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End-Ordovician mass extinction, faunal diversification, glaciation and true polar wander

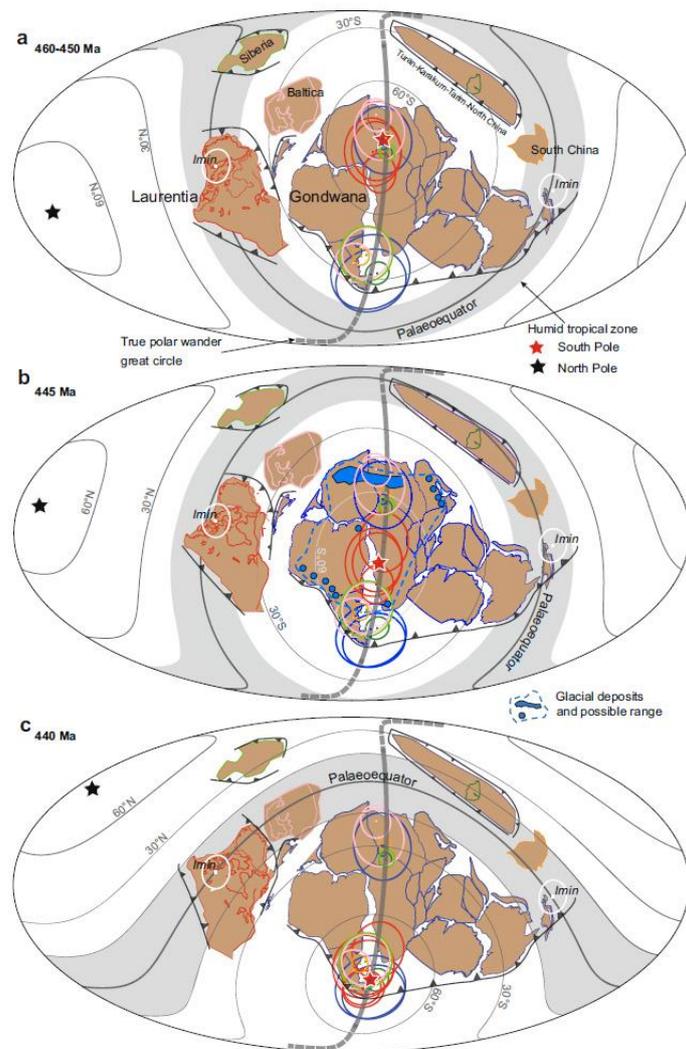
PUBLISHED ON *January 4, 2023*

Enormous events occurred between 460 and 435 Ma around the mid-point of the Palaeozoic Era and spanning the Ordovician-Silurian (O-S) boundary. At around 443 Ma the second-most severe mass extinction in Earth's history occurred, which eliminated 50 to 60% of all marine genera and almost 85% of species: not much less than the Great Dying at the end of the Permian Period. The event was accompanied by one of the greatest biological diversifications known to palaeontology, which largely replaced the global biota initiated by the Cambrian Explosion. Centred on the Saharan region of northern Africa, Late Ordovician glacial deposits also occur in western South America and North America. At that time all the current southern continents and India were assembled in the Gondwana supercontinent, with continental masses that became North America, the Baltic region, Siberia and South China not far off: all the components that eventually collided to form Pangaea from the Late Silurian to the Carboniferous.

The mass extinction has troubled geologists for quite a while. There are few signs of major volcanism having been involved, although some geochemists have suggested that [very high mercury concentrations](#) in some Late Ordovician marine sediments bear witness to large, albeit invisible, igneous events. No large impact crater is known from those times, although there is a curious [superabundance of extraterrestrial debris](#), including high helium-3, chromium and iridium concentrations, preserved in earlier Ordovician sedimentary rocks, around the Baltic Sea. Another suggestion, poorly supported by evidence, is destruction of the atmospheric ozone layer by a gamma-ray burst from some distant but stupendous supernova. A better supported idea is that the oceans around the time of the event lacked oxygen. Such anoxia can encourage solution of toxic metals and hydrogen sulfide gas. Unlike other mass extinctions, this one was long-drawn out with several pulses.

