

# Palaeobiology 2025

## *The origin of life on Earth: new developments*

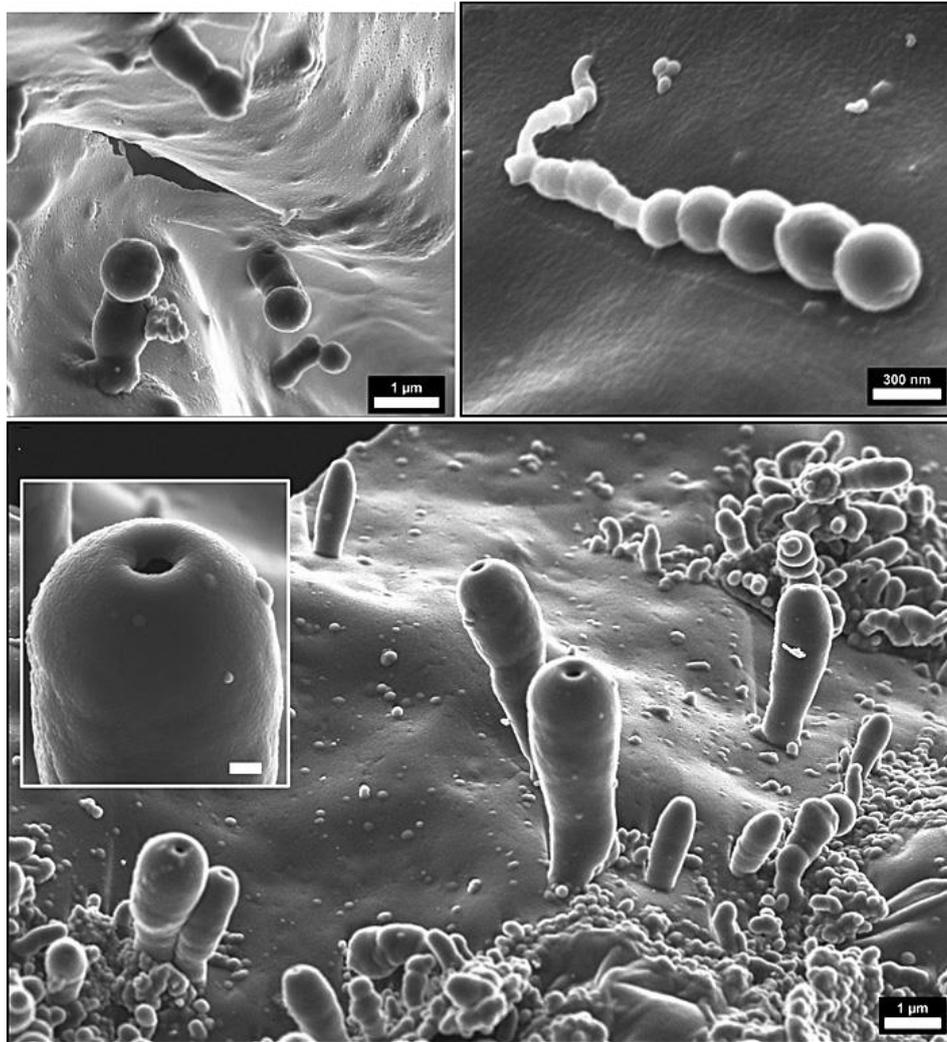
PUBLISHED ON *January 22, 2025*

Debates around the origin of Earth's life and what the first organism was like resemble the mythical search for the Holy Grail. Chivalric romanticists of the late 12<sup>th</sup> and early 13<sup>th</sup> centuries were pretty clear about the Grail – some kind of receptacle connected either with the Last Supper or Christ's crucifixion – but never found it. Two big quests that engage modern science centre on how the chemical building blocks of the earliest cells arose and the last universal common ancestor (LUCA) of all living things. Like the Grail's location, neither is likely to be fully resolved because they can only be sought in a very roundabout way: both verge on the imaginary. The fossil record is limited to organisms that left skeletal remains, traces of their former presence, and a few degraded organic molecules. The further back in geological time the more sedimentary rock has either been removed by erosion or fundamentally changed at high temperatures and pressures. Both great conundrums can only be addressed by trying to reconstruct processes and organisms that occurred or existed more than 4 billion years ago.



Artistic impression of the early Earth dominated by oceans (Credit: Sci-news.com)

In the 1950s Harold Urey of the University of Chicago and his student Stanley Miller mixed water, methane, ammonia and hydrogen sulfide in lab glassware, heated it up and passed electrical discharges through it. They believed the simple set-up crudely mimicked Hadean conditions at the Earth surface. They were successful in generating more complex organic chemicals than their starting materials, though the early atmosphere and oceans are now considered to have been chemically quite different. Such a 'Frankenstein' approach has been repeated since with more success ([see Earth-logs April 2024](#)), creating 10 of the 20 amino acids plus the peptide bonds that link them up to make all known proteins, and even amphiphiles, the likely founders of cell walls. The latest attempt has been made by Spanish scientists at the Andalusian Earth Sciences Institute, the Universities of Valladolid and Cadiz, and the International Physics Centre in San Sebastian (Jenewein, C. *et al* 2024. [Concomitant formation of protocells and prebiotic compounds under a plausible early Earth atmosphere](#). *Proceedings of the National Academy of Sciences*, v. **122**, article 413816122; DOI: 10.1073/pnas.241381612).



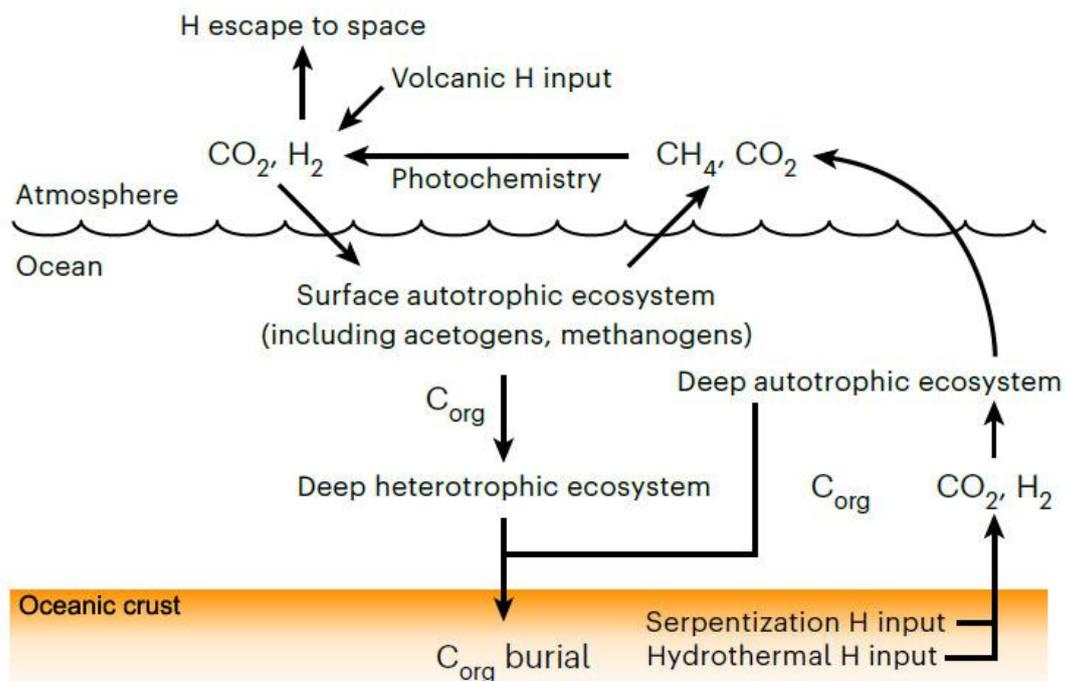
Biomorphs formed by polymerisation of HCN (Credit: Jenewein, C. et al 2024, Figure 2)

Jenewein and colleagues claim to have created cell-like structures, or ‘biomorphs’ at nanometre- and micrometre scale – spheres and polyp-like bodies – from a more plausible atmosphere of  $\text{CO}_2$ ,  $\text{H}_2\text{O}$ , and  $\text{N}_2$ . These ‘protocells’ seem to have formed from minutely thin (150 to 3000 nanometres) polymer films built from hydrogen cyanide that grew on the surface of the reaction chamber as electric discharges and UV light generated HCN and more complex ‘prebiotic’ chemicals. Apparently, these films were catalysed by  $\text{SiO}_2$  (silica) molecules from the glass reactor. **Note:** In the Hadean breakdown of olivine to serpentinite as sea water reacted with ultramafic lavas would have released abundant silica. Serpentinisation also generates hydrogen. Intimate release of gas formed bubbles to create the spherical and polyp-like ‘protocells’. The authors imagine the [Hadean global ocean](#) permanently teeming with such microscopic receptacles. Such a veritable ‘primordial soup’ would be able to isolate other small molecules, such as amino acids, oligopeptides, nucleobases, and fatty acids, to generate more complex organic molecules in micro-reactors *en route* to the kind of complex, self-sustaining systems we know as life.

