Palaeobiology 2024

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Darwin's 'warm little pond': a new discovery

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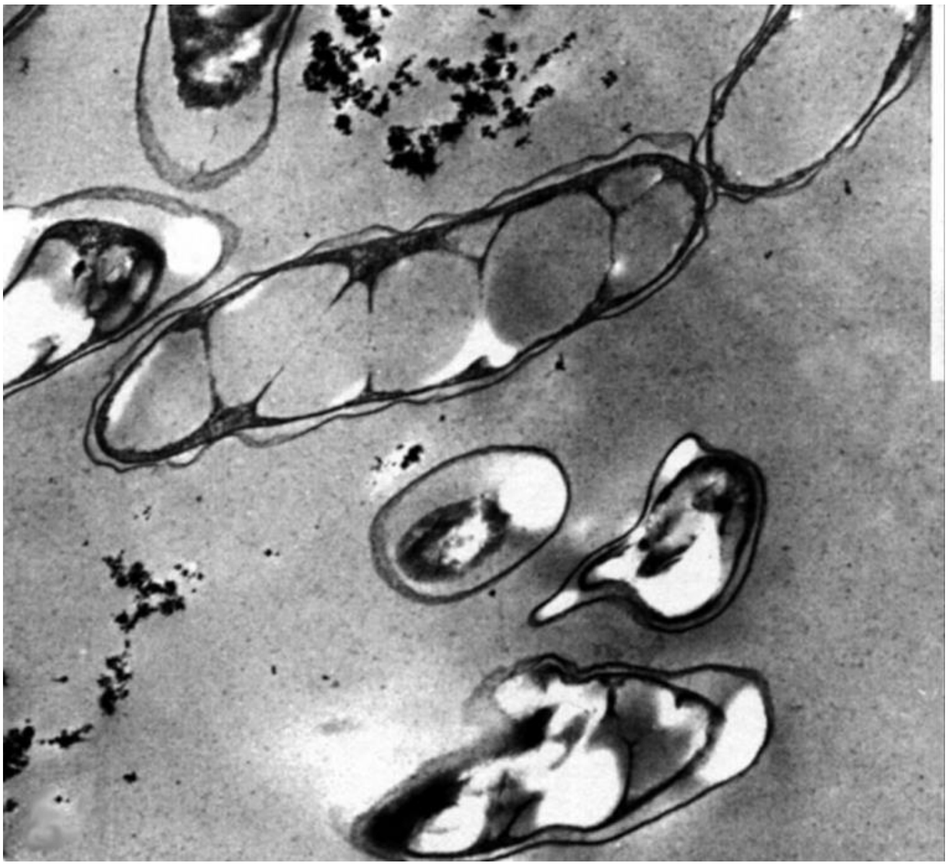
There may still be a few people around today who, like Aristotle did, reckon that frogs form from May dew and that maggots and rats spring into life spontaneously from refuse. But the idea that life emerged somehow from the non-living is, to most of us, the only viable theory. Yet the question, 'How?', is still being pondered on. Readers may find Chapter 13 of Stepping Stones useful. There I tried to summarise in some detail most of the modern lines of research. But the issue boils down to means of inorganically creating the basic chemical building blocks from which life's vast and complex array of molecules might have been assembled. Living materials are dominated by five cosmically common elements: carbon, hydrogen, oxygen, nitrogen and phosphorus – CHONP for short. Organic chemists can readily synthesise countless organic compounds from CHONP. And astronomers have discovered that life is not needed to assemble the basic ingredients: amino acids, carbon-ring compounds and all kinds of simpler CHONP molecules occur in meteorites, comets and even interstellar molecular clouds. So an easy way out is to assume that such ingredients ended up on the early Earth simply because it grew through accretion of older materials from the surrounding galaxy. Somehow, perhaps, their mixing in air, water and sediments together with a kind of chaotic shuffling did the job, in the way that an infinity of caged monkeys with access to typewriters might eventually create the entire works of William Shakespeare. But, aside from the statistical and behavioural idiocy of that notion, there is a real snag: the vaporisation of the proto-Earth's outer parts by a Moon-forming planetary collision shortly after initial accretion.

In 1871 Charles Darwin suggested to his friend Joseph Hooker that:

> *'… if (and Oh, what a big if) we could conceive in some warm little pond, with all sorts of ammonia and phosphoric salts, light, heat, electricity, etc., present that a protein compound was chemically formed, ready to undergo still more complex changes, at the present day such matter would be instantly devoured or absorbed, which would never have been the case before living creatures were formed'.*

Followed up in the 1920s by theorists Alexander Oparin and J.B.S. Haldane, a similar hypothesis was tested practically by Harold Urey and Stanley Miller at the University of Chicago. They devised a Heath-Robinson simulation of an early atmosphere and ocean seeded with simple CHONP (plus a little sulfur) chemicals, simmered it and passed electrical discharges through it for a week. The resulting dark red 'soup' contained 10 of the 20 amino acids from which a vast array of proteins can be built. A repeat in 1995 also yielded two of the four nucleobases at the heart of DNA – adenine and guanine. But simply having such chemicals around is unlikely to result in life, unless they are continually in close contact: a vessel or bag in which such chemicals can interact. The best candidates for such a containing membrane are fatty acids of a form known as amphiphiles. One end of an **amphiphile chain** has an affinity for water molecules, whereas the other repels them. This duality enables layers of them, when assembled in water, spontaneously to curl up to make three dimensional membranes looking like bubbles. In the last year they too have been created *in vitro* (Purvis, G. *et al*. 2024. **Generation of long-chain fatty acids by hydrogen-driven bicarbonate reduction in ancient alkaline hydrothermal vents**. *Nature Communications (Earth & Environment)*, v. **5**, article 30; DOI: 10.1038/s43247-023-01196-4).