The glacial epoch also seems implicated somehow in the mass die-off, being the only one known to coincide with a mass extinction. It included spells of frigidty that exceeded those of the last Pleistocene glacial maximum, with the main ice cap having a volume of from 50 to 250 million cubic kilometres. The greatest of these, around 445 Ma, involved a 5°C fall in global sea-surface temperatures and a large negative spike in $\delta^{13}\text{C}$ in carbon-rich sediments, both of which lasted for about a million years. The complex events around that time coincided with the highest ever extinction and speciation rates, the number of marine species being halved in a short space of time: a possible explanation for the $\delta^{13}\text{C}$ anomaly. Yet estimates of atmospheric CO_2 concentration in the Late Ordovician suggests it was perhaps 8–16 times higher than today; Earth should have been a warm planet then. One probable contributor to extreme glacial conditions has been suggested to be that the South Pole at that time was well within Gondwana and thus isolated from the warming effect of the ocean. So, severe glaciation and a paradoxical combination of mass extinction with considerable biological diversification present quite an enigma.

A group of scientists based in Beijing, China set out to check the palaeogeographic position of South China between 460 and 435 Ma and evaluate those in O-S sediments at locations on 6 present continents (Jing, X., Yang, Z., Mitchell, R.N. *et al.* 2022. [Ordovician–Silurian true polar wander as a mechanism for severe glaciation and mass extinction](#). *Nature Communications*, v. 13, article 7941; DOI: 10.1038/s41467-022-35609-3). Their key tool is determining the position of the magnetic poles present at various times in the past from core samples drilled at different levels in these sedimentary sequences. The team aimed to test a hypothesis that in O-S times not only the entire lithosphere but the entire mantle moved relative to the Earth’s axis of rotation, the ‘slippage’ probably being at the Core-mantle boundary [thanks to Steve Rozario for pointing this out]. Such a ‘[true polar wander](#)’ spanning 20° over a mere 2 Ma has been detected [during the Cretaceous](#), another case of a 90° shift over 15 Ma may have occurred at the time when Snowball Earth conditions first appeared in the Neoproterozoic around the time [when the Rodinia supercontinent broke up](#) and a similar event was proposed in 1994 for C-O times albeit based on sparse and roughly dated palaeomagnetic pole positions.



Palaeogeographic reconstructions charting true polar wander and the synchronised movement of all continental masses between 460 and 440 Ma. Note the changes in the trajectories of lines of latitude on the Mollweide projections. The grey band either side of the palaeo-Equator marks intense chemical weathering in the humid tropics. Credit Jing *et al.* Fig 5.

Xianqing Jing and colleagues report a wholesale 50° rotation of the lithosphere between 450 and 440 Ma that would have involved speeds of about 55 cm per year. It involved the Gondwana supercontinent and other continental masses still isolated from it moving synchronously in the same direction, as shown in the figure. From 460 to 450 Ma the geographic South Pole lay at the centre of the present Sahara. At 445 Ma its position had shifted to central Gondwana during the glacial period. By 440 Ma Gondwana had moved further northwards so that the South Pole then lay at Gondwana's southernmost extremity.

As well as a possible key to the brief but extreme glacial episode this astonishing journey by a vast area of lithosphere may help account for the mass extinction with rapid speciation and diversification associated with the O-S boundary. While the South Pole was traversing Gondwana as the supercontinent shifted the 'satellite' continental masses remained in or close to the humid tropics, exposed to silicate weathering and erosion. That is a means for extracting CO₂ from the atmosphere and launching global cooling, eventually to result in glaciation over a huge tract of Gondwana around 445 Ma. Gondwana then moved rapidly into more clement climatic zones and was deglaciated a few million years later. The rapid movement of the most faunally diverse continental-shelf seas through different climate zones would have condemned earlier species to extinction simultaneous adaptation to changed conditions could have encouraged the appearance of new species and ecosystems. This does not require the catastrophic mechanisms largely established for the other mass extinction events. It seems that during the stupendous, *en masse* slippage of the Earth's lithosphere plate tectonic processes still continued, yet it must have had a dynamic effect throughout the underlying mantle.