So, is it possible to make a reasonable stab at what that first kind of life may have been? It was without doubt single celled. To reproduce it must have carried a genetic code enshrined in DNA, which is unique not only to all species, but to individuals. The key to tracking down LUCA is that it represents the point at which the evolutionary trees of the fundamental domains of modern life – eukarya (including animals, plants and fungi), bacteria, and archaea – converge to a single evolutionary stem. There is little point in using fossils to resolve this issue because only multicelled life leaves tangible traces, and the

first of those was found in 2,100 Ma old sediments in Gabon (see: [The earliest multicelled life](#); July 2010). The key is using AI to compare the genetic sequences of the hugely diverse modern biosphere. Modern molecular phylogenetics and computing power can discern from their similarities and differences the relative order in which various species and broader groups split from others. It can also trace the origins of specific genes that provides clues about earlier genetic associations. Given a rate of mutation the modern differences provide estimates of when each branching occurred. The most recent genetic delving has been achieved by a consortium based at various institutions in Britain, the Netherlands, Hungary and Japan (Moody, E.R.R. and 18 others 2024. [The nature of the last universal common ancestor and its impact on the early Earth system](#). *Nature Ecology & Evolution*, v.8, pages 1654–1666; DOI: 10.1038/s41559-024-02461-1).

Moody *et al* have pushed back the estimated age of LUCA to halfway through the Hadean, between 4.09 to 4.33 billion years (Ga), well beyond the geologically known age of the earliest traces of life (3.5 Ga). That age for LUCA in itself is quite astonishing: it could have been only a couple of hundred million years after the Moon-forming interplanetary collision. Moreover, they have estimated that Darwin’s Ur-organism had a genome of around 2 million base pairs that encoded about 2600 proteins: roughly comparable to living species of bacteria and archaea, and thus probably quite advanced in evolutionary terms. The gene types probably carried by LUCA suggest that it may have been an anaerobic acetogen; i.e. an organism whose metabolism generated acetate ( $\text{CH}_3\text{COO}^-$ ) ions. Acetogens may produce their own food as autotrophs, or metabolise other organisms (heterotrophs). If LUCA was a heterotroph, then it must have subsisted in an ecosystem together with autotrophs which it consumed, possibly by fermentation. To function it also required hydrogen that can be supplied by the breakdown of ultramafic rocks to serpentinites, which tallies with the likely ocean-world with ultramafic igneous crust of the Hadean (see the earlier paragraphs about protocells). If an autotroph, LUCA would have had an abundance of  $\text{CO}_2$  and  $\text{H}_2$  to sustain it, and may have provided food for heterotrophs in the early ecosystem. The most remarkable possibility discerned by Moody *et al* is that LUCA may have had a kind of immune system to stave off viral infection.



The carbon cycle on the Hadean Earth (Credit: Moody et al. 2024; Figure 3e)

The Hadean environment was vastly different to that of modern times: a [waterworld](#) seething with volcanism; no continents; a target for errant asteroids and comets; more rapidly spinning with a 12 hour day; a much closer Moon and thus far bigger tides. The genetic template for the biosphere of the following four billion years was laid down then. LUCA and its companions may well have been unique to the Earth, as are their descendants. It is hard to believe that other worlds with the potential for life, even those in the solar system, could have followed a similar biogeochemical course. They may have life, but probably not as we know it . . .

**See also:** Ball, P. 2025. [Luca is the progenitor of all life on Earth. But its genesis has implications far beyond our planet.](#) *The Observer*, 19 January 2025.

## *Life's origins: a new variant on Darwin's "warm little pond"*

PUBLISHED ON [March 3, 2025](#)

In 1871 Charles Darwin wrote to his friend Joseph Hooker, a botanist:

*"It is often said that all the conditions for the first production of a living organism are now present, which could ever have been present. But if (& oh what a big if) we could conceive in some warm little pond with all sorts of ammonia & phosphoric salts, light, heat, electricity &c present, that a protein compound was chemically formed, ready to undergo still more complex changes, at the present day such matter w<sup>d</sup> be instantly devoured, or absorbed, which would not have been the case before living creatures were formed."*

There have been several attempts over the last 150 years, starting with Miller and Urey in 1952, to create physical analogues for this famous insight (See: [The origin of life on Earth: new developments](#)). What such a physico-chemical environment on the early Earth could have been like has also been a fertile topic for discussion: literally warm pools at the surface; hot springs; seawater around deep-ocean hydrothermal vents; even droplets in clouds in the early atmosphere. Attention has recently moved to Darwin's original surface pools through examination of modern ones. The most important content would be dissolved phosphorus compounds, because that element helps form the 'backbone' of the helix structure of RNA and DNA. But almost all natural waters today have concentrations of phosphorus that are far too low for such linkages to form by chemical processes, and also to produce lipids that form cell membranes and the ATP (adenosine triphosphate) so essential in all living metabolism. Phosphorus availability has been too low for most of geological time simply because living organisms are so efficient at removing what they need in order to thrive.



Mono Lake in semi-arid eastern California – a ‘soda lake’ - is so concentrated by evaporation that pillars of carbonate grow above its surface

For the first life to form, phosphorus would somehow have had to be concentrated in watery solution as phosphate ions –  $[\text{PO}_4]^{3-}$ . The element’s source, like that of all others in the surface environment, is in magmas and the volcanic rocks that they form. Perhaps early chemical weathering or reactions between lavas and hydrothermal fluids could have released phosphate ions to solution from a trace mineral present in all lavas: the complex phosphate [apatite](#) ( $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH},\text{F},\text{Cl})_2$ ). But that would still require extreme concentration for it to be easily available to the life-forming process. In January 2024 scientists at the University of Washington in Seattle, USA (Haas, S. *et al.* 2024. [Biogeochemical explanations for the world’s most phosphate-rich lake, an origin-of-life analog](#). *Nature Communications*, v. 5, article 28; DOI: 10.1038/s43247-023-01192-8) showed that the highest known concentrations of dissolved phosphorus occur in the so called “soda lakes” that are found in a variety of modern environments, from volcanically active continental rifts to swampy land. They contain dissolved sodium carbonate (washing soda) at very high concentrations so that they are extremely alkaline and often highly salty. Usually, they are shallow and have no outlet so that dry weather and high winds evaporate the water. Interestingly, the streams that flow into them are quite fresh, so soda lakes form where evaporation exceeds annual resupply of rainwater.

The high evaporation increases the dissolved content of many ions in such lakes to levels high enough for them for them to combine and precipitate calcium, sodium and magnesium as carbonates. In some, but not all soda lakes, such evaporative concentration also increases their levels of dissolved phosphate ions higher than in any other bodies of water. That is odd, since it might seem that phosphate ions should combine with dissolved calcium to form solid calcium phosphate making the water less P-rich. Haas *et al.* found that lakes which precipitate calcium and magnesium together in the form of dolomite ( $\text{Ca},\text{Mg}\text{CO}_3$ ) have high dissolved phosphate. Removal of Ca and other metal ions through bonding to carbonate ( $\text{CO}_3$ ) deprives dissolved phosphate ions in solution of metal ions with which they can bond. But why has dissolved phosphate not been taken up by organisms growing in the lakes: after all, it is an essential nutrient. The researchers found that some soda lakes that contain algal mats have much lower dissolved phosphate – it has been removed by the algae. But such lakes are not as salty as

those rich in dissolved phosphate. They in turn contain far less algae whose metabolism is suppressed by high levels of dissolved NaCl (salt). Hass *et al.*'s hypothesis has now been [supported by more research on soda lakes](#).

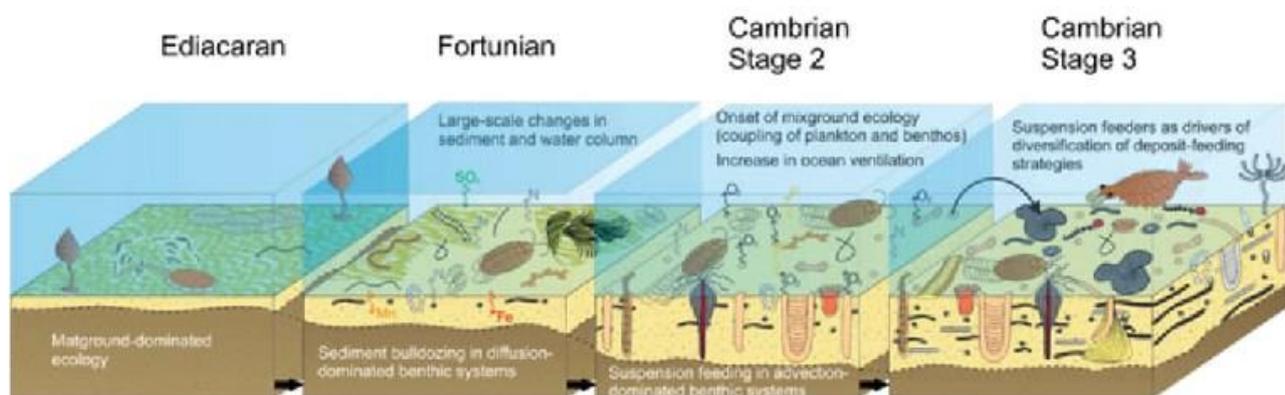
In an early, lifeless world phosphate concentrations in alkaline, salty lakes would be controlled by purely inorganic reactions. This strongly suggests that 'warm little soda lakes' enriched in dissolved sodium carbonate by evaporation, and which precipitated dolomite could have enabled phosphorus compounds to accumulate to levels needed for life to start. They might have been present on any watery world in the cosmos that sustained volcanism.