Cell-like membranes formed by fatty acid amphiphiles

Graham Purvis and colleagues from Newcastle University, UK allowed three very simple ingredients – hydrogen and bicarbonate ions dissolved in water and the iron oxide magnetite (Fe_3O_4) – to interact. Such a simple, inorganic mixture commonly occurs in hydrothermal vents and hot springs. Bicarbonate ions (HCO_3^-) form when CO_2 dissolves in water, the hydrogen and magnetite being generated during the breakdown of iron silicates (olivines) when [ultramafic igneous rocks react with water]:

$3Fe_2SiO_4 + 2H_2O \rightarrow 2\ Fe_3O_4 + 3SiO_2 + 3H_2$

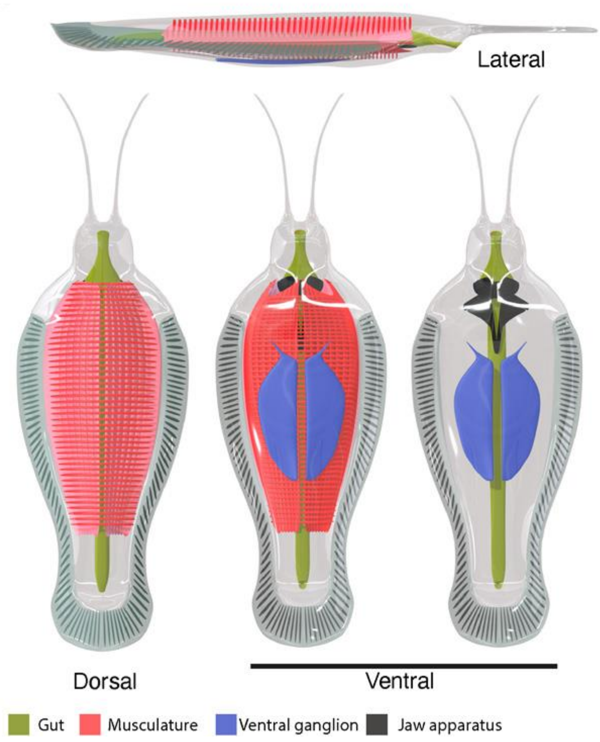
Various simulations of hydrothermal fluids had previously been tried without yielding amphiphile molecules. Purvis *et al*. simplified their setup to a bicarbonate solution in water that contained dissolved hydrogen – a simplification of the fluids emitted by hydrothermal vents – at 16 times atmospheric pressure and a temperature of 90°C. This was passed over magnetite. Under alkaline conditions their reaction cell yielded a range of chain-like hydrocarbon molecules. Among them was a mixture of fatty acids up to 18 carbon atoms in length. The experiment did not incorporate P, but its generation of amphiphiles that can create cell-like structures are but a step away from forming the main structural components of cell membranes, phospholipids.

When emergence of bag-forming membranes took place is, of course, hard to tell. But in the oldest geological formations ultramafic lava flows are far more common than they are today. In the Hadean and Eoarchaean, even if actual mantle rocks had not been obducted as at modern plate boundaries, at the surface there would have been abundant source materials for the vital amphiphiles to be generated through interaction with water and gases: perhaps in '*hot* little ponds'. To form living, self-replicating cells requires such frothy membranes to have captured and held amino acids and nucleobases. Such proto-cells could become organic reaction chambers where chemical building blocks continually interacted, eventually to evolve the complex forms upon which living cells depend.

When giant worms roamed the seas!

PUBLISHED ON *January 8, 2024*

At the start of the Cambrian Period animal life began to diversify from that of the Ediacaran world. For the first time sediments on the seafloor were explored for sustenance, leading to a variety of burrows that disrupted fine depositional layers. The basal Cambrian sandstones found in Britain and elsewhere are pervasively bioturbated: good evidence for the start of a 'Worm world' that marks the Precambrian-Phanerozoic boundary. That is probably a misnomer for the shallow seabed of that time, as fossils of burrowers with a variety of hard parts turn up in the oldest Cambrian sequences. Also appearing for the first time are tooth-like microfossils that took on such a range of bizarre shapes that they have long been used for correlating sedimentary strata in the absence of larger creatures. Some of these conodonts have been attributed to early vertebrates akin to modern lampreys and hag fish, but others may have been the grasping mouth-spines of a group of predatory worms which also survive to the present: chaetognaths. Apart from these oral spines chaetognaths lack hard parts, so anatomical details of ancient ones are only found in sites of exquisite preservation or lagerstätten. In such rare, tranquil places soft tissues such as muscles may be preserved by phosphatisation during decay.



