphs synthesized in this study. Images adapted from Wacey et al. (2013, 2011), Schopf et al. (2015), Barlow and Van Kranendonk (2018), Javaux and Lepot (2018), and Baumgartner et al. (2019). For descriptions of additional arrows, asterix, letters, and boxes in A, C, K, M, and O, see the original figures.

Archaean are prokaryotic microbes. They are single cells with no organelles, and no nuclei. They are found at modern hydrothermal vents and other extreme environments. The 3.48 Ga Dresser formation (Pilbara, WA) hosts what resembles prokaryotic microfossils in the form of filaments preserved in silica veins. But are they? Traces of ancient microbial life can be chemical or morphological, but their correct identification is particularly challenging as abiotic processes can generate microstructures mimicking prokaryotic cell morphologies and their chemicals (Nims et al., 2021, Geology, Figure 1 on the right).

Microbial mats and stromatolites - Although archaea and bacteria exist as single cells, they form nevertheless colonies in the form of laminated, cohesive microbial mats. These mats form at the interface between different environments (rock/water, rock/air, water/air) where physico-chemical gradients exist. They are held together by slimy substances secreted by the microorganisms, and entangled into a network of filaments. They often involve layers of closely related microorganisms that uses compounds excreted from adjacent layers where other microorganisms dominate. With the development of photosynthesis at around 3.5 Ga, microbial mats could develop away from hydrothermal vents, and use sunlight, a more widely available energy source.

Stromatolites are microbial mats with dome-like shapes often separated by carbonate pillars. The domes are made of biochemical accretion of alternating gray calcite and brown ferrous dolomite (ankerite). They form in shallow water and are build by photosynthetic prokaryotic cyanobacteria, processing H_2O, CO_2 and sunlight to grow organic matter. The layering is the expression of the trapping and binding of sedimentary grains and bio-minerals with the microbial mats. The dome shape is the outcome of cyanobacteria phototaxis behaviour, which drives them toward the source of light to maximise their photosynthetic output key to their survival.

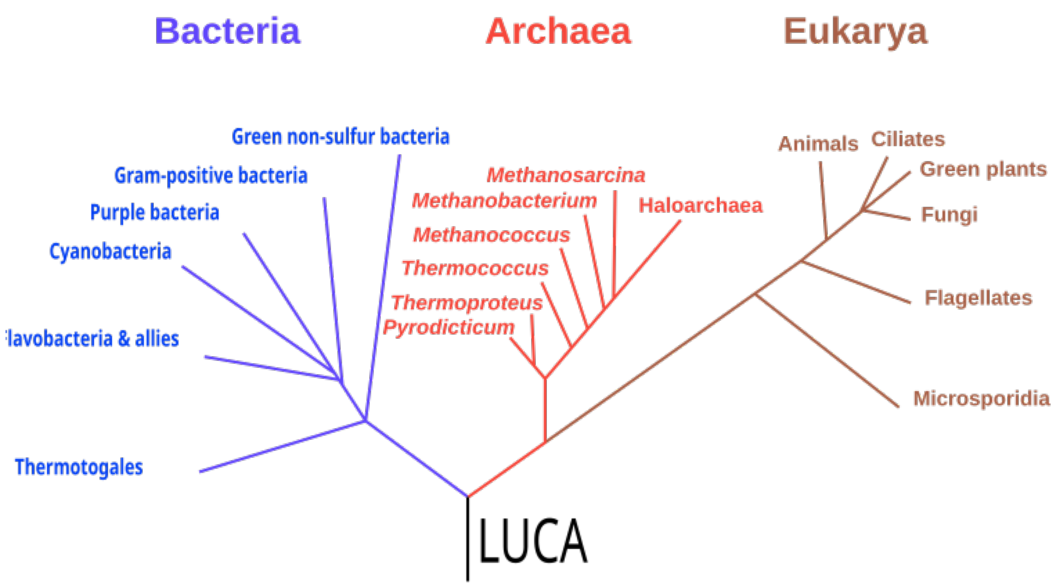
2.74 Ga Stromatolites from the Kylena formation, Pilbara (WA)