**See also:** Service, R.F. 2025. [Early life's phosphorus problem solved?](#) *Science*, v. **387**, p. 917; DOI: 10.1126/science.z78227f; [Soda Lakes: The Missing Link in the Origin of Life?](#) *SciTechDaily*, 26 January 2024.

## *What drove the Cambrian Explosion?*

PUBLISHED ON *March 28, 2025*

The origin of animals occurred sometime during the Proterozoic Eon, [perhaps as early as 2.1 Ga](#) (billion years ago) after the Great Oxygenation Event. Available oxygen is a prerequisite for animal life, and that is about as far back as palaeobiologists can push it. More familiar are the trace fossils known as [the Ediacaran fauna](#) which emerged after the environmentally highly stressful Cryogenian Period that was marked by two Snowball Earth events. Traces of these animals may have been big enough to be easily found, but they were not particularly diverse and are difficult to place in any particular modern group. Most modern animals have front- and rear ends, tops and bottoms, and input and output orifices. The earliest of these [bilaterian beasts may have emerged during the Ediacaran](#) as well, but were not very prepossessing. It was during the Cambrian Period (541 to 485 Ma) that most modern animal phyla became recognisable to palaeobiologists. That carnival of diversification is widely known as the [Cambrian Explosion](#). Yet it was later in geological time that the full panoply of Phanerozoic diversity among taxa below the level of the phylum truly exploded, punctuated by mass extinctions and the diversification that followed each of them. So, what lay behind the initial emergence of the characteristics that form the basic templates of the phyla themselves?



Cartoon of the Cambrian Explosion in benthic faunas. Credit: Gabriela Mangano and Luis A. Buatois, 2016 *The Cambrian Explosion*, Fig 3.15

A multinational team of modellers and geoscientists have moved the focus from long-term shifts in climate and atmospheric chemistry to what might change from day to night in an ecosystem during the diel cycle (Hammarlund, E.U. and 13 others 2025. [Benthic diel oxygen variability and stress as potential](#)

[drivers for animal diversification in the Neoproterozoic-Palaeozoic](#) *Nature Communications*, v. **16**, article 2223; DOI:10.1038/s41467-025-57345-0). During the Neoproterozoic oxygen levels in Earth atmosphere rose to about half the amount present today. But animals arose and evolved in sea water. The most prolific source of food for them would have been in shallow water (the benthic zone), simply because sunlight in the photic zone encourages photosynthesis. As well as a thriving base for animal life's food chain shallow water is where oxygen is produced; but only during daylight hours. At night decay of organic matter on the seabed draws down dissolved oxygen. Emma Hammarlund and colleagues wondered if day-night changes in oxygen levels might have exerted sufficient stress to force early animals to adapt and thus diversify. Their model shows that in warm, shallow water the lower oxygen levels at the start of the Phanerozoic could change dramatically in the diel cycle. Algae at the base of the food chain would swiftly oxygenate the water in daylight, but at night would consume it to produce much lower levels. Animals that were better adapted to the stress of this daily 'feast-and-famine' cycle in oxygen availability would outcompete others that were less resilient for the available nutrients. Environmental stress had flipped from an obstacle to evolution to a catalyst for it. The earliest appearances of organisms in the 10 modern phyla seem to coincide with global warming at low latitudes to an air temperature of about 25° C at the start of the Cambrian, perhaps when this shift began.

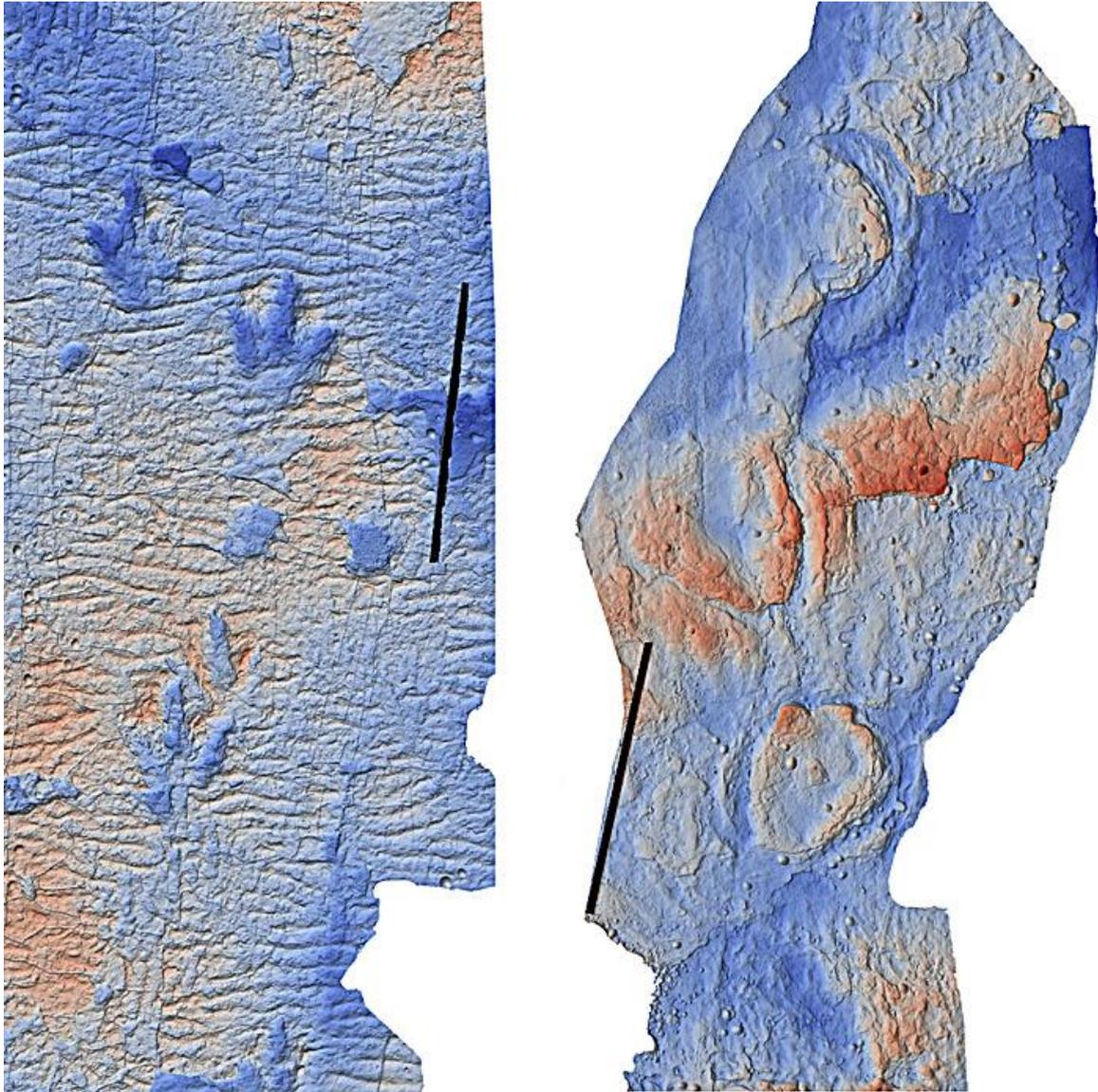
Another empirical coincidence lies in the sedimentary rock record. On modern continents the base of Phanerozoic sediments is widely marked by shallow-water sandstones often at an unconformity. Often white and containing abundant burrows, the sandstones are signs of abundant life, though rarely contain body fossils. They represent global sea-level rise that flooded the existing continents, so the highly productive benthic environment became about four times more widespread at the end of the Cambrian than it was during the previous Ediacaran Period. Abundant life forms were under stress more or less everywhere. Thereafter these 'shelf seas' halved in total area, but the basic 'templates' for animal life were well-established and the numbers of classes, orders, families *etcetera* steadily burgeoned. By the end of the [Cambrian oxygen production rose](#) so that atmospheric concentration of the gas reached 25%, higher than it is at present.

**See also:** Hammarlund, E. 2025. [How dramatic daily swings in oxygen shaped early animal life](#). *The Conversation*, 21 March 2025.

## ***More dinosaur trackways from the Jurassic of the Isle of Skye, Scotland***

PUBLISHED ON *April 7, 2025*

The Isle of Skye off the northwestern coast of Scotland is one of several areas in Britain that are world-class geological gems. Except for the Cuillin Hills that require advanced mountaineering skills it is easy to explore and has become a major destination for both beginners and expert geoscientists of all kinds. Together with the adjacent Isle of Raasay the area is covered by a superb, free geological guidebook (Bell, B. 2024. *The Geology of the Isles of Skye and Raasay*. *Geological Society of Glasgow*) together with 60 standalone excursion guides, and even an introduction to Gaelic place names and pronunciation. It is freely available from <https://www.skyegeology.com/>



Fig

Dinosaur trackways at Prince Charles's Point on the Isle of Skye: Left carnivorous theropods; Right herbivorous sauropods. The black scales are 1 m long. The images are enhanced fine-scale elevation models of the exposed surfaces that were derived from vertical photographs. Credit: Blakesley et al., Figs 9 and 27.