Reconstruction of *Timorebestia koprii* showing its musculature, nerve system and mouthparts, It probably propelled itself by fluttering its outer and rear flaps, much like a modern flatfish. Credit: Park et al., Fig 4

One of the earliest Phanerozoic lagerstätten (Sirius Passet) occurs in northern Greenland. It is curiously named after the Sirius Dog Sled Patrol, an elite pair of naval troops with a sledge and 12 dogs that enforces Danish sovereignty over the Greenlandic shore of the Arctic Ocean. The Sirius Passet fauna includes a monstrous chaetognath over 30 cm long (Park, T.-Y. S. and 12 others 2024. **A giant stem-group chaetognath**. *Science Advances*, v. **10** article eadi6678; DOI: 10.1126/sciadv.adi6678). It is called *Timorebestia koprii* (*Timorebestia* is Latin for 'terror beast') and was related to the living, but tiny, arrow worms that prey on zooplankton in modern oceans. This description and moniker may seem to be somewhat hyperbolic, but *Timorobestia* outranks in size any Early Cambrian predatory arthropods. It was probably high in the Early Cambrian trophic pyramid, but was soon relegated by the later Cambrian rise of trilobites and then of cephalopods and eventually jawed vertebrate fishes in the Silurian. One specimen contained shells of a swimming arthropod whose protective spines did not deter the 'terrible' chaetognath from swimming them down.

See also: 'Giant' predator worms more than half a billion years old discovered in North Greenland. *Science Daily*, 3 January 2024.

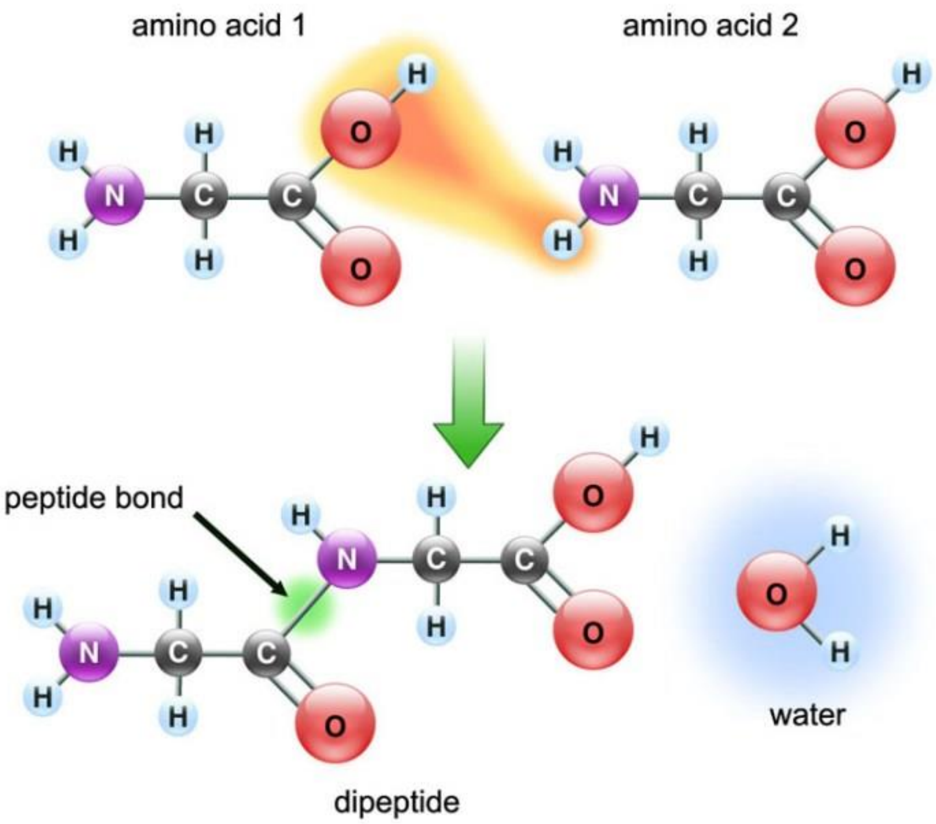
The peptide bond that holds life together may have an interstellar origin

PUBLISHED ON *April 24, 2024*

In the 1950s Harold Urey of the University of Chicago and his student Stanley Miller used basic lab glassware containing 200 ml of water and a mix of the gases methane (CH_4), ammonia (NH_3) and hydrogen sulfide (H_2S) to model conditions on the early Earth. Heating this crude analogue for ocean and atmosphere and continuous electrical discharge through it did, in a Frankensteinian manner, generate amino acids. Repeats of the Miller-Urey experiment have yielded 10 of the 20 amino acids from which the vast array of life's proteins have been built. Experiments along similar lines have also produced the possible precursors of cell walls – amphiphiles. In fact, all kinds of 'building blocks' for life's chemistry turn up in analyses of carbonaceous chondrite meteorites and in light spectra from interstellar gas clouds. The 'embarrassment of riches' of life's precursors from what was until the 20th century regarded as the 'void' of outer space lacks one thing that could make it a candidate for life's origin, or at least for precursors of proteins and the genetic code DNA and RNA. Both kinds of keystone chemicals depend on a single kind of connector in organic chemistry.