Yet the fascinating story does have a weak point. What if the position of the magnetic poles shifted during O-S times from their assumed rough coincidence with the geographic poles? In other words, did the self-exciting dynamo in the liquid outer core undergo a large and lengthy wobble? How the outer core's circulation behaves depends on its depth to the solid core, yet the [inner core seems only to have begun solidifying](#) just before the onset of the Cambrian, about 100 Ma before the O-S events. It grew rapidly during the Palaeozoic, so the thickness of the outer core was continuously increasing. Fluid dynamic suggests that the form of its circulation may also have undergone changes, thereby affecting the shape and position of the geomagnetic field: perhaps even shifting its poles away from the geographic poles ...

Geochemical evidence for the origin of eukaryotes

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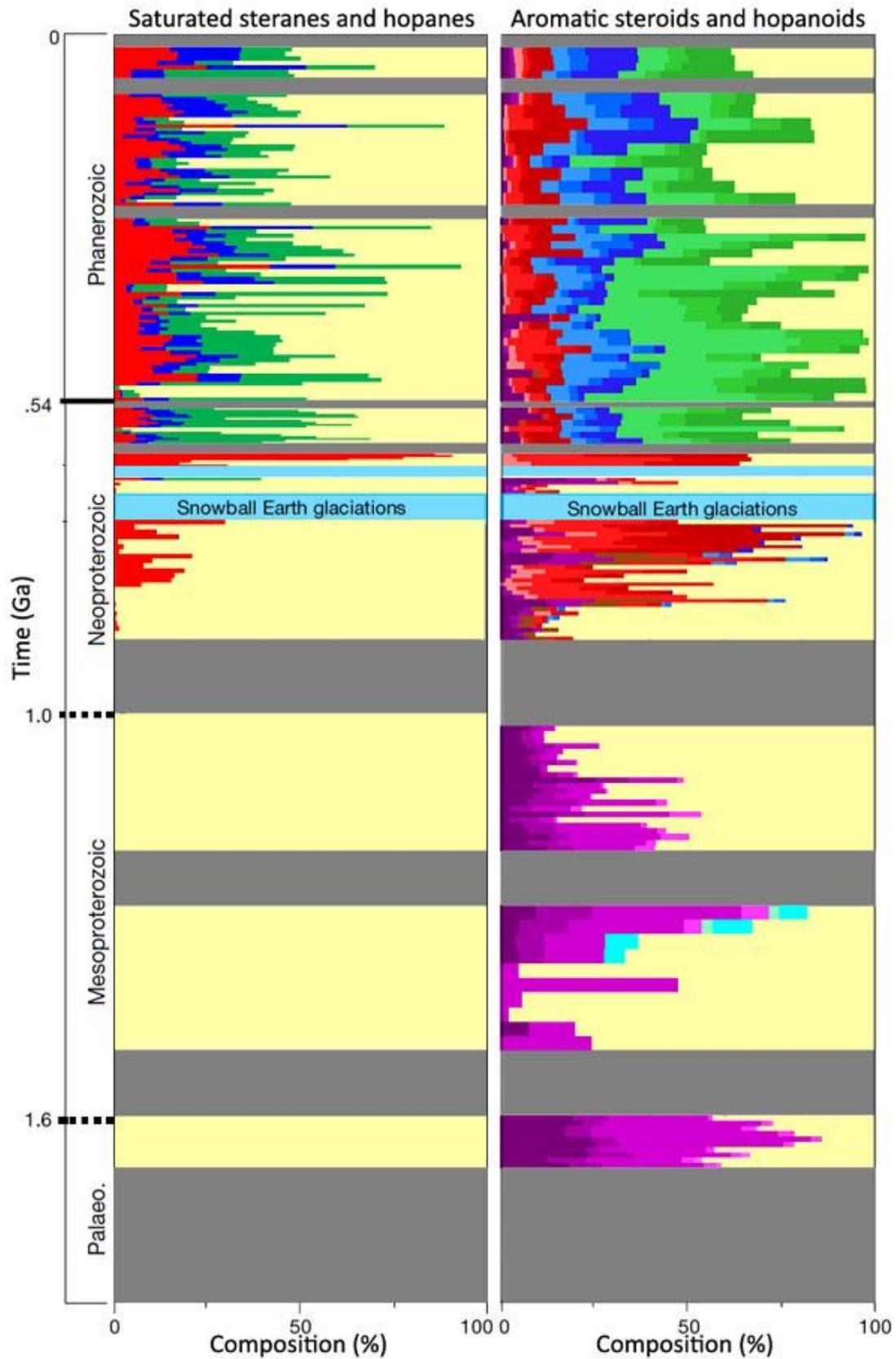
Along with algae, jellyfish, oak trees, sharks and nearly every organism that can be seen with the naked eye, we are eukaryotes. The cells of every member of the [Eukarya](#), one of the three great domains of life, all contain a nucleus – the main location of genetic material – and a variety of other small bodies known as organelles, such as the mitochondria of animals and the chloroplasts of plant cells. The vast bulk of organisms that we can't see unaided are prokaryotes, divided into the domains of Bacteria and Archaea. Their genetic material floats around in their cells' fluid. The DNA of eukaryotes shares some stretches with prokaryotes, but no prokaryotes contain any eukaryote genetic material. This suggests that the Eukarya arose *after* the Bacteria and Archaea, and also that