Extremophile and early life - Extremophiles are a category of bacteria, archaea, and eucarya that thrives in a large range of extreme environments that would be lethal to most complex organisms. On present-day Earth, they have been found at depth of 10 km (pressure up to 100 MPa), in extreme acidic or basic environment (0 < pH < 12.8), in hot springs (up to 122°C) and frozen sea water (down to -20°C), hypersaline conditions, etc. Extremophiles not only tolerate extreme conditions, they need them for their survivals. These extreme environments, may have been ubiquitous during the Hadean and Archean Eons, and there are strong evidence that some extremophiles are genetically close the the Last Universal Common Ancestor.

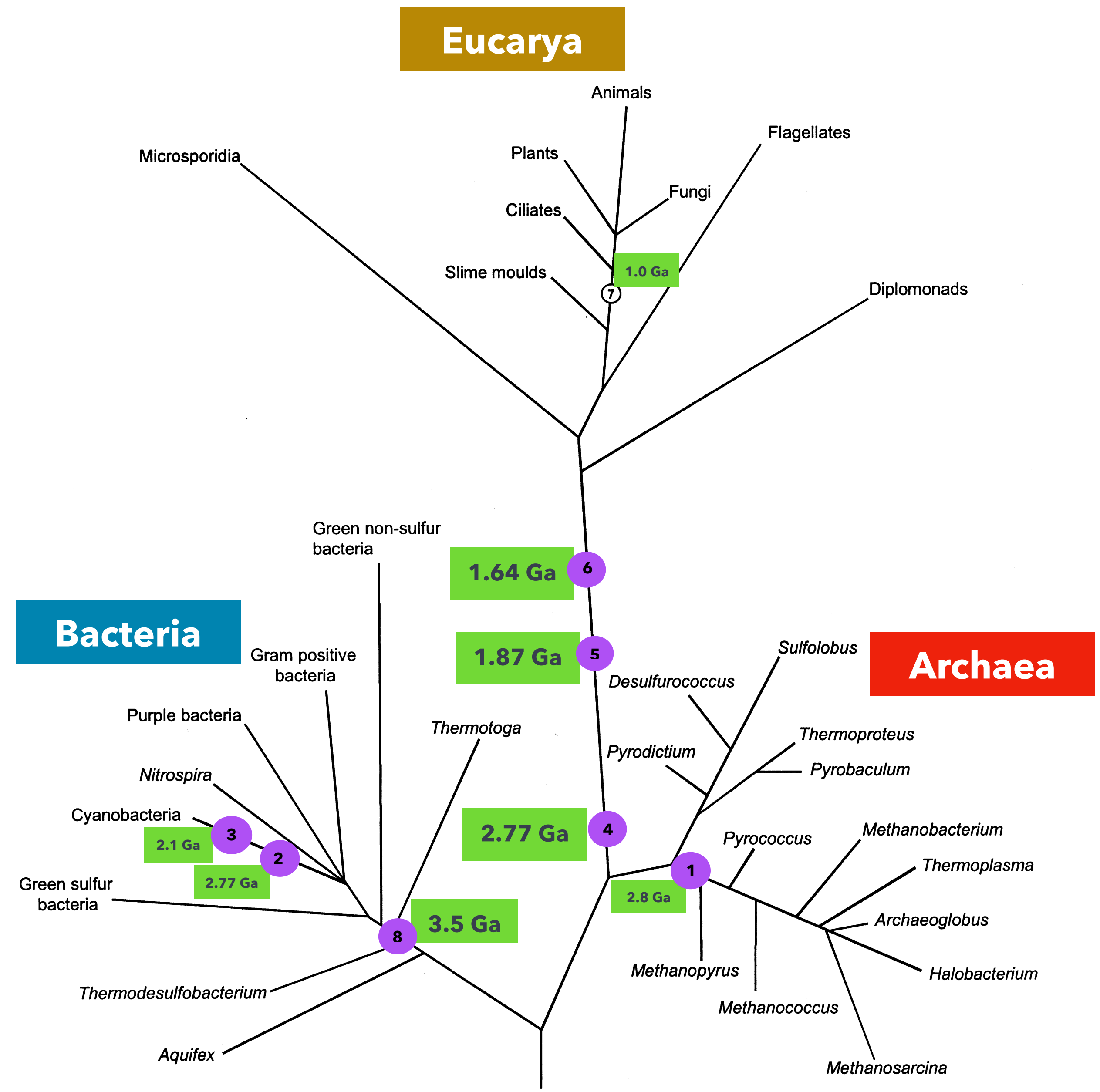
Grand prismatic spring, Yellowstone National Park.