Molecules of amino acids have acidic properties (COOH – carboxyl) at one end and their other end is basic (NH_2 – amine). Two can react by their acid and basic 'ends' neutralising. A hydroxyl (OH^-) from carboxyl and a proton (H^+) from amine produce water. This gives the chance for an end-to-end linkage between the nitrogen and carbon atoms of two amino acids – the **peptide bond.** The end-product is a dipeptide molecule, which also has carboxyl at one end and amine at the other. This enables further linkages through peptide bonds to build chains or polymers based on amino acids – proteins. Only 20 amino acids contribute to terrestrial life forms, but linked in chains they can form potentially an unimaginable diversity of proteins. Formation of even a small protein that links together 100 amino acids taken from that small number illustrates the awesome potential of the peptide bond. The number of possible permutations and combinations to build such a protein is

20^{100} – more than the estimated number of atoms in the observable universe! Protein-based life has almost infinite options: no wonder that ecosystems on Earth are so diverse, despite using a mere 20 building blocks. Simple amino acids can be chemically synthesised from C, H, O and N. About 500 occur naturally, including 92 found in a single carbonaceous chondrite meteorite. They vastly increase the numbers of conceivable proteins and other chain-molecules analogous to RNA and DNA: a point seemingly lost on exobiologists and science fiction writers!



Reaction between two molecules of the amino acid glycene that links them by a peptide bond to form a dipeptide. (Credit: Wikimedia Commons)

Serge Kranokutski of the Max Planck Institute for Astronomy at the Friedrich Schiller University in Jena, German and colleagues from Germany, the Netherlands and France have assessed the likelihood of peptides forming in interstellar space in two publications (Kranokutski S.A. and 4 others 2022. A pathway to peptides in space through the condensation of atomic carbon. *Nature Astronomy*, v, **6**, p. 381–386; DOI: 10.1038/s41550-021-01577-9. Kranokutski, S.A. *et al*. 2024. Formation of extraterrestrial peptides and their derivatives. *Science Advances*, v. **10**, article eadj7179; DOI: 10.1126/sciadv.adj7179). In the first paper the authors show experimentally that condensation of carbon atoms on cold cosmic dust particles can combine with carbon monoxide (CO) and ammonia (NH_3) form amino acids. In turn, they can polymerise to produce peptides of different lengths. The second demonstrates that water molecules, produced by peptide formation, do not prevent such reactions from happening. In other words, proteins can form inorganically anywhere in the cosmos. Delivery of these products, through comets or meteorites, to planets forming in the habitable 'Goldilocks' zone around stars may have been 'an important element in the origins of life' – anywhere in the universe. Chances are that, compared with the biochemistry of

Earth, such life would be alien in an absolute sense. There are effectively infinite options for the proteins and genetic molecules that may be the basis of life elsewhere, quite possibly on Mars or the moons of Jupiter and Saturn: should it or its chemical fossils be detectable.

Snowball Earth and the rise of multi-celled life

PUBLISHED ON *July 15, 2024*

You can follow my 'reportage' on the long running story of the Snowball Earth events during the Neoproterozoic Cryogenian Period (850 to 635 Ma) since 2000 through the index to annual Palaeoclimatology logs (15 posts). Once these dramatic events were over sedimentary rocks deposited around the world during the Ediacaran Period (635 to 541 Ma) record the sudden appearance of large-bodied fossils: the first multicellular animals. This explosion from slimy biofilms and colonies of single-celled prokaryotes and eukaryotes laid the basis for the myriad ecological niches that have characterised Planet Earth ever since. The change saw specialised eukaryote cells (see: The rise of the eukaryotes; *December 2017*), whose precursors had originated in single-celled forms, begin to cooperate inthe development of complex tissues, organs, and organ systems to form bodies rather than just cell walls. The pulsating evolution, diversification and repeated extinction that followed during the last one tenth of geological time shaped a planet that is unique in the Solar System and possibly in the galaxy, if not the entire universe. The simple biosphere that preceded it, on the other hand, may have emerged on innumerable rocky planets blessed with liquid water to survive little changed for billions of years, as have Earths' prokaryotes, the Archaea and Bacteria.

Artist's impression of the Ediacaran Fauna (credit: Science)

The Ediacaran biological revolution followed repeated changes in the geochemistry of the oceans, which carbon isotope data from the Cryogenian and Ediacaran suggest to have 'gone haywire'. This turmoil involved dramatic changes in the cycling of sulfur and phosphorus that help 'fertilise' the marine food chain and in the production of oxygen by photosynthesis that is essential for metazoan animals. The episodes when the Earth was iced over reduced the availability of nutrients through decreased rates of ocean-floor burial of dead organisms. Such Snowball events would also have reduced penetration of sunlight in the oceans. Less photosynthesis would not only have reduced oxygen production but also the amounts of autotrophic organisms. Furthermore, decreased water temperature would have increased its viscosity thereby slowing the spread of nutrients. The food chain for heterotrophs was decimated. Each Snowball event ended with warming, ice-free conditions so that the marine biosphere could burgeon