they are a product of evolution from prokaryotes, probably by several combining in symbiotic relationships inside a shared cell membrane. Earth-logs has followed developments surrounding this major issue since 2002, as reflected in some of the posts linked to what follows.

While prokaryotes can live in every conceivable environment at the Earth's surface and even in a few kilometres of crust beneath, the vast majority of eukaryotes depend on free oxygen for their metabolism. Logically, [the earliest of the Eukarya](#) could only have emerged when oxygen began to appear in the oceans following the [Great Oxidation Event](#) around 2.4 billion years ago. That is more than a billion years after the first prokaryotes had left their geological signature in the form of curiously bulbous, layered carbonate structures ([stromatolites](#)), probably formed by bacterial mats. The oldest occur in the Archaean rocks of Western Australia as far back as 3.5 Ga, and disputed examples have been found in the [3.7 Ga Isua sediments of West Greenland](#). The oldest of them are thought to have been produced through the anoxygenic photosynthesis of purple bacteria (See: [Molecular 'fossils' and the emergence of photosynthesis](#); September 2000), suggested by organic molecules found in [kerogen](#) from early Archaean sediments. Later stromatolites (<3.0 Ga) have provided similar evidence for oxygen-producing cyanobacteria.

[Acritarchs](#) are microfossils of single-celled organisms made of kerogen that have been found in sediments up to 1.8 billion years old. Features protruding from their cell walls distinguish them from prokaryote cells, which are more or less 'smooth': acritarchs have been considered as possible early eukaryotes. Yet the oldest undisputed eukaryote microfossils – red and green algae – are much younger (about 1.0 Ga). A means of estimating an age for the crown group from which every later eukaryote organism evolved – [last eukaryotic common ancestor](#) (LECA) – is to use an assumed rate of mutation in DNA to deduce the time when differences in genetics between living eukaryotes began to diverge: i.e. a '[molecular clock](#)'. This gives a time around 2 Ga ago, but the method is fraught with uncertainties, not the least being the high possibility of mutation rates changing through time. So, when the Eukarya arose is blurred within the so-called '[boring billion](#)' of the early Proterozoic Eon. A way of resolving this uncertainty to some extent is to look for 'biomarker' chemicals in the geological record that provide a 'signature' for eukaryotes.

A new study has been undertaken by a group of Australian, German and French scientists to analyse sediments ranging in age from 635 to 1640 Ma from Australia, China, Asia, Africa, North and South America (Brocks, J.J and 9 others 2023. Lost world of complex life and the late rise of the eukaryotic crown. *Nature*, v. 618, p. 767–773; DOI: 10.1038/s41586-023-06170-w; [contact for PDF](#)). Their chosen biomarkers are [sterols](#) (steroids) that regulate eukaryote cell membranes. Some prokaryotes also synthesise steroids but all of them produce [hopanepolyols](#) (hopanoids), which eukaryotes do not. The key measures for the presence/absence of eukaryote remains in ancient sea-floor sediments is thus the relative proportions of preserved steroids and hopanoids, together with those for the breakdown products of both – steranes and hopanesthat are, crudely speaking, carbon 'skeletons' of the original chemicals.

