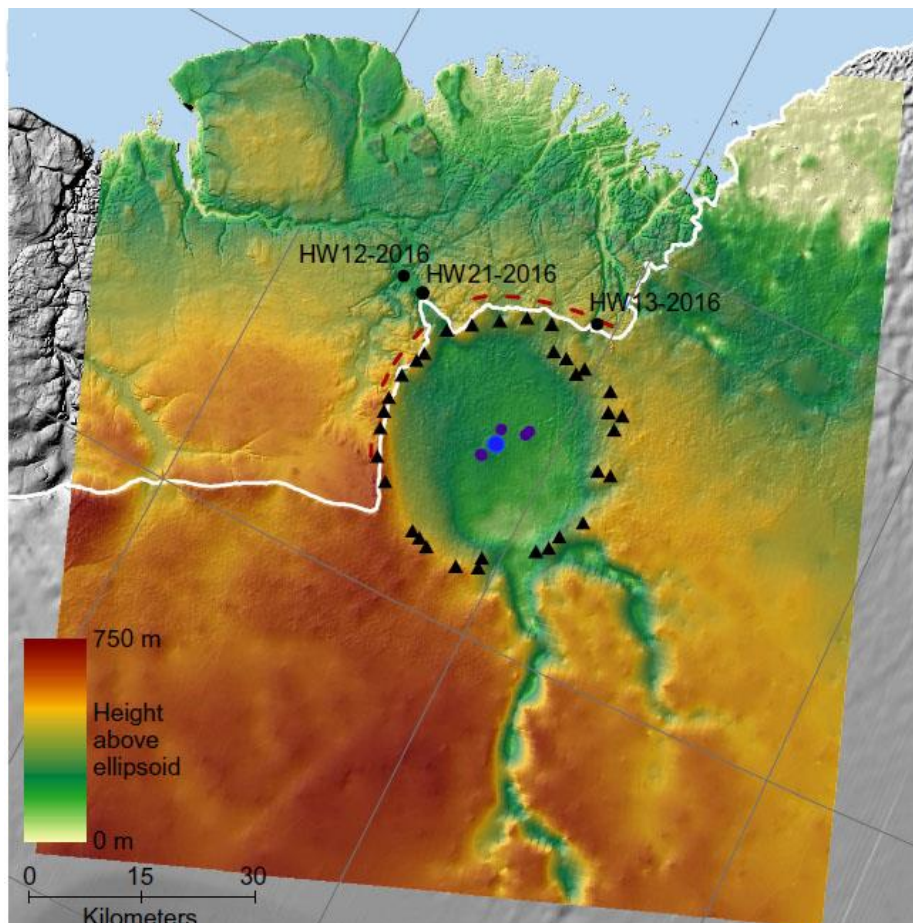


Palaeoclimatology 2022

‘Smoking gun’ for Younger Dryas trigger refuted

PUBLISHED ON *March 16, 2022*

In 2018 airborne ice-penetrating radar over the far northwest of the Greenland revealed [an impact crater](#) as large as the extent of Washington DC, USA beneath the Hiawatha Glacier. The ice surrounding it was estimated to be younger than 100 ka. This seemed to offer a measure of support for the controversial hypothesis that an impact may have triggered the start of the millennium-long Younger Dryas episode of frigidity (12.9 to 11.7 ka). This notion had been proposed by a group of scientists who claimed to have found mineralogical and geochemical signs of an asteroid [impact at a variety of archaeological sites](#) of roughly this age in North America, Chile and Syria. A new study of the Hiawatha crater by a multinational team, including the original discoverers of the impact structure, has focussed on sediments deposited beyond the edge of the Greenland ice cap by meltwater streams flowing along its base. (Kenny, G.G. *et al.* 2022. [A Late Paleocene age for Greenland’s Hiawatha impact structure](#). *Science Advances*, v.8, article eabm2434; DOI: 10.1126/science.eabm2434).



Colour-coded subglacial topography from airborne radar sounding over the Hiawatha Glacier of NW Greenland (Credit: Kjaer et al. 2018; Fig. 1D)

Where meltwater emerges from the Hiawatha Glacier downstream of the crater there are glaciofluvial sands and gravels that began to build up after 2010 when rapid summer melting began, probably due to global warming. As luck would have it, the team found quartz grains that contained distinctive planar features that are characteristic of impact shock. They also found pebbles of glassy impact melts that contain clasts of bedrock, further grains of shocked quartz and tiny needles of plagioclase feldspar that crystallised from the melt. Also present were small grains of the mineral zircon ($ZrSiO_4$), both as pristine crystals in the bedrock clasts and porous, grainy-textured grains showing signs of deformation in the feldspathic melt rock. So, two materials that can be radiometrically dated are available: feldspars suitable for the $^{40}Ar/^{39}Ar$ method and zircons for uranium-lead (U-Pb) dating. The feldspars proved to be about 58 million years old; i.e. of Late Palaeocene age. The pristine zircon grains from bedrock clasts yielded Palaeoproterozoic U-Pb ages (~1915 Ma), which is the general age of the Precambrian metamorphic basement that underpins northern Greenland. The deformed zircon samples have a very precise U-Pb age of 57.99 ± 0.54 Ma. There seems little doubt that the impact structure beneath the Hiawatha Glacier formed towards the beginning of the Cenozoic Era.