A great deal of data and numerous theories have accumulated since the Snowball concept was first mooted, but there has been little progress in understanding the rise of multi-celled life. Four geoscientists from the Massachusetts Institute of Technology, the Santa Fe Institute and the University of Colorado (Boulder), USA have developed an interesting hypothesis for how this enormous evolutionary step may have developed (Crockett, W.W. *et al*. 2024. **Physical constraints during Snowball Earth drive the evolution of multicellularity**. *Proceedings of the Royal Society B: Biological Sciences*, v. **291**; DOI: 10.1098/rspb.2023.2767). The concatenation of huge events during the Cryogenian and Ediacaran presented continually changing patterns of selective pressures on simple organisms that preceded that time period. Crockett *et al*. review them in the light of fundamental biology to suggest how multicellular animals emerged as the Ediacara Fauna. Intuitively, such harsh conditions suggest at worst mass, even complete, extinction, at best a general reduction in size of all organism to cope with scarce resources. That the size of eukaryotes should have grown hugely goes against the grain of most biologists' outlook.

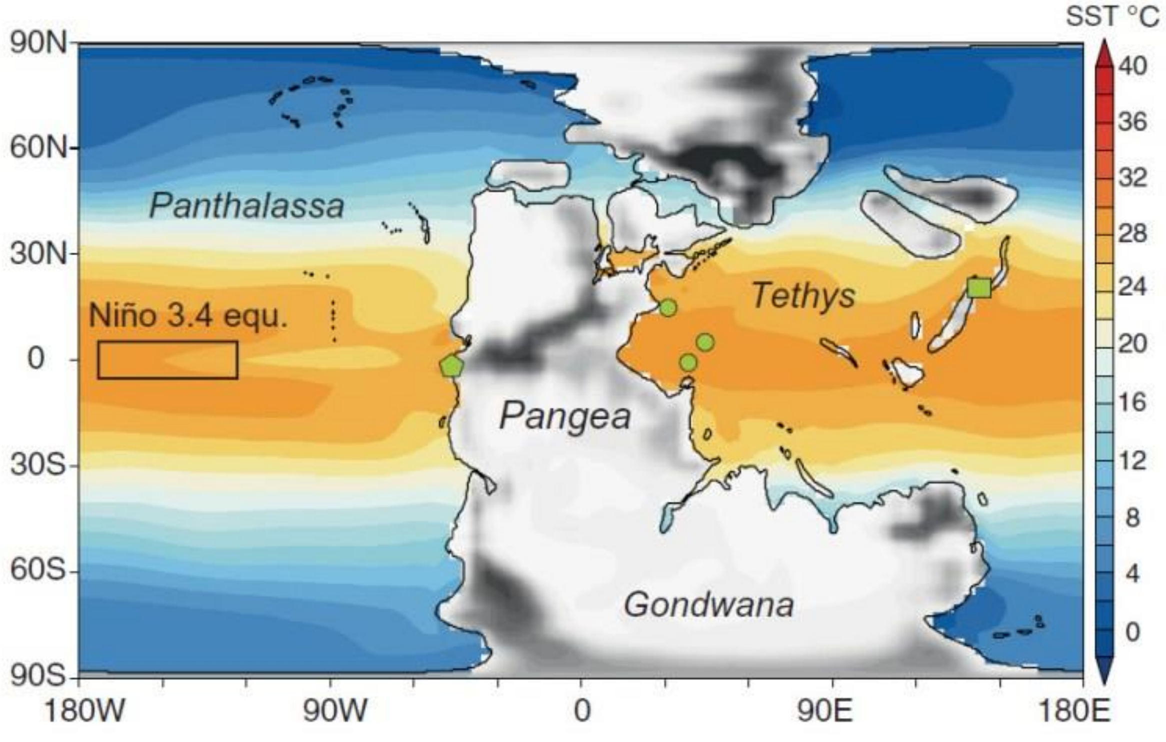
The authors consider the crucial factor to be fundamental differences between prokaryotes and early eukaryotes. Prokaryote cells are very small, and whether autotrophs of heterotrophs they absorb nutrients through their walls by diffusion. Single-celled eukaryotes are far larger than prokaryotes and typically have a flagellum or 'tail' so that they can move independently and more easily gather resources. Crockett *et al*. used computer modelling to simulate the type of life form that could grow and thrive under Snowball conditions. They found that prokaryotes could only grow smaller, being 'stunted' by scarce resources. On the other hand eukaryotes would be better equipped to gather resources, the more so if they adopted a simple multicellular form – a hollow, self-propelled sphere about the size of a pea, which the authors dub a *choanoblastula*. Although no such form is known today, it does resemble the green *Volvox* algae, and plausibly could have evolved further to the simple forms of the Ediacaran fauna. The next task is either to find a fossil of such an organism, or to grow one.

Climate changes and the mass extinction at Permian-Triassic boundary

PUBLISHED ON *September 18, 2024*

The greatest mass extinction in Earth's history at around 252 Ma ago snuffed out 81% of marine animal species, 70% of vertebrates and many invertebrates that lived on land. It is not known how many land plants were removed, but the complete absence of coals from the first 10 Ma of the Early Triassic suggests that luxuriant forests that characterised low-lying humid area in the Permian disappeared. A clear sign of the sudden dearth of plant life is that Early Triassic river sediments were no longer deposited by meandering rivers but by braided channels. Meanders of large river channels typify land surfaces with abundant vegetation whose root systems bind alluvium. Where vegetation cover is sparse, there is little to constrain river flow and alluvial erosion, and wide braided river courses develop (**see:** End-Permian devastation of land plants; September 2000. You can follow 21st century developments regarding the P-Tr extinction using the Palaeobiology index).