While no fossil evidence of LUCA exists, the biochemical similarities that exist amongst bacteria, archaea, and eucarya makes its existence most likely. Research on the specifi c metabolic pathways used by the Last Universal Common Ancestor (LUCA) helps understand its environment. If LUCA was a chemoautotroph, it might have relied on naturally occurring hydrogen and carbon dioxide, but it probably didn't live in isolation, as its processes would have created opportunities for other life forms.

LUCA may have thrived in two main places: deep-sea hydrothermal vents, which provided H_2, CO_2 and sulfur, or on the ocean floor in the vicinity of volcanic centres. Evidence suggests LUCA adapted to these high-temperature environments, which would also have offered protection from harmful radiation.



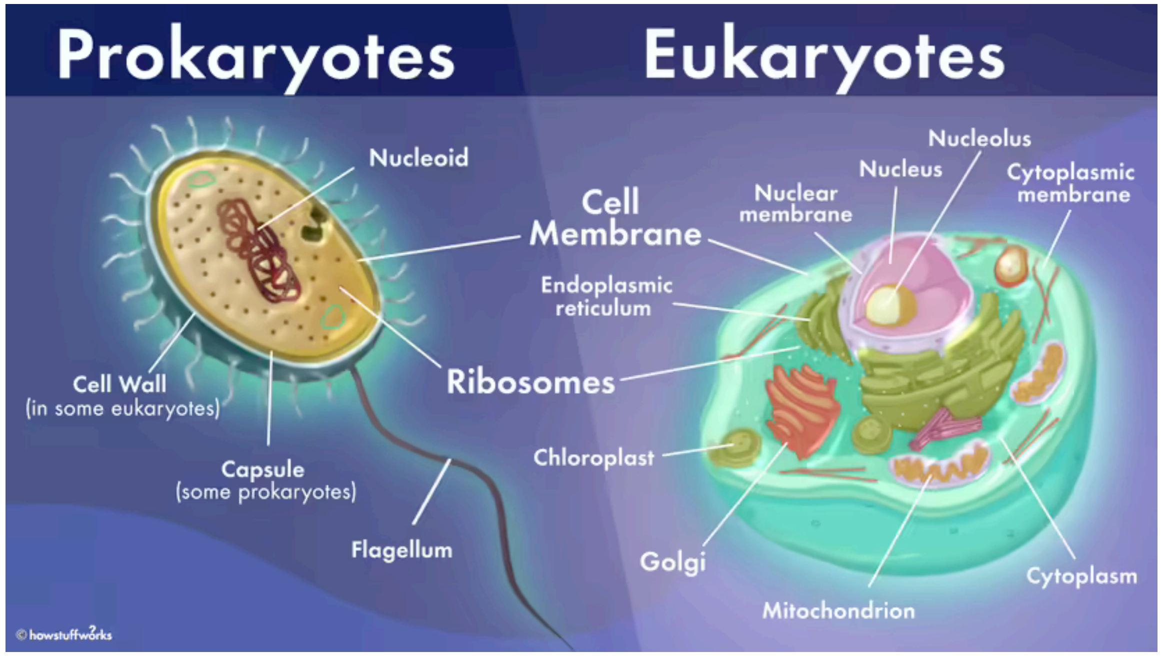
Tree of life with minimum ages of selected branches (Brocks et al., 2003).