Since 2018 Skye has also become a must-visit area for vertebrate palaeontologists. Beneath Palaeocene flood basalts is a sequence of Jurassic strata, both shallow marine and terrestrial. One formation, the [Great Estuarine Group](#) of Middle Jurassic (Bathonian, 174–164 Ma) age covers the time when meat-eating theropod- and herbivorous sauropod dinosaurs began to grow to colossal sizes from diminutive forebears. While other Jurassic sequences on Skye have notable marine faunas, its Bathonian strata have yielded a major surprise: some exposed bedding surfaces are liberally dotted with trackways of the two best known groups of dinosaur. The first to be discovered were at [Rubha Nam Brathairean \(Brothers' Point\)](#) suggesting [a rich diversity of species](#) that had wandered across a wide coastal plain, also including the somewhat bizarre *Stegosaurus*. The latest finds are from a rocky beach at Prince Charles's Point where the Young Pretender to the British throne, Charles Edward Stuart, landed and hid during his flight from the disastrous Battle of Culloden (16 April 1746). It was only in the last year or so that palaeontologists from the universities of Edinburgh and Liverpool, and the Staffin Museum came across yet more footprints (131 tracks) left there by numerous dinosaurs in the rippled sands of a Bathonian lagoon (Blakesley, T. et al. 2025. [A new Middle Jurassic lagoon margin assemblage](#)

[of theropod and sauropod dinosaur trackways from the Isle of Skye, Scotland](#). *PLOS One*, v. **20**, article e0319862; DOI: 10.1371/journal.pone.0319862.

The Prince Charles's Point site is partly covered by large basalt boulders, which perhaps account for the excellent preservation of the bedding surfaces from wave action. Two kinds of footprint are preserved (see image): those made by three-toed feet and by elephant-like feet that 'squidged-up' sediment surrounding than. Respectively these are suggested to represent the hind limbs of bipedal carnivorous theropods and quadrupedal herbivorous sauropods. They show that individual dinosaurs moved in multiple directions, but there is no evidence for gregarious behaviour, such as parallel trackways of several animals. They occur on two adjacent bedding surfaces so represent a very short period of time, perhaps a few days. The authors suggest that several individual animals were milling around, with more sauropods than theropods. What such behaviour represents is unclear. The water in an estuarine lagoon would likely have been fresh or brackish. They may have been drinking or perhaps there was some plants or carcasses worth eating ? That might explain both kinds of dinosaurs' milling around. The sizes of both sauropod and theropod prints average about 0.5 m. The stride lengths of the theropods suggest that they were between 5 to 7 metres long with a hip height of around 1.85 m. Their footprints resemble those reconstructed from skeletal remains of Middle Jurassic *Megalosaurus*, the first dinosaur to be named (by William Buckland in 1827). The sauropods had estimated hip heights of around 2 m so they may have been similar in size (around 16 m) to the Middle Jurassic *Cetiosaurus*, the first sauropod to be named (by Richard Owen in 1842).

## *A sign of life on another planet? Should we be excited?*

PUBLISHED ON *April 19, 2025*

Judging by the coverage in the media, there is huge excitement about a possible sign of life on a very distant planet. It emerged from a Letter to *The Astrophysical Journal* posted by a British-US team of astronomers led by Nikku Madhusudhan that was publicised by the Cambridge University Press Office (Madhusudhan, N. *et al.* 2025. [New Constraints on DMS and DMDS in the Atmosphere of K2-18 b from JWST MIRI](#). *The Astrophysical Journal*, v. **983**, article adc1c8; DOI: 10.3847/2041-8213/adc1c8). K2-18 b is a planet a bit smaller than Neptune that orbits a red dwarf star (K2-18) about 124 light years away. The planet was discovered by NASA's now-defunct Kepler space telescope tasked with the search for planets orbiting other stars. An infrared spectrometer on the Hubble Space Telescope revealed in 2019 that the atmosphere of K2-18 b contained water vapour, making the planet a target for further study as it may possess oceans. The more sophisticated James Webb Space Telescope IR spectrometer was trained on it a year later to reveal methane and CO<sub>2</sub>: yet more reason to investigate more deeply, for water and carbon compounds imply both habitability and the potential for life forms being there.

The latest results suggest that that the atmosphere of K2-18 b may contain simple carbon-sulfur gases: dimethyl sulfide ((CH<sub>3</sub>)<sub>2</sub>S) and dimethyl disulfide (CH<sub>3</sub>SSCH<sub>3</sub>). Bingo! for exobiologists, because on Earth both DMS and DMDS are only produced by algae and bacteria. Indeed they are responsible for the odour of the seaside. They became prominent in 1987 when biogeochemist James Lovelock fitted them into his Gaia Hypothesis. He recognised that they encourage cloud formation and thus increase Earth's reflectivity (albedo) and also yield sulfuric acid aerosols in the stratosphere when they oxidise: that too increases albedo. DMS generates a cooling feedback loop to counter the warming feedback of greenhouse emissions. That is an idea of planetary self-regulation not much mentioned nowadays. Such gases were proposed by Carl Sagan as unique molecular indicators that could be used to search for extraterrestrial life.



The coma of Comet Churyumov-Gerasimenko yielded both dimethyl sulfide and amino acids to the mass spectrometer carried by ESA's Rosetta. Credit: ESA.

The discovery of possible DMS and DMDS in K2-18 b's atmosphere is, of course, currently under intense scientific scrutiny. For a start, the statistics inherent in Madhusudhan *et al.*'s methodology ( $3\sigma$  or 99.7% probability) fall short of the 'gold standard' for discoveries in physics ( $5\sigma$  or 99.99999% probability). Moreover, there's also a chance that exotic, inorganic chemical processes could also create the gases, such as lightning in an atmosphere containing C, H and S. But this is not the first time that DMS has been discovered in an extraterrestrial body. Comets, having formed in the infancy of the Solar System much further from the Sun than any planets, are unlikely to be 'teeming with life'. The European Space Agency's Rosetta spacecraft chased comet 67P/Churyumov-Gerasimenko for 2 years, directly sampling dust and gas that it shed while moving closer to the Sun. [A single day's data from Rosetta's mass spectrometer](#) showed up DMS, and also amino acids. Both could have formed in comets or interstellar dust clouds by chemistry driven by radiation, possibly to contaminate planetary atmospheres. Almost certainly, further remote sensing of K2-18 b will end up with five-sigma precision and some will say, 'Yes, there is life beyond Earth!' and celebrate wildly. But that does not constitute proof, even by the 'weight of evidence' criterion of some judiciaries. To me such a conclusion would be unseemly romanticism. Yet such is the vastness of the material universe and the sheer abundance of the elements C H O N and P that make up most living matter that life elsewhere, indeed everywhere – 'but not life as we know it, Jim' – is a near certainty. The issue of *intelligent* lifeforms 'out there' is, however, somewhat less likely to be resolved . . .

# *Arsenic: an agent of evolutionary change?*

PUBLISHED ON [June 2, 2025](#)

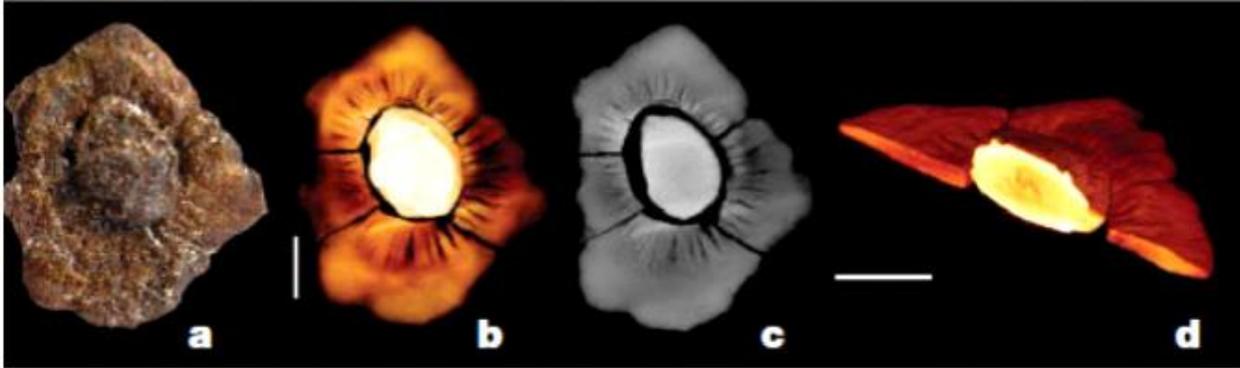
The molecules that make up all living matter are almost entirely (~98 %) made from the elements Carbon, Hydrogen, Oxygen, Nitrogen and Phosphorus (CHONP) in order of their biological importance. All have low atomic numbers, respectively 6<sup>th</sup>, 1<sup>st</sup>, 8<sup>th</sup>, 7<sup>th</sup> and 15<sup>th</sup> in the Periodic Table. Of the 98 elements found in nature, about 7 occur only because they form in the decay schemes of radioactive isotopes. Only the first 83 (up to Bismuth) are likely to be around 'for ever'; the fifteen heavier than that are made up exclusively of unstable isotopes that will eventually disappear, albeit billions of years from now. There are other oddities that mean that the [92 widely accepted to be naturally occurring is not strictly correct](#). That CHONP are so biologically important stems partly from their abundances in the inorganic world and also because of the ease with which they chemically combine together. But they are not the only ones that are essential.