The most likely culprit was the Siberian Trap flood basalts effusion whose lavas emitted huge amounts of CO_2 and even more through underground burning of older coal deposits (**see:** Coal and the end-Permian mass extinction; March 2011) which triggered severe global warming. That, however, is a broad-brush approach to what was undoubtedly a very complex event. Of about 20 volcanism-driven global warming events during the Phanerozoic only a few coincide with mass extinctions. Of those none comes close the devastation of 'The Great Dying', which begs the question, 'Were there other factors at play 252 Ma ago?' That there must have been is highlighted by the terrestrial extinctions having begun significantly earlier than did those in marine ecosystems, and they preceded direct evidence for climatic warming. Also temperature records – obtained from shifts in oxygen isotopes held in fossils – for that episode are widely spaced in time and tell palaeoclimatologists next to nothing about the details of the variation of air- and sea-surface temperature (SST) variations.



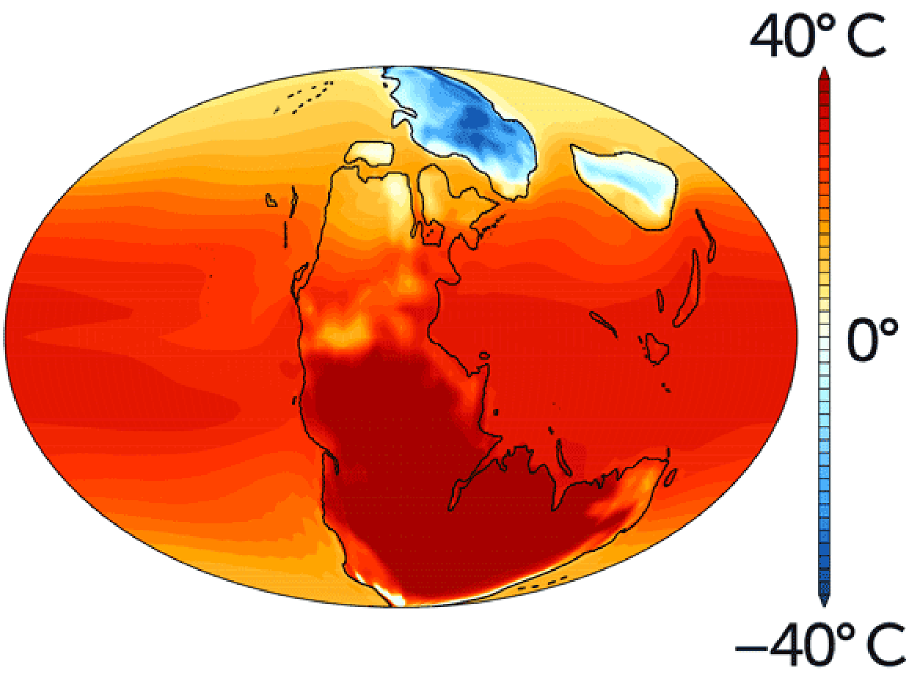
Modelled sea-surface temperatures in the tropics in the early stages of Siberian Trap eruptions with atmospheric CO¬2 at 857 ppm – twice today's level. (Credit: Sun et al., Fig. 1A)

Earth at the end of the Permian was very different from its current wide dispersal of continents and multiple oceans and seas. Then it was dominated by Pangaea, a single supercontinent that stretched almost from pole to pole, and a surrounding vast ocean known as Panthalassa. Geoscientists from China, Germany, Britain and Austria used this simple palaeogeography and the available Early Triassic greenhouse-gas and palaeo-temperature data as input to a climate prediction model (HadCM3BL) (Yadong Sun and 7 others 2024. Mega El Niño instigated the end-Permian mass extinction. *Science* 385, p. 1189–1195; DOI: 10.1126/science.ado2030 – contact yadong.sun@cug.edu.cn for PDF).. The computer model was developed by the Hadley

Centre of the UK Met Office to assess possible global outcomes of modern anthropogenic global warming. It assesses heat transport by atmospheric flow and ocean currents and their interactions. The researchers ran it for various levels of atmospheric CO_2 concentrations over the estimate 100 ka duration of the P-Tr mass extinction.

The pole-to-pole continental configuration of Pangaea lends itself to equatorial El Niño and El Niña type climatic events that occur today along the Pacific coast of the Americas, known as the El Niño-Southern Oscillation. In the first, warm surface water builds-up in the eastern tropical Pacific Ocean. It then then drifts westwards to allow cold surface water to flow northwards along the Pacific shore of South America to result in El Niña. Today, this climatic 'teleconnection' not only affects the Americas but also winds, temperature and precipitation across the whole planet. The simpler topography at the end of the Permian seems likely to have made such global cycles even more dominant.