- 1/ Evidence for methanogenic Archaea derived from global carbon isotopic anomalies in kerogen of ~2.8 to ~2.5 Ga sedimentary rocks.
- 2/ Biomarker evidence (2α-methylhopanes) for cyanobacteria.
- 3/ Oldest known fossils with diagnostic cyanobacterial biomorphs from the 2.15-Ga Belcher Supergroup, Canada.
- 4/ 2.77 Ga steranes of Eucarya (Brocks et al., 2003).
- 5/ Oldest fossils with possible eukaryotic morphology from the 1.87 Ga Negaunee Iron Formation, Michigan.
- 6/ Previous oldest sterane biomarkers from the ~1.64-Ga Barney Creek Formation, McArthur Basin (NT).
- 7/ Oldest known eukaryotic fossils assigned with confidence to an extant phylum (Rhodophyta) from the 1.26 to 0.95 Ga Hunting Formation, Somerset Island, Canada.
- 8/ Sulfur-isotopic evidence for mesophilic sulfate-reducing Bacteria from North Pole, Pilbara Craton, Western Australia. Branch lengths and branching order are based on SSU rRNA.

nb/ Rasmussen et al., (2008, Nature) revisited 2/ and 4/ and showed that these biomarkers were post 2.2 Ga contaminants, reverting the oldest fossil evidence for eukaryote and cyanobacteria to 1.78–1.68 Ga and 2.15 Ga respectively.

The rise of Eukaryotes - Most of the living organism visible to us, plants, animals, fungi belong to the eukaryotes branch. They are multicellular organisms in which cells include a nucleus, in contrast to Archaea and Bacteria cells. The origin of eukaryotes, or Eukarya, is a complex story.



According to the endosymbiotic hypothesis, eukaryotes arose from a symbiotic relationship between different species of prokaryotes. This theory posits that an ancient archaeon engulfed an aerobic bacterium. Over time, these internalised prokaryotes evolved into mitochondria, the powerhouse of eukaryotic cells.

Symbiogenesis encompasses endosymbiosis and includes the merging of different organisms. A second symbiotic event occurred when a eukaryotic cell engulfed a photosynthetic cyanobacterium, leading to the formation of chloroplasts in plants and algae. Sustaining the symbiogenesis hypothesis is the observation that mitochondria and chloroplasts have their own DNA, which is similar to bacterial DNA. They also reproduce independently within the cell, similar to Bacteria.