During the Palaeocene, Northern Greenland was experiencing warm conditions and sediments of that age show that it was covered with dense forest. The group that since 2007 has been advocating the influence of an impact over the rapid onset of the Younger Dryas acknowledges that the Hiawatha crater cannot support their view. But they have an alternative: an airburst of an incoming projectile. Although scientists know such phenomena do occur, as one did over the Tunguska area in Siberia on the morning of 30 June 1908. Research on the Tunguska Event has discovered geochemical traces that may implicate an extraterrestrial object, but coincidentally the area affected is underlain by the giant Siberian Traps large igneous province that arguably might account for geochemical anomalies. Airbursts need to have been observed to have irrefutable recognition. Two posts from October 2021 – [A Bronze Age catastrophe: the destruction of Sodom and Gomorrah?](#) and [Wide criticism of Sodom airburst hypothesis emerges](#) – suggest that some scientists question the data used repeatedly to infer extraterrestrial events by the team that first suggested an impact origin for the Younger Dryas.

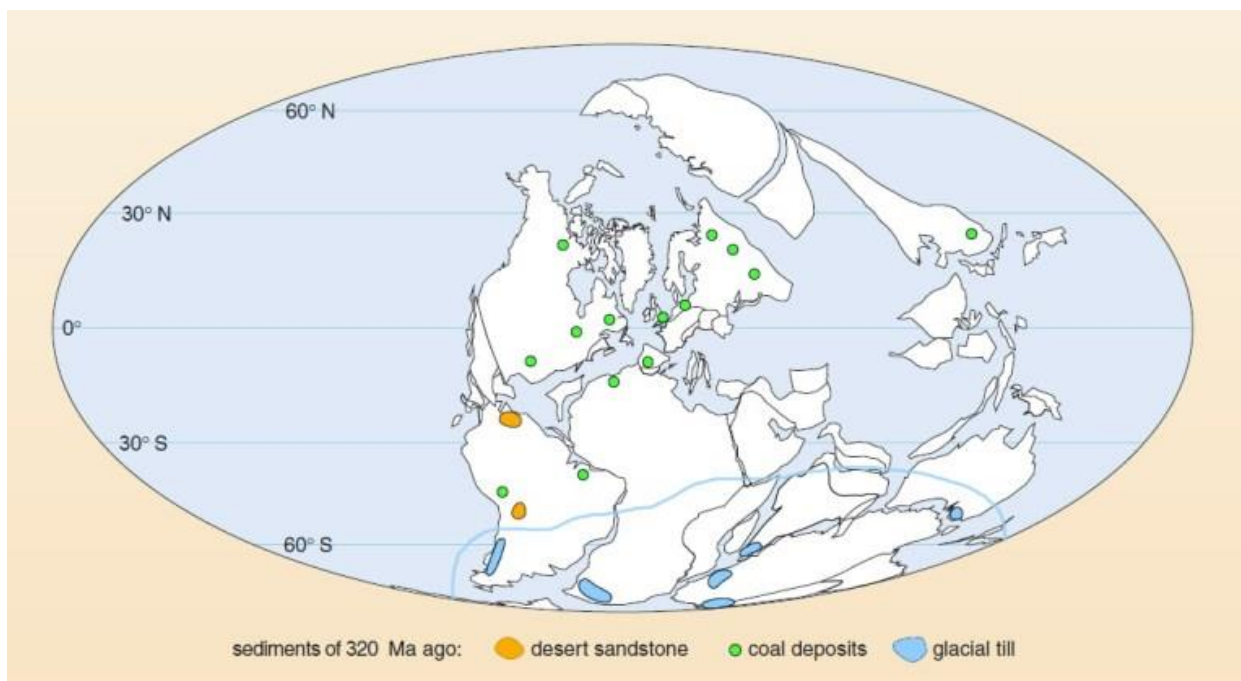
See also: Voosen, P, 2022. [Controversial impact crater under Greenland's ice is surprisingly ancient](#). *Science*, v. 375, article adb1944; DOI: 10.1126/science.adb1944

The end of the Carboniferous 'icehouse' world

PUBLISHED ON *May 10, 2022*

From about 340 to 290 Ma the Earth experienced the longest episode of repeated ice ages of the Phanerozoic. The climate then was similar in many ways to that of the Pleistocene. The South Polar region was then within the Pangaea supercontinent and thus isolated from any warming effect from the surrounding ocean: much the same as modern Antarctica but on a much larger scale. Glaciation extended as far across what became the southern continents and India as did the continental ice sheets of the Northern Hemisphere during Pleistocene glacial maxima. Tropical sedimentary rocks of the time, display evidence for repeated alternations of high and low sea levels that mark cycles of glacial maxima and interglacial episodes akin to those of the Pleistocene. In fact they probably

reflect the influence of changes in the Earth's orbit and geometry of its axis of rotation very similar to those predicted by Milankovich from astronomical factors to explain Pleistocene climatic cycles. At the end of the Carboniferous what was an 'ice-house' world changed suddenly to its opposite – 'greenhouse' conditions – that persisted through the Mesozoic Era until the later part of the Cenozoic, when Antarctica developed its ice cap and global climate slowly cooled to become extremely cyclical once again.