About 20 to 25% of the other elements are also literally *vital*, even though many are rare. Most of the rest are inessential except in vanishingly small amounts that do no damage, and may or may not be beneficial. However some are highly toxic. Any element can produce negative biological outcomes if above certain levels. Likewise, deficiencies can result in ill thrift and event death. For the majority of elements, biologists have established concentrations that define deficiency and toxic excess. The World Health Organisation has charted the [maximum safe levels of elements in drinking water](#) in milligrams per litre. In this regard, the lowest safe level is for thallium (Tl) and mercury (Hg) at 0.002 mg l<sup>-1</sup>. Other highly toxic elements are cadmium (Cd) (0.003 mg l<sup>-1</sup>), then arsenic (As) and lead (Pb) (0.01 mg l<sup>-1</sup>) that 'everyone knows' are elements to avoid like the plague. In nature lead is very rarely at levels that are unsafe because it is insoluble, but arsenic is soluble under reducing conditions and is currently responsible for a pandemic of related ailments, especially in the [Gangetic plains of India and Bangladesh and similar environments worldwide](#).

Biological evolution has been influenced since life appeared by the availability, generally in water, of both essential and toxic elements. In 2020 Earth-logs summarised a paper about [modern oxygen-free springs in Chile in which photosynthetic purple sulfur bacteria form thick microbial mats](#). The springs contain levels of arsenic that vary from high in winter to low in summer. This phenomenon can only be explained by some process that removes arsenic from solution in summer but not in winter. The purple bacteria's photosynthesis uses electrons donated by sulfur, iron-2 and hydrogen – the spring water is highly reducing so they thrive in it. In such a simple environment this suggested a reasonable explanation: the bacteria use arsenic too. In fact they contain a gene (*aio*) that encodes for such an eventuality. The authors suggested that purple sulfur bacteria may well have evolved before the Great Oxygenation Event (GOE). They reasoned that in an oxygen-free world arsenic, as well as Fe<sup>2+</sup> would be readily available in water that was in a reducing state, whereas oxidising conditions after the GOE would suppress both: iron-2 would be precipitated as insoluble iron-3 oxides that in turn efficiently absorb arsenic (see: [Arsenic hazard on a global scale](#), May 2020).

A group of geoscientists from France, the UK, Switzerland and Austria have investigated the paradox of probably high arsenic levels before the GOE and the origin and evolution of life during the Archaean (El Khoury *et al.* 2025. [A battle against arsenic toxicity by Earth's earliest complex life forms](#). *Nature Communications*, v. **16**, article 4388; DOI: 10.1038/s41467-025-59760-9). Note that the main, direct evidence for Archaean life are fossilized microbial mats known as [stromatolites](#), some palaeobiologists reckoning they were formed by oxygenic photosynthesising cyanobacteria others favouring the purple sulfur bacteria (above). The purple sulfur bacteria in Chile and other living prokaryotes that tolerate and even use arsenic in their metabolism clearly evolved that potential plus necessary chemical defence mechanisms, probably when arsenic was more available in the anoxic period before the GOE. Anna El

Khoury and her colleagues sought to establish whether or not eukaryotes evolved similar defences by investigating the earliest-known examples; the 2.1 Ma old [Francevillian biota of Gabon](#) that post-dates the GOE. They are found in black shales, look like tiny fried eggs and are associated with clear signs of burrowing. The shales contain steranes that are breakdown products of steroids, which are unique to eukaryotes.



Colour photograph and CT scans of Palaeoproterozoic discoidal fossils from the Francevillian Series in Gabon. (Credit: El Albani et al. 2010; Fig. 4).

The fossils have been preserved by precipitation of pyrite ( $\text{Fe}_2\text{S}$ ) granules under highly reducing conditions. Curiously, the cores of the pyrite granules in the fossils are rich in arsenic, yet pyrite grains in the host sediments have much lower As concentrations. The latter suggest that seawater 2.1 Ma ago held little dissolved arsenic as a result of its containing oxygen. The authors interpret the apparently biogenic pyrite's arsenic cores as evidence of the organism having sequestered As into specialized compartments in their bodies: their ancestors must have evolved this efficient means of coping with significant arsenic stress before the GOE. It served them well in the highly reducing conditions of black shale sedimentation. Seemingly, some modern eukaryotes retain an analogue of a prokaryote As detoxification gene.

## *Detecting oxygenic photosynthesis in the Archaean Earth System*

PUBLISHED ON *June 9, 2025*

For life on Earth, one of the most fundamental shifts in ecosystems was the Great Oxygenation Event 2.5 to 2.3 billion years (Ga) ago. The first evidence for its occurrence was from the sedimentary record, particularly ancient soils (palaeosols) that mark exposure of the continental surface above sea level and rock weathering. Palaeosols older than 2.4 Ga have low iron contents that suggest iron was soluble in surface waters, i.e. in its reduced bivalent form  $\text{Fe}^{2+}$ . Sediments formed by flowing water also contain rounded grains of minerals that in today's oxygen-rich environments are soon broken down and dissolved through oxidising reactions, for instance pyrite ( $\text{FeS}_2$ ) and uraninite ( $\text{UO}_2$ ). After 2.4 Ga palaeosols are reddish to yellowish brown in colour and contain insoluble oxides and hydroxides of  $\text{Fe}^{3+}$  principally hematite ( $\text{Fe}_2\text{O}_3$ ) and goethite ( $\text{FeO.OH}$ ). After this time sediments deposited by wind action and rivers are similar in colour: so-called 'redbeds'. Following the GOE the atmosphere initially contained only traces of free oxygen, but sufficient to make the surface environment oxidising. In fact such an atmosphere defies [Le Chatelier's Principle](#): free oxygen should react rapidly with the rest of the environment through oxidation. That it doesn't shows that it is continually generated as a result of

oxygenic photosynthesis. The  $\text{CO}_2 + \text{H}_2\text{O} = \text{carbohydrate} + \text{oxygen}$  equilibrium does not reach a balance because of continual burial of dead organic material.

Free oxygen is a prerequisite for all multicelled eukaryotes, and it is probably no coincidence that fossils of the [earliest known ones](#) occur in sediments in Gabon dated at 2.1 Ga: 300 Ma after the Great Oxygenation Event. However, the GOE relates to *surface* environments of that time. From 2.8 Ga – in the Mesoarchaeon Era – to the late Palaeoproterozoic around 1.9 Ga, vast quantities of  $\text{Fe}^{3+}$  were locked in iron oxide-rich banded iron formations (BIFs): roughly  $10^5$  billion tons in the richest deposits alone (see: [Banded iron formations \(BIFs\) reviewed](#); December 2017). Indeed, similar ironstones occur in Archaean sedimentary sequences as far back as 3.7 Ga, albeit in uneconomic amounts. Paradoxically, enormous amounts of oxygen must have been generated by marine photosynthesis to oxidise  $\text{Fe}^{2+}$  dissolved in the early oceans by hydrothermal alteration of basalt lava upwelling from the Archaean mantle. But none of that free oxygen made it into the atmosphere. Almost as soon as it was released it oxidised dissolved  $\text{Fe}^{2+}$  to be dumped as iron oxide on the ocean floor. Before the GOE that aspect of geochemistry did obey Le Chatelier!



A limestone made of stromatolites

The only likely means of generating oxygen on such a gargantuan scale from the earliest Archaean onwards is through teeming prokaryote organisms capable of oxygenic photosynthesis. Because modern cyanobacteria do that, the burden of the BIFs has fallen on them. One reason for that hypothesis stems from cyanobacteria in a variety of modern environments building dome-shaped bacterial mats. Their forms closely resemble those of Archaean [stromatolites](#) found as far back as 3.7 Ga. But these are merely peculiar carbonate bodies that could have been produced by bacterial mats which deploy a wide variety of metabolic chemistry. Laureline Patry of the Université de Bretagne Occidentale, Plouzané, France, and colleagues from France, the US, Canada and the UK have developed a novel way of addressing the opaque mechanism of Archaean oxygen production (Patry, L.A. and 12

others. Dating the evolution of oxygenic photosynthesis using La-Ce geochronology. *Nature*, v. **642**, p. 99-104; DOI: 10.1038/s41586-025-09009-8).

They turned to the basic geochemistry of rare earth elements (REE) in Archaean stromatolitic limestones from the Superior Craton of northern Canada. Of the 17 REEs only cerium (Ce) is capable of being oxidised in the presence of oxygen. As a result Ce can be depleted relative to its neighbouring REEs in the Periodic Table, as it is in many Phanerozoic limestones. Five samples of the limestones show consistent depletion of Ce relative to all other REE. It is also possible to date when such fractionation occurred using  $^{138}\text{La}$ - $^{138}\text{Ce}$  geochronology. The samples were dated at 2.87 to 2.78 Ga (Mesoarchaeon), making them the oldest limestones that show Ce anomalies and thus oxygenated seawater in which the microbial mats thrived. But that is only 300 Ma earlier than the start of the GOE. Stromatolites are abundant in the Archaean record as far back as 3.4 Ga, so it should be possible to chart the link between microbial carbonate mats and oxygenated seawater to a billion years before the GOE, although that does not tell us about the kind of microbes that were making stromatolites.

See also: [Tracing oxygenic photosynthesis via La-Ce geochronology](#). Bioengineer.org, 29 May 2025; Allen, J.F. 2016. [A proposal for formation of Archaean stromatolites before the advent of oxygenic photosynthesis](#). *Frontiers in Microbiology*, v. **7**; DOI: 10.3389/fmicb.2016.01784.