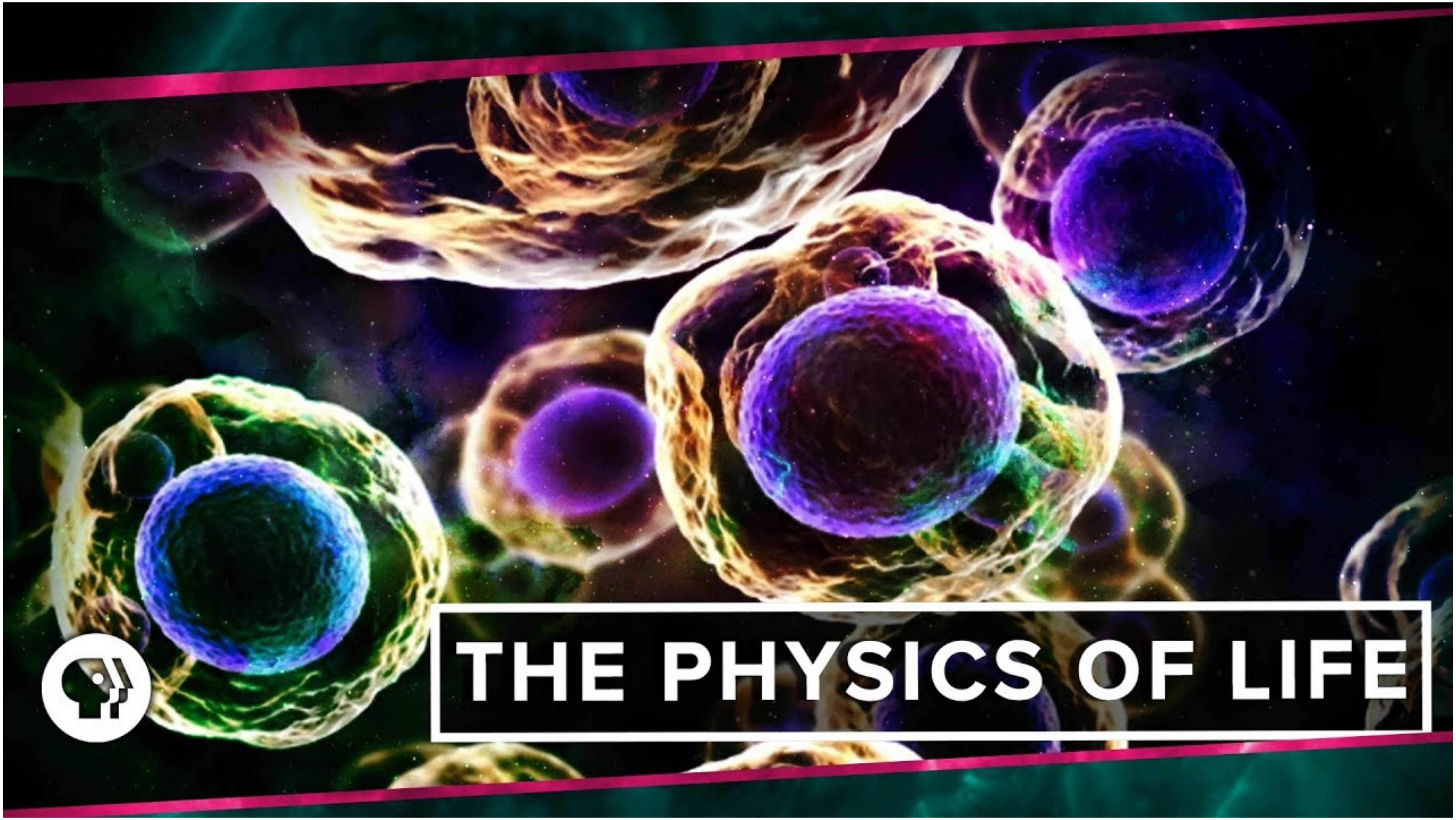
Timeline: The first fossils of eukaryotes are from the Paleoproterozoic era. However, eukaryote's biomarkers in ancient rocks suggests that they have first emerged in the Neoarchean, and possibly before. This emergence is marked by a significant evolutionary milestone, as eukaryotic cells are significantly more complex than prokaryotic cells, featuring a nucleus and other membrane-bound organelles.

Evolutionary significance: The development of eukaryotic cells allowed for greater cellular complexity and specialization, paving the way for the evolution of complex life forms.

Diversity: Eukaryotes include a vast array of organisms, from single-celled protists to complex multicellular organisms like plants, animals, and fungi. This diversity is a testament to the evolutionary success of eukaryotic cells.

Humble beginning - The unexpected discovery of an entirely new domain of life was pretty huge and surprising - even if archaea do just look like bacteria. But, in recent years, it's been their connection to us that's turned out to be particularly full of surprises - ones that may mean we have a connection to a group known as Asgard.

Is life a thermodynamic requirement?



How I smuggled a piece of the oldest deep-sea fan delta on Earth (Pilbara, WA) to Mars ...

A geological postcard from Australia to Mars: How a bit of the Australian desert is heading to the Red Planet

Patrice Rey, Nicolas Coltice and Claire Mallard

A small piece of the Pilbara holds the secret of an ancient geological environment that was common to Earth and Mars 3.5 billion years ago. On 19 February at 7.55am, Sydney time, NASA is scheduled to land the *Perseverance* rover on Mars. A little-known fact is that a piece of the Australian continent is part of this mission to the red planet.

NASA's Mission to Mars 2020 targets the Jezero crater on the western edge of the Isidi Basin at latitude 18°38′ north of the Martian equator. Jezero is a crater of Noachian age (4.1 to 3.7 billion years ago) of about 50 kilometres in diameter.