Sun *et al*'s simulations used stepwise increases in the atmospheric concentration of CO_2 from an estimated 412 parts per million (ppm) before the eruption of the Siberian Traps (similar to those today) to a maximum of 4000 ppm during the late-stage magmatism that set buried coals ablaze. As levels reached 857 ppm SSTs peaked at 2 °C above the mean level during El Niño events and the cycles doubled in length. Further increase in emissions led to greater anomalies that lasted longer, rising to 4°C above the mean at 4000 ppm. The El Niña cooler parts of the cycle steadily became equally anomalous and long lasting. This amplification of the 252 Ma equivalent of the El Niño-Southern Oscillation would have added to the environmental stress of an ever increasing global mean surface temperature. The severity is clear from an animation of mean surface temperature change during a Triassic ENSO event.



Animation of monthly average surface temperatures across the Earth during an ENSO event at the height of the P-Tr mass extinction. (Credit: Alex Farnsworth, University of Bristol, UK)

The results from the modelling suggest increasing weather chaos across the Triassic Earth, with the interior of Pangaea locked in permanent drought. Its high latitude parts would undergo extreme heating and then cooling from 40°C to -40°C during the El Niño- El Niña cycles. The authors suggest that conditions on the continents became inimical for terrestrial life, which would be unable to survive even if they migrated long distances. That can explain why terrestrial extinctions at the P-Tr boundary preceded those in the global ocean. The marine biota probably succumbed to anoxia (**See:** Chemical conditions for the end-Permian mass extinction; November 2008)

There is a timely warning here. The El Niño-Southern Oscillation is becoming stronger, although each El Niño is a mere 2 years long at most, compared with up to 8 years at the height of the P-Tr extinction event. But it lay behind the record 2023-2024 summer temperatures in both northern and southern hemispheres, the North American heatwave of June 2024 being 15°C higher than normal. Many areas are now experiencing unprecedentedly severe annual wildfires. There also finds a parallel with conditions on the fringes of Early Triassic Pangaea. During the early part of the warming charcoal is common in the relics of the coastal swamps of tropical Pangaea, suggesting extensive and repeated wildfires. Then charcoal suddenly vanishes from the sedimentary record: all that could burn had burnt to leave the supercontinent deforested.

See also: Voosen, P. 2024. Strong El Niños primed Earth for mass extinction. *Science* 385, p. 1151; DOI: 10.1126/science.z04mx5b; Buehler, J. 2024. Mega El Niños kicked off the world's worst mass extinction. *ScienceNews*, 12 September 2024.