## *The end-Triassic mass extinction and ocean acidification*

PUBLISHED ON *July 22, 2025*



Triassic reef limestones in the Dolomites of northern Italy. Credit: © Matteo Volpone

Four out of six mass extinctions that ravaged life on Earth during the last 300 Ma coincided with large igneous events marked by basaltic flood volcanism. But not all such bursts of igneous activity match significant mass extinctions. Moreover, some rapid rises in the rate of extinction are not clearly linked to peaks in igneous activity. Another issue in this context is that 'kill mechanisms' are generally speculative rather than based on hard data. Large igneous events inevitably emit very large amounts of gases and dust-sized particulates into the atmosphere. Carbon dioxide, being a greenhouse gas, tends to heat up the global climate, but also dissolves in seawater to lower its pH. Both global warming and more acidic oceans are possible 'kill mechanisms'. Volcanic emission of sulfur dioxide results in acid rain and thus a decrease in the pH of seawater. But if it is blasted into the stratosphere it combines with oxygen and water vapour to form minute droplets of sulfuric acid. These form long-lived haze, which reflects solar energy back into space. Such an increased albedo therefore tends to cool the planet and create a so-called 'volcanic winter'. Dust that reaches the stratosphere reduces penetration of visible light to the surface, again resulting in cooling. But since photosynthetic organisms rely on blue and red light to power their conversion of CO<sub>2</sub> and water vapour to carbohydrates and oxygen, these primary producers at the base of the marine and terrestrial food webs decline. That presents a fourth kill mechanism that may trigger mass extinction on land and in the oceans: starvation.

Palaeontologists have steadily built up a powerful case for occasional mass extinctions since fossils first appear in the stratigraphic record of the Phanerozoic Eon. Their data are simply the numbers of species, genera and families of organisms preserved as fossils in packages of sedimentary strata that represent roughly equal 'parcels' of time (~10 Ma). Mass extinctions are now unchallengeable parts of life's history and evolution. Yet, assigning specific kill mechanisms involved in the damage that they create remains very difficult. There are *hypotheses* for the cause of each mass extinction, but a dearth of data that can test *why* they happened. The only global die-off near hard scientific resolution is that at the end of the Cretaceous. The K-Pg (formerly K-T) event has been [extensively covered in Earth-logs](#) since 2000. It involved a mixture of global ecological stress from the Deccan large igneous event spread over a few million years of the Late Cretaceous, with the near-instantaneous catastrophe induced by [the Chicxulub impact](#), with a few remaining dots and ticks needed on 'i's and 't's. Other possibilities have been raised: gamma-ray bursts from distant supernovae; belches of methane from the sea floor; emissions of hydrogen sulfide gas from seawater itself during ocean anoxia events; sea-level changes etc.

The mass extinction that ended the Triassic (~201 Ma) coincides with evidence for intense volcanism in South and North America, Africa and southern Europe, then at the core of the Pangaea supercontinent. Flood basalts and large igneous intrusions – the [Central Atlantic Magmatic Province \(CAMP\)](#) – began the final break-up of Pangaea. The end-Triassic extinction deleted 34% of marine genera. Marine sediments aged around 201 Ma reveal a massive shift in sulfur and carbon isotopes in the ocean that has been interpreted as a sign of acute anoxia in the world's oceans, which may have resulted in massive burial of oxygen-starved marine animal life. However, there is no sign of Triassic, carbon-rich deep-water sediments that characterise ocean anoxia events in later times. But it is possible that bacteria that use the reduction of sulfate (SO<sub>4</sub><sup>2-</sup>) to sulfide (S<sup>2-</sup>) ions as an energy source for them to decay dead organisms, could have produced the sulfur isotope 'excursion'. That would also have produced [massive amounts of highly toxic hydrogen sulfide gas](#), which would have overwhelmed terrestrial animal life at continental margins. The solution of H<sub>2</sub>S in water would also have acidified the world's oceans.

Molly Trudgill of the University of St Andrews, Scotland and colleagues from the UK, France, the Netherlands, the US, Norway, Sweden and Ireland set out to test the hypothesis of end-Triassic oceanic acidification (Trudgill, M. and 24 others 2025. [Pulses of ocean acidification at the Triassic–Jurassic boundary](#). *Nature Communications*, v. **16**, article 6471; DOI: 10.1038/s41467-025-61344-6). The team used Triassic fossil oysters from before the extinction time interval. Boron-isotope data from the shells are a means of estimating variations in the pH of seawater. Before the extinction event the average pH

in Triassic seawater was about the same as today, at 8.2 or slightly alkaline. By 201 Ma the pH had shifted towards acidic conditions by at least 0.3: the biggest detected in the Phanerozoic record. One of the most dramatic changes in Triassic marine fauna was the disappearance of reef limestones made by the recently evolved modern corals on a vast scale in the earlier Triassic; a so-called 'reef gap' in the geological record. That suggests a possible analogue to the waning of today's coral reefs that is thought to be a result of increased dissolution of CO<sub>2</sub> in seawater and acidification, related to global greenhouse warming. Using the fossil oysters, Trudgill *et al.* also sought a carbon-isotope 'fingerprint' for the source of elevated CO<sub>2</sub>, finding that it mainly derived from the mantle, and was probably emitted by CAMP volcanism. So their discussion centres mainly on end-Triassic ocean acidification as an analogy for current climate change driven by CO<sub>2</sub> largely emitted by anthropogenic burning of fossil fuels. Nowhere in their paper do they mention any role for acidification by hydrogen sulfide emitted by massive anoxia on the Triassic ocean floor, which hit the scientific headlines in 2020 (see earlier link).

## *A 'worm' revolution and ecological transition before the Cambrian explosion*

PUBLISHED ON *November 4, 2025*



Bioturbated 'pipe rock' of the basal Cambrian sandstones of NW Scotland. Credit: British Geological Survey photograph P531881

About 530 Ma ago most of the basic body plans of today's living organisms can be detected as fossils, i.e. preserved hard parts. Yet studies of trace fossils (ichnofossils) – marks left in sediments by active soft bodied creatures suggest that [many modern phyla arose before the start of the Cambrian](#) (~539 Ma), as early as 545 Ma. So the term 'Cambrian explosion' seems to be a bit of a misnomer on two counts: it lasted around 15 Ma and began before the Cambrian. Preceding it was the Ediacaran Period

that began around 100 Ma earlier in the Neoproterozoic Era. Traces of its [eponymous fauna of large soft-bodied organisms](#) are found on all continents, but apparently none of them made it into the Phanerozoic fossil record. Another characteristic of the Ediacaran is that its sedimentary rocks – and those of earlier times – show no signs of burrowing: they are not bioturbated. That may be why the Ediacaran pancake-, bun-, bag- and pen-like lifeforms are so remarkably well preserved. But a lack of burrowing did not extend to the beginning of Cambrian times. The most likely reason why it was absent during the early Ediacaran Period is that sea-floor sediments then were devoid of oxygen so eukaryote animals could not live in them. But the presence of these large organisms showed that seawater must have been oxygenated. Now clear signs of burrowing have emerged from study of Ediacaran rocks exposed in the Yangtze Gorge of Hubei, southern China ( Zhe Chen & Yarong Liu 2025. [Advent of three-dimensional sediment exploration reveals Ediacaran-Cambrian ecosystem transition](#). *Science Advances*, v. **11**, article eadx9449; DOI: 10.1126/sciadv.adx9449).



Tadpole-like trace fossils from the Ediacaran Dengying Formation in the Yangtze Gorge: 5 cm scale bars.

The ‘heads’ show tiny depressions suggesting that they maker probed into the sediments as well as foraging horizontally. Credit: Zhe Chen & Yarong Liu; Figs 3B and 3D

Zhe Chen and Yarong Liu of the Nanjing Institute of Geology and Palaeontology and Chinese Academy of Sciences in China examined carbonates of the upper Ediacaran Dengying Formation. This overlies the Doushantuo Formation (550 to 635 Ma), known for tiny fossils of possibly [the oldest deuterostome \*Saccorhytus coronaries\*](#); a potential candidate for the ancestor of modern bilaterian phyla. In the Yangtze Gorge locality sediments at this level show only traces of browsing of bacterial mats on the sediment surface; i.e. 2-D feeders. The basal Dengying sediments host clear signs that organisms could then penetrate into the sediments. These 3-D feeders, would have had access to buried organic remains, hitherto unexploited by living organisms. Such animal-sediment interactions would have disturbed and diminished the living microbial mats that held the sediment surface in place, and thus began to dismantle the substrate for the typical Ediacaran fauna. Similar 3-D feeders occur throughout the 11 Ma represented by the Dengying Formation to the start of the Cambrian. This beginning of [bioturbation](#) heralded a period during which the Ediacaran fauna steadily waned. It also released nutrients into deep water, and opened up new ecological niches for more advanced animals on the seabed. Dissolved oxygen could only slowly enter the sediments since atmospheric and oceanic O<sub>2</sub> levels were low. But by the earliest Cambrian it had risen to about 5 to 10% by volume to support many other kinds of burrowing animals that could penetrate more deeply, as witnessed by the abundant sandstones that occur at the base of the Cambrian in Britain.