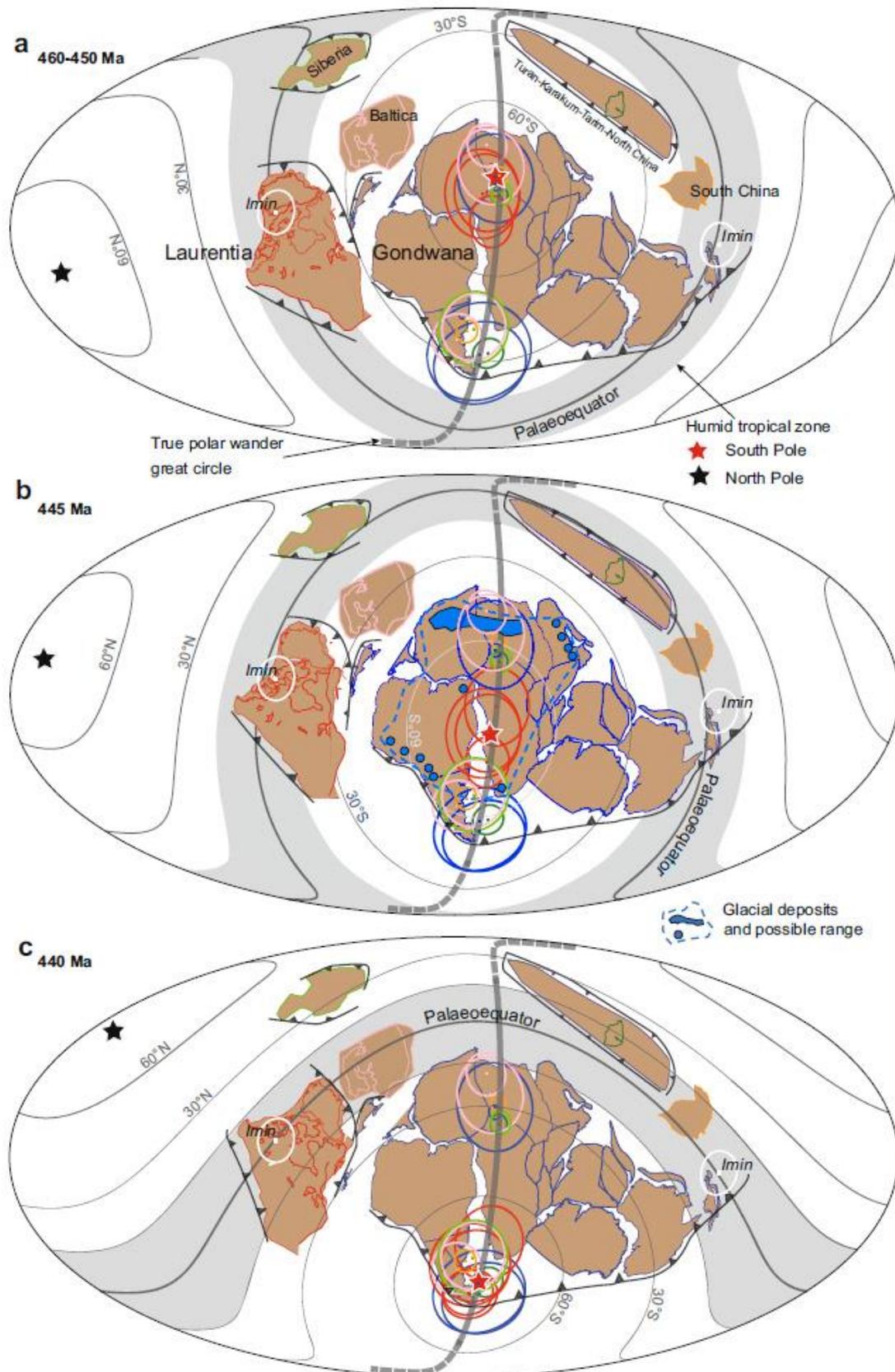


Proportions of biomarkers in sediments from present to 1.64 Ga. Cholesteroids – reds; ergosteroids – blues; stigmasteroids – greens; protosteroids magentas, hopanoids – yellows; unsampled – grey. Snowball glaciations are shown in pale blue. (Credit: Simplified from Figure 3 in Brocks et al.)