In the Late Noachian to Early Hesperian (3.7 to 3.0 billion years ago), this crater hosted a lake in which fluvial and deltaic sediments eroded from the basaltic crust were deposited, before being blanketed by volcanic activity around 3.5 billion years ago. This environment is considered to be a geological analogue to conditions on Earth 4.0 to 3.5 billion years ago, when microbial life was taking hold on our planet. Whether or not life was also emerging on Mars at the same time is the focus of Mission to Mars 2020, building on the legacy of the 2003-2018 Mars Opportunity mission.

Perseverance is carrying seven miniature laboratories and the drone *Ingenuity*. The aim of this remote sensing facility is to scan, probe and analyse the surface and sub-surface of the red planet, to search for life-related organic compounds, and to prepare rock samples that will be brought back to Earth in a future mission.

Dr Claire Mallard and Prof Nicolas Coltice collecting samples for the Mars2020 mission (Photo Prof. Patrice Rey, 2015)

Where is the Australian rock hidden?

SuperCam is one of the seven miniature laboratories attached to Perseverance. It is a remote sensing multi-instrument device able to analyse tiny samples within a distance of up to seven metres from the rover. SuperCam relies on a powerful laser to blast tiny spots of rocks and analyse the ejected cloud of dust to map its mineralogy and search for organic molecules. SuperCam is the product of an International collaboration involving research and engineers from the University of Lyon, University of Toulouse, University of Valladolid and NASA.

Key to the accuracy and precision of these analyses is a periodic calibration of the SuperCam's instruments on a set of known targets attached to it. One of these 22 calibration targets is a tiny piece of the Australian continent, a fine grained siliceous sedimentary rock called chert, a rock commonly found in all Archean cratons.

Where does it come from?

In 2015, Professor Patrice Rey (School of Geosciences, University of Sydney), Professor Nicolas Coltice (ENS Paris) and Dr Claire Mallard went on a field expedition to the Pilbara in Western Australia on the traditional land of the Nyamal people, in search of the perfect sample for the Mars 2020 mission.

Together, they carefully removed from its place of origin the sample of red chert which is now about to land on Mars. The outcrop, conveniently located near the Iron Clad pub in Marble Bar, is a well-known geological site where travellers and scientists alike are welcome to collect chert specimens.

What is the significance of this sample?

In 2003, this site was selected as one of the four drill holes of the Archean Biosphere Drilling Project (ABDP), an International project involving researchers from Australia, Japan, France and the USA searching for ancient life of Earth. This colourful outcrop is part of the Marble Bar Chert Member, a rock formation that was deposited in a deep subaqueous fan, the oldest documented deep-sea fan on Earth (Olivier et al., 2012).

The Marble Bar Chert (MBC) sits at the top of the volcaniclastic Duffer Formation whose uppermost volcanic unit is dated at 3.459 billion years ago. The Marble Bar Chert is itself overlain by the Apex basalt underneath the 3.449-billion-year-old Panorama Formation. Hence, the age of the Marble Bar Chert is constrained between 3.459 and 3.449 billion years ago, which fits well with the estimated age of the rock formations where *Perseverance* will land this week.

The very low uranium concentration of the Marble Bar Chert, as well as the presence of grains of pyrite, points to an oxygen-free environment of deposition. However, the red cherts of the MBC contain a few percent of hematite, an oxidised form of iron oxide, which suggests that some oxygen was already available 3.46 billion years ago.

There is debate on origin of the hematite and its significance for the oxygenation of the Earth. This hematite could have formed in-situ in a deep oxygenated body of water. Alternatively, it could have been formed in shallow pools where oxygen-producing cyanobacteria where thriving, before being transported into deeper anoxic water.

Lastly, it could have formed well after the deposition of the chert via the oxidation of much older ferrous oxide. Regardless of the solution to this debate, the Australian sample used to calibrate SuperCam holds the secret of an ancient geological environment that was common to both Earth and Mars 3.5 billion years ago.

Mission to Mars 2020 will eventually bring back to Earth rock specimens from Mars. In the meantime, a remarkable piece of Australia will now play its role discovering whether there has been life on Mars.


3.46 Ga Marble Bar Chert (Pilbara, WA)