## *AI unravels chemical signs of the earliest life on Earth*

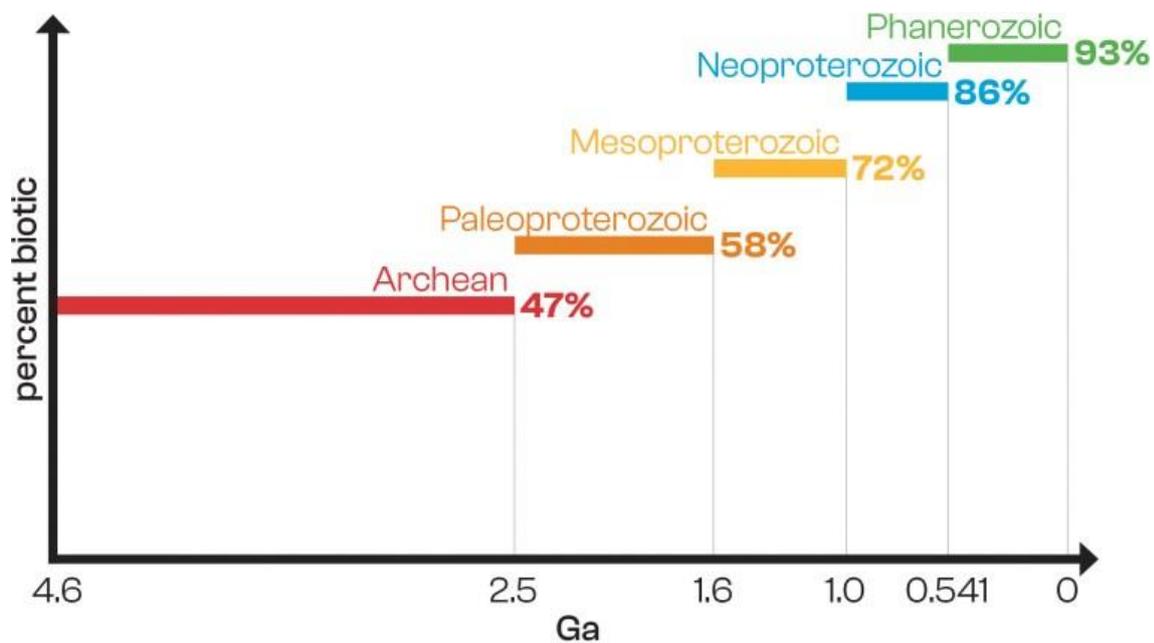
PUBLISHED ON [November 23, 2025](#)

Evidence for the earliest life on Earth has largely relied on finding signs of structures that may have been created during the Archaean Eon by micro-organisms. Actual fossils don't turn up until the Proterozoic. The most distinctive and diverse of these are members of the Ediacaran fauna dated at around 635 Ma. The oldest widely accepted multi-celled eukaryote fossil was found in 2.1 billion-year old sediments from Gabon (see: [The earliest multicelled life](#); July 2010). There have been a few claims for biogenic material, such as microscopic tubular structures in 3.5 billion-year (Ga) old pillow lavas and 3.2 Ga cherts from South Africa (see: [Early biomarkers in South African pillow lavas](#); April 2004 and [Believable Archaean fossils](#); March 2010) which some researchers dispute. Then there are Archaean stromatolites, which may be evidence for bacterial mats. The oldest of them have been claimed to occur in the famous, 3.77 Ga [Isua metasediments of West Greenland](#). But such early fossils are chance finds, so geochemists have entered the arena with attempts to find irrefutable chemical signatures for life in ancient rocks.

One approach is isotope geochemistry. Carbon isotope data have been widely used, because life processes, such as photosynthesis, result in a deficiency of <sup>13</sup>C relative to <sup>12</sup>C. This was tried on graphite crystals trapped in sedimentary phosphate minerals from Isua. The results were at first acclaimed as a sign of life at around 3.8 Ga, but then refuted. In 2015 a similar approach was applied to graphite trapped in a 4.1 Ga detrital zircon, seemingly pushing back evidence for life into the Hadean. But zircon is a mineral produced by crystallisation of magma, so the fractionation of carbon isotopes in trapped graphite seem unlikely to shed light on the earliest life. The main drawback to using carbon isotopes is because metamorphism, [Fischer-Tropsch](#) mechanisms in hydrothermal environments, and volcanic processes may be responsible for enrichment of lighter carbon isotopes relative to <sup>13</sup>C. The relative abundance of the different isotopes of iron in Archaean sediment may give clues to the transient availability of oxygen generated by bacterial photosynthesis that would oxidise soluble Fe<sup>2+</sup> to insoluble Fe<sup>3+</sup>. [Promising results were obtained in 2013 from 3.8 Ga banded ironstones at Isua](#). But doubt was again raised, so the only generally accepted evidence is that of the microfossils found in hydrothermal

cherts in Palaeoarchaeon pillow lavas from South Africa and Western Australia and the earliest stromatolites, all around 3.4 to 3.5 Ga old. However, recent research may have opened up a more convincing route to tracking down ancient life forms –actual organic molecules that make up or are produced by organisms.

Michael Wong and co-workers at the Carnegie Institution for Science in Washington, DC, USA together with other colleagues from the US, Austria, Canada, China, Belgium, Norway, Australia, the UK and France used artificial intelligence to wade through the results of geochemical analysis of over 400 ancient and modern carbon-bearing samples. (Wong, M.I. and 28 others 2025. [Organic geochemical evidence for life in Archean rocks identified by pyrolysis–GC–MS and supervised machine learning](#). *Proceedings of the National Academy of Sciences*, v. **122**, article e2514534122: DOI: [10.1073/pnas.2514534122](#)). Their objective was to track the presence of organically derived molecules as far back as possible. Their approach bears a passing resemblance to that used to build genomes of ancient fossils from broken bits of DNA that reside in them. Like DNA, bio-molecules degrade over time, but leave fragments in rocks that can be detected using pyrolysis gas chromatography and mass spectrometry. In itself PGC-MS is not especially new, but using artificial intelligence (machine learning) on a massive data set certainly is: perhaps the first major trial of AI in geology.



Percentages of samples designated as biogenic by Wong et al's AI analysis. Credit: Wong et al, Fig 4

Their samples were not just ancient rocks going back into the Archean as far back as 3.5 Ga, but included modern biological material, meteorites presumed to have been devoid of life since their origin in pre-solar system times and synthetic samples. Wong *et al* divided 272 samples with known biological affinities into 9 groups to train the AI algorithm. The analytical method breaks down organic and inorganic carbonaceous materials into fragments of molecules: the opposite of DNA sequencing. When subjected to PGC-MS each type of living organism, from bacteria to animals produces a distinct pattern of molecular fragments. The AI analysis is based on a sophisticated statistical algorithm being trained to recognise 'debris' from organic and inorganic carbonaceous compounds according to each sample's geochemical 'fingerprint'. Part of the 'training' was based on sediments that contain irrefutable fossil samples from as far back in time as the Mesoproterozoic (1000 Ma). Another part was based on definitely inorganic materials, such as carbonaceous meteorites. AI proved able to distinguish biological from inorganic material with a probability up to 0.9 (90%). These results suggested that older, more biologically uncertain material could be assessed.

The AI was able to distinguish general biogenic affinities from inorganic ones in samples with decreasing success going back in time: as high as 0.93 in the Phanerozoic to 0.47 in the Archaean. The oldest samples that reached the probability threshold for this distinction (0.6) were 3.3 Ga cherts from the Barberton Greenstone Belt in South Africa. Another distinction between photosynthetic and non-photosynthetic affinities among the samples that ‘passed’ as probably biotic reached the 0.6 probability threshold at 2.5 Ga for a sample from South Africa. Non-photosynthetic, but still probably biotic samples extend as far back as 3.5 Ga in South African and Western Australian Greenstone Belts.

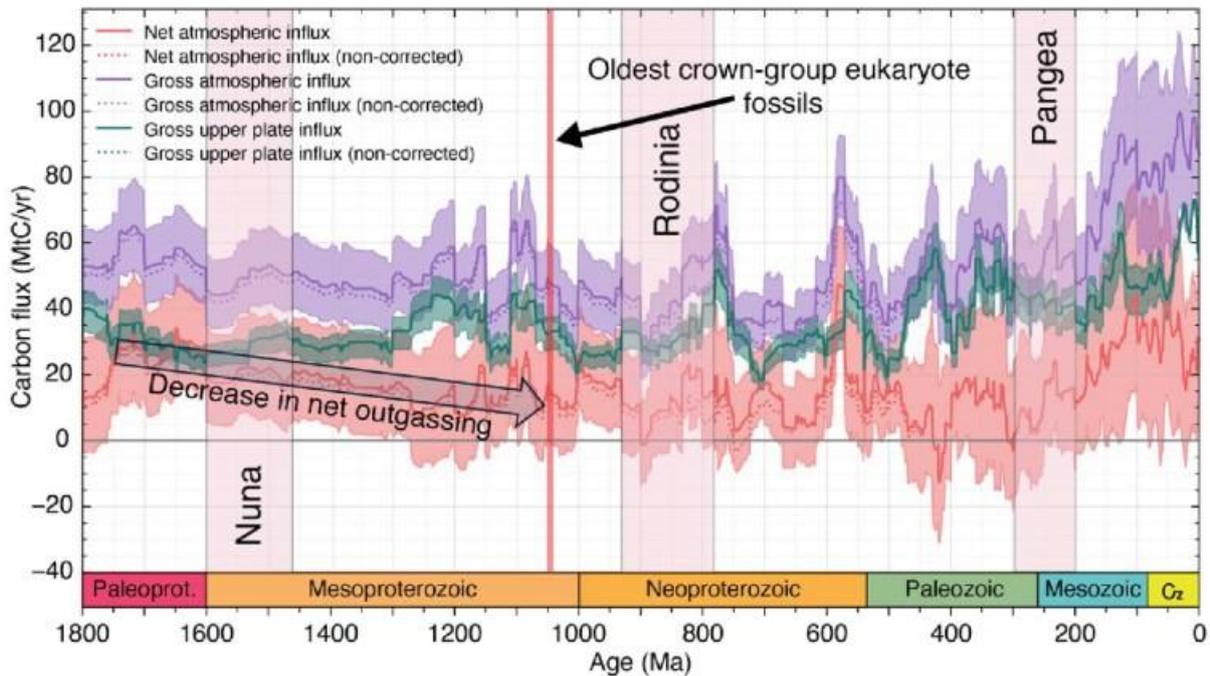
Although Wong *et al.*'s preliminary exploration with their novel approach doesn't take us beyond the current 3.4 to 3.5 Ga age for the earliest tangible suggestions of life. However, they note ‘...our sample inventory is notably lacking in ancient *abiogenic* samples’. This is a good indication of the promise for further progress that the approach offers. Previous research has sought intact biogenic molecules, with not a great deal of luck, over several decades. Their final conclusion is ‘...information-rich attributes of ancient organic matter, even though highly degraded and with few if any surviving biomolecules, have much to reveal about the nature and evolution of life.’ They have opened a very important avenue in palaeobiological research, as their methodology seems capable of fine tuning to all manner of pro- and eukaryote biochemical distinctions. It could even be used with extraterrestrial material, should we ever get any ...