Interpretation of the results by Jochen Brocks and colleagues is complicated, and what follows is a summary based partly on an accompanying *Nature News & Views* article (Kenig, F. 2023. The long infancy of sterol biosynthesis. *Nature*, v. 618, p. 678-680; DOI: 10.1038/d41586-023-01816-1). The conclusions of Brocks *et al.* are surprising. First, the break-down products of steroids (saturated steranes) that can be attributed to crown eukaryotes (left on the figure above) are only present in sediments going back to about 200 Ma before the first Snowball Earth event (~900 Ma). Before that only hopanes formed by hopanoid degradation are present: a suggestion that LECA only appeared around that time – the authors suggest sometime between 1 and 1.2 Ga. That is far later than the time when eukaryotes *could have* emerged: i.e. once there was available oxygen after the Great Oxidation Event (~2.4 to 2.2 Ga). So what was going on before this? The authors broke new ground in analysis of biomarkers by being able to detect signs of the presence of actual hopanoids and steroids of several different kinds. Steroids were present as far back as 1.6 Ga in the oldest sediments that were analysed.

Steroids of crown eukaryotes are represented by cholesteroloids, ergosteroids and stigmasteroids. All three are present throughout the Phanerozoic Eon and into the time of the Ediacaran Fauna that began 630 Ma ago. In that time span they generally outweigh hopanoids, thus reflecting the dominance of eukaryotes over prokaryotes. Back to about 900 Ma, only cholesteroloids are present, together with archaic forms that are not found in living Eukarya, termed protosteroids. Before that, only protosteroids are found. Moreover, these archaic steroids are *not* present in sediments that follow the Snowball Earth episodes (the Cryogenian Period).

Thus, it is possible that crown group eukaryotes – and their descendants, including us – evolved from and completely replaced an earlier primitive form (acritarchs?) at around the time of the greatest climatic changes that the Earth had experienced in the previous billion years or more. Moreover, the Cryogenian and Ediacaran Periods seem to show a rapid emergence of stigmasteroid- and ergosteroid production relative to cholesteroloid: perhaps a result of explosive evolution of the Eukarya at that time. The organisms that produced protosteroids were present in variable amounts throughout the Mesoproterozoic. Clearly there need to be similar analyses of sediments going back to the Great Oxygenation Event and the preceding Archaean to see if the protosteroid producers arose along with increasing levels of molecular oxygen. The [‘boring billion’ \(2.0 to 1.0 Ga\) may well be more interesting than previously thought.](#)



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Repeated climate and ecological stress during the run-up to the K-Pg extinction

PUBLISHED ON [October 17, 2023](#)

The Cretaceous-Palaeogene mass extinction is no longer an event that polarises geologists' views between a slow volcanic driver (The Deccan large igneous province) and a near instantaneous asteroid impact (Chicxulub). There is now [a broad consensus](#) that both processes were involved in weakening the Late Cretaceous biosphere and snuffing out much of it around 66 Ma ago. Yet is still no closure as regards the details. From a palaeontologist's standpoint [the die-off varied dramatically](#) between major groups of animals. For instance, the non-avian dinosaurs disappeared completely while those that evolved to modern birds did not. Crocodiles came through it largely unscathed unlike aquatic dinosaurs. In the seas those animals that lived in the water column, such as ammonites, were far more affected than were denizens of the seafloor. But much the same final devastation was visited on every continent and ocean. However, lesser and more restricted extinctions occurred before the Chicxulub impact.