Multiple Archaean gigantic impacts, perhaps beneficial to some early life

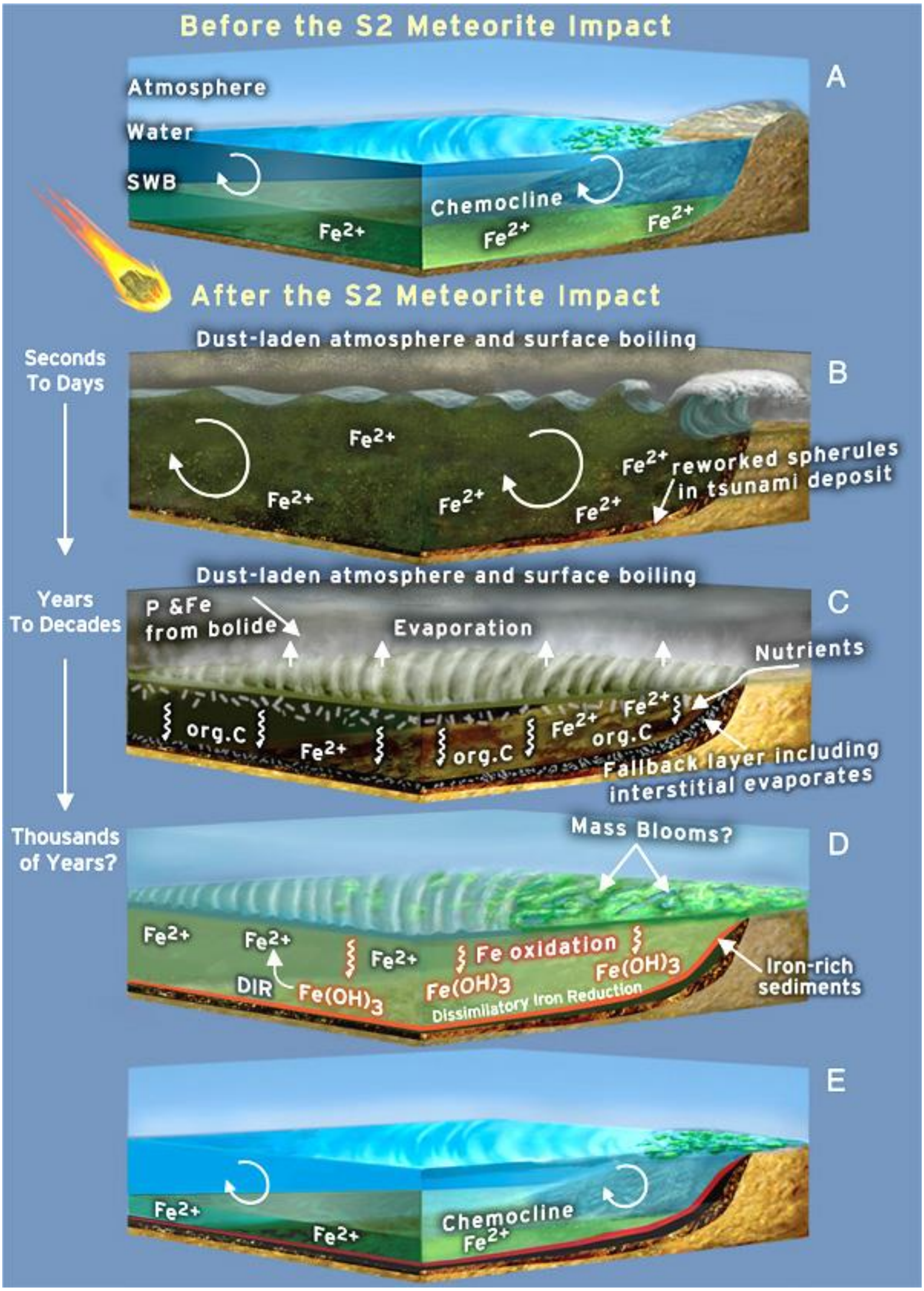
PUBLISHED ON *October 29, 2024*

In March 1989 an asteroid half a kilometre across passed within 500 km of the Earth at a speed of 20 km s^{-1}. Making some assumptions about its density, the kinetic energy of this near miss would have been around 4 x 10^{19} J: a million times more than Earth's annual heat production and humanity's annual energy use; and about half the power of detonating every thermonuclear device ever assembled. Had that small asteroid struck the Earth all this energy would have been delivered in a variety of forms to the Earth System in little more than a second – the time it would take to pass through the atmosphere. The founder of "astrogeology" and NASA's principal geological advisor for the Apollo programme, the late Eugene Shoemaker, likened the scenario to a '*small hill falling out of the sky*'. (Read a summary of what would happen during such an asteroid strike). But that would have been dwarfed by the 10 to 15 km impactor that resulted in the ~200 km wide Chicxulub crater and the K-Pg mass extinction 66 Ma ago. Evidence has been assembled for Earth having been struck during the Archaean around 3.6 billion years (Ga) ago by an asteroid 200 to 500 times larger: more like four Mount Everests '*falling out of the sky*' (Drabon, N. *et al*. 2024. **Effect of a giant meteorite impact on Paleoarchean surface environments and life**. *Proceedings of the National Academy of Sciences*, v. **121**, article e2408721121; DOI: 10.1073/pnas.2408721121

Impact debris layer in the Palaeoarchaean Barberton greenstone belt of South Africa, which contains altered glass spherules and fragments of older carbonaceous cherts. (Credit: Credit: Drabon, N. et al., Appendix Fig S2B)

In fact the Palaeoarchaean Era (3600 to 3200 Ma) was a time of multiple large impacts. Yet their recognition stems not from tangible craters but strata that contain once glassy spherules, condensed from vaporised rock, interbedded with sediments of Palaeoarchaean 'greenstone belts' in Australia and South Africa (see: Evidence builds for major impacts in Early Archaean; August 2002, and Impacts in the early Archaean; April 2014), some of which contain unearthly proportions of different chromium isotopes (see: Chromium isotopes and Archaean impacts; March 2003). Compared with the global few millimetres of spherules at the K-Pg boundary, the Barberton greenstone belt contains eight such beds up to 1.3 m thick in its 3.6 to 3.3 Ga stratigraphy. The thickest of these beds (S2) formed by an impact at around 3.26 Ga by an asteroid estimated to have had a mass 50 to 200 times that of the K-Pg impactor.

Above the S2 bed are carbonaceous cherts that contain carbon-isotope evidence of a boom in single-celled organisms with a metabolism that depended on iron and phosphorus rather than sunlight. The authors suggest that the tsunami triggered by impact would have stirred up soluble iron-2 from the deep ocean and washed in phosphorus from the exposed land surface, perhaps some having been delivered by the asteroid itself. No doubt such a huge impact would have veiled the Palaeoarchaean Earth with dust that reduced sunlight for years: inimical for photosynthesising bacteria but unlikely to pose a threat to chemo-autotrophs. An unusual feature of the S2 spherule bed is that it is capped by a layer of altered crystals whose shapes suggest they were originally sodium bicarbonate and calcium carbonate. They may represent flash-evaporation of up to tens of metres of ocean water as a result of the impact. Carbonates are less soluble than salt and more likely to crystallise during rapid evaporation of the ocean surface than would NaCl.



Time line of possible events following a huge asteroid impact during the Palaeoarchaean. (Credit: Drabon, N. et al. Fig 8)

So it appears that early extraterrestrial bombardment in the early Archaean had the opposite effect to the Chicxulub impactor that devastated the highly evolved life of the late Mesozoic. Many repeats of such chaos during the Palaeoarchaean could well have given a major boost to some forms of early, chemo-autotrophic life, while destroying or setting back evolutionary attempts at photo-autotrophy.

See also: King, A. 2024. Meteorite 200 times larger than one that killed dinosaurs reset early life. *Chemistry World* 23 October 2024.