**See also:** Walsh, E. 2025. [Researchers report earliest molecular evidence of photosynthetic life](#). *Chemical & Engineering News*, 18 November 2025.

## ***The ‘boring billion’ years of the Mesoproterozoic: plate tectonics and the eukaryotes***

PUBLISHED ON [December 10, 2025](#)

The emergence of the eukaryotes – of which we are a late-entry member – has been debated for quite a while. In 2023 *Earth-logs* reported that a study of ‘biomarker’ [organic chemicals in Proterozoic sediments](#) suggests that eukaryotes cannot be traced back further than about 900 Ma ago using such an approach. At about the same time another biomarker study showed signs of a eukaryote presence at around 1050 Ma. Both outcomes seriously contradicted a ‘molecular-clock’ approach based on the DNA of modern members of the Eukarya and estimates of the rate of genetic mutation. That method sought to deduce the time in the past when the [last eukaryotic common ancestor](#) (LECA) appeared. It pointed to about 2 Ga ago, i.e. a few hundred million years after the Great Oxygenation Event got underway. Since eukaryote metabolism depends on oxygen, the molecular-clock result seems reasonable. The biomarker evidence does not. But were the Palaeo- and Mesoproterozoic Eras truly ‘boring’? A recent paper by Dietmar Müller and colleagues from the Universities of Sydney and Adelaide, Australia definitely shows that geologically they were far from that (Müller, R.D. *et al.* 2025. [Mid-Proterozoic expansion of passive margins and reduction in volcanic outgassing supported marine oxygenation and eukaryogenesis](#). *Earth and Planetary Science Letters*, v. **672**; DOI: 10.1016/j.epsl.2025.119683).

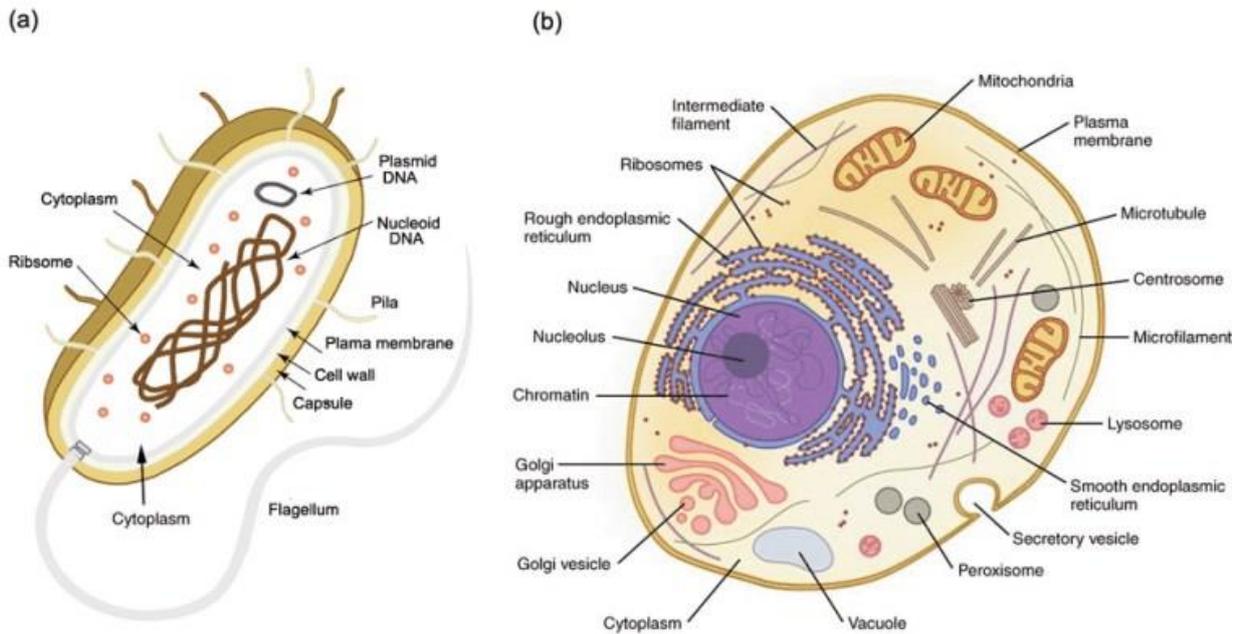


Carbon influx (megatons  $\text{yr}^{-1}$ ) into tectonic plates and into the ocean-atmosphere system from 1800 Ma to present. Colour bands represent: total carbon influx into the atmosphere (mauve); sequestered into tectonic plates (green); net atmospheric influx i.e. total minus carbon in plates (pink). The widths of the bands show the uncertainties of the calculated masses shown as darker coloured lines.

From 1800 to 800 Ma two supercontinents— [Nuna-Columbia](#) and [Rodinia](#) – aggregated nearly all existing continental masses, and then broke apart. Continents had collided and then split asunder to drift. So plate tectonics was very active and encompassed the entire planet, as Müller *et al.*'s [palaeogeographic animation](#) reveals dramatically. Tectonics behaved in much the same fashion through the succeeding Neoproterozoic and Phanerozoic to build-up then fragment the more familiar supercontinent of Pangea. Such dynamic events emit magma to form new oceanic lithosphere at oceanic rift systems and arc volcanoes above subduction zones, interspersed with plume-related large igneous provinces and they wax and wane. Inevitably, such partial melting delivered carbon dioxide to the atmosphere. Reaction on land and in the rubble flanks of spreading ridges between new lithosphere and dissolved  $\text{CO}_2$  drew down and sequestered some of that gas in the form of solid carbonate minerals. Continental collisions raised the land surface and the pace of weathering, which also acted as a carbon sink. But they also involved metamorphism that released carbon dioxide from limestones involved in the crustal transformation. This protracted and changing tectonic evolution is completely bound up through the rock cycle with geochemical change in the carbon cycle.

From the latest knowledge of the tectonic and other factors behind the accretion and break-up of Nuna and Rodinia, Müller *et al.* were able to model the changes in the carbon cycle during the 'boring billion' and their effects on climate and the chemistry of the oceans. For instance, about 1.46 Ga ago, the total length of continental margins doubled while Nuna broke apart. That would have hugely increased the area of shallow shelf seas where living processes would have been concentrated, including the photosynthetic emission of oxygen. In an evolutionary sense this increased, diversified and separated the ecological niches in which evolution could prosper. It also increased the sequestration of greenhouse gas through reactions on the flanks of a multiplicity of oceanic rift systems, thereby cooling the planet. Translating this into a geochemical model of the changing carbon cycle (see figure) suggests that the rate of carbon addition to the atmosphere (outgassing) halved during the Mesoproterozoic. The carbon cycle and probable global cooling bound up with Nuna's breakup ended with the start of

Rodinia's aggregation about 1000 Ma ago and the time that biomarkers first indicate the presence of eukaryotes.



Simplified structures of (a) a prokaryote cell; (b) a simple eukaryote animal cell (at very different scales).  
Plants also contain organelles called chloroplasts

So, did tectonics play a major role in the rise of the Eukarya? Well, of course it did, as much as it was subsequently the changing background to the appearance of the Ediacaran animals and the evolutionary carnival of the Phanerozoic. But did it affect the billion-year delay of 'eukaryogenesis' during prolonged availability of the oxygen that such a biological revolution demanded? Possibly not. Lyn Margulis's hypothesis of the [origin of the basic eukaryote cell by a process of 'endosymbiosis'](#) is still the best candidate 50 years on. She suggested that such cells were built from various forms of bacteria and archaea successively being engulfed within a cell wall to function together through symbiosis. Compared with prokaryote cells those of the eukaryotes are enormously complex. At each stage the symbionts had to be or become compatible to survive. It is highly unlikely that all components entered the relationship together. Each possible kind of cell assembly was also subject to evolutionary pressures. This clearly was a slow evolutionary process, probably only surviving from stage to stage because of the global presence of a little oxygen. But the eukaryote cell may also have been forced to restart again and again until a stable form emerged.

**See also:** [New Clues Show Earth's "Boring Billion" Sparked the Rise of Life](#). *SciTechDaily*, 3 November 2025