Scientists from Norway, Canada, the US, Italy, the UK and Sweden have now thrown light on the possibility that climate change during the last half-million years of the Cretaceous may have been eroding biodiversity and disrupting ecosystems (Callegaro, S. *et al.* 2023. [Recurring volcanic winters during the latest Cretaceous: Sulfur and fluorine budgets of Deccan Traps lavas](#). *Science Advances*,

v. 9, article eadg8284; DOI: 10.1126/sciadv.adg8284). Almost inevitably, they turned to the record of Deccan volcanism that overlapped the K-Pg event, specifically the likely composition of the gases that the magmas may have belched into the atmosphere. Instead of choosing the usual suspect carbon dioxide and its greenhouse effect, their focus was on sulfur and fluorine dissolved in pyroxene grains from 15 basalts erupted in the 10 Formations of the Deccan flood-basalt sequence. From these analyses they were able to estimate the amounts of the two elements in the magma erupted in each of these 10 phases.



Exposed section through a small part of the Deccan Traps in the Western Ghats of Maharashtra, India. (Credit: Gerta Keller, Princeton University)

The accompanying image of a famous section through the Deccan Traps SE of Mumbai clearly shows that 15 sampled flows could reveal only a fraction of the magmas' variability: there are 12 flows in the foreground alone. The mountain beyond shows that the pale-coloured sequence is underlain by many more flows, and the full Deccan sequence is about 3.5 km thick. Clearly, flood-basalt volcanism is in no way continuous, but builds up from repeated lava flows that can be as much as 50 m thick. Each of them is capped by a red, clay-rich soil or bole – from the Greek word bolos (**βόλος**) meaning 'clod of earth'. Weathering of basalt would have taken a few centuries to form each bole. Individual Deccan flows extend over enormous areas: one can be traced for 1500 km. At the end of volcanism the pile extended over roughly 1.5 million km² to reach a volume of half a million km³.

Fluorine is a particularly toxic gas with horrific effects on organisms that ingest it. In the form of hydrofluoric acid (HF) – routinely used to dissolve rock – it penetrates tissue very rapidly to react with calcium in the blood to form calcium fluoride. This causes very severe pain, bone damage and other symptoms of [skeletal fluorosis](#). The 1783-4 eruption of the Laki volcanic fissure in Iceland emitted an estimated 8,000 t of HF gas that wiped out more than half the domestic animals as a result of their eating contaminated grass. The famine that followed the eruption killed 20 to 25% of Iceland's people: exhumed human skeletons buried in the aftermath show the distinctive signs of endemic skeletal fluorosis. This small flood-basalt event had global repercussions, as the [Wikipedia entry for Laki](#) documents. Volcanic sulfur emissions in the form of SO₂ gas react with water vapour to form sulphuric acid aerosols in a reflective haze. If this takes place in the stratosphere as a result of powerful eruptions, as was the case with the 1991 Pinatubo eruption in the Philippines, the high-altitude haze lingers and spreads. This results in reduced solar warming: a so-called 'volcanic winter'.

In the Pinatubo aftermath global temperatures fell by about 0.5°C during 1991-3. Unsurprisingly, volcanic sulfur emissions also result in acid rainfall. Moreover, [inhaling the sulphur-rich haze](#) at low altitudes causes victims to choke as their respiratory tissues swell: an estimated 23,000 people in Britain died in this way when the 1783-4 Laki eruption haze spread southwards. Sara Calegari and colleagues found that the fluorine and sulfur contents of Deccan magmas fluctuated significantly during the eruptive phases. They suggest that fluorine emissions were far above those from Laki, perhaps leading to regional fluorine toxicity around the site of the Deccan flood volcanism but not extinctions. Global cooling due to sulphuric acid aerosols in the stratosphere is suggested to have happened repeatedly, albeit briefly, as eruption waxed and waned during each phase. Magmas rich in volatiles would have been more likely to erupt explosively to inject SO₂ to stratospheric altitudes (above 10 to 20 km). The authors do not attempt to model when such cooling episodes may have occurred: data from only 15 levels in the Deccan Traps do not have the time-resolution to achieve that. They do, however, show that this large igneous province definitely had the potential to generate 'volcanic winters' and toxic episodes. Time and time again ecosystems globally and regionally would have experienced severe stress, the most important perhaps being disruption of the terrestrial and marine food chains.