Sedimentary evidence for global climates 320 Ma ago. As well as the large tracts of glaciogenic sediments, smaller occurrences and examples of polished rock surfaces over which ice had passed show the probable full extent (blue line) of ice sheets across the southern, Gondwana sector of Pangaea (Credit: after Fig 7.3, S104, Earth and Space, ©Open University 2007)

The end of the Carboniferous witnessed the collapse of the vast Equatorial rainforests, which formed the coal deposits that put 'Carbon' into the name of the Period. By its end this ecosystem had vanished to result in a minor mass extinction of both flora and fauna. Temperatures rose and aridity set in, to the extent that the latest Carboniferous in the British coalfields is marked by redbeds that presage the spread of desert conditions across the Equatorial parts of Pangaea during the succeeding Permian. A team of researchers based at the University of California at Davis have been studying data pertaining to this sudden change have now published their findings (Chan J. and 17 others 2022. [Marine anoxia linked to abrupt global warming during Earth's penultimate icehouse](#). *Proceedings of the National Academy of Sciences*, v. 119, article e2115231119; DOI: 10.1073/pnas.2115231119). They used carbon-, oxygen- and uranium isotopes, together with proxies for changes in atmospheric CO₂ concentrations, to model changes in the carbon cycle in the Late Carboniferous of China.

Changes in uranium isotopes within marine carbonates are useful indicators of the amount of oxygen available in ocean water at the sea floor. Between 304 and 303.5 Ma ago oxygen content declined by around 30%, the peak of this anoxia being at 303.7 Ma. This occurred about 100 ka after atmospheric CO₂ had risen to ~700 parts per million (ppm) from around 350 ppm in the preceding

300 ka, as marked by several proxies. The authors suggest that the lower 'baseline' for the main greenhouse gas marked an extreme glacial maximum. Changes in the proportions of ^{18}O relative to 'lighter' ^{16}O in fossil shells suggest that sea-surface temperatures increased in step with the doubling of the greenhouse effect. At the same time there was a major marine transgression as sea level rose. This would have been accompanied by a massive increase in low density freshwater in surface ocean water derived from melting of Pangaea's ice cap. The team suggests that the freshened surface layer could not sink to carry oxygen to deeper levels, thereby creating anoxic conditions across an estimated 23% of the global seafloor, and thus toxic 'death zones' for marine organisms.

One possibility for this sudden rise of atmospheric CO_2 is a massive episode of volcanism, perhaps a large igneous province, but there is scanty evidence for that at the end of the Carboniferous. A coinciding sharp decrease in $\delta^{13}\text{C}$ in carbonate shells suggests that the excess carbon dioxide probably had an organic origin. So a more plausible hypothesis is massive burning on the continental surface. In the tropics, the huge coals swamps would have contained vast amounts of peat-like decayed vegetable matter as well as living green vegetation. How might that have caught fire? The peat precursor to Carboniferous coal deposits derived from photosynthesis on an unprecedented, and never repeated, scale during tens of million years of thriving tropical rain forest during that Period. This built up atmospheric oxygen levels to about 35%, compared with about 21% today. Insects, whose maximum size is governed by their ability to take in oxygen through spiracles in their bodies, and by the atmospheric concentration of oxygen, became truly huge during the earlier Carboniferous. The more oxygen in the air, the greater the chance that organic matter will catch fire. In fact wet vegetation can burn if oxygen levels rise above 25%. At the levels reached in the Carboniferous huge wildfires in forests and peatlands would have been inevitable. Evidence that huge fires did occur comes from the amount of charcoal found in Carboniferous coal seams, which reach 70% compared with the 4 to 8 % in more recent coals. They may have been ignited by lightning strikes or even spontaneous combustion if decay of vegetation generated sufficient heat, as sometimes happens today in wet haystacks or garden compost heaps. But how in a short period around 304 Ma could 9 trillion tons of carbon dioxide be released in this way. The preceding glacial super-maximum, like glacial maxima of the Pleistocene, may have been accompanied by decreased atmospheric humidity: this would dry out the vast surface peat deposits.

The succeeding Permian is famous for its extensive continental redbeds, and so too those of the Triassic. They are red because sediment grains are coated in the iron oxide hematite (Fe_2O_3). As on Mars, the redbeds are a vast repository for oxygen sequestered from the atmosphere by the oxidation of dissolved Fe^{2+} to insoluble Fe^{3+} . This had been going on throughout the Permian, the nett result being that by 250 Ma atmospheric oxygen content has slumped to 16% and remained so low for another 50 million years. Photosynthesis failed to resupply oxygen against this inorganic depletion, and there are few coal deposits of Permian or Triassic age: for about 100 Ma Earth ceased to have green continents.

See also: [Carbon, climate change and ocean anoxia in an ancient icehouse world](#). *Science Daily*, 2 May 2022.

Climate and tectonics since 250 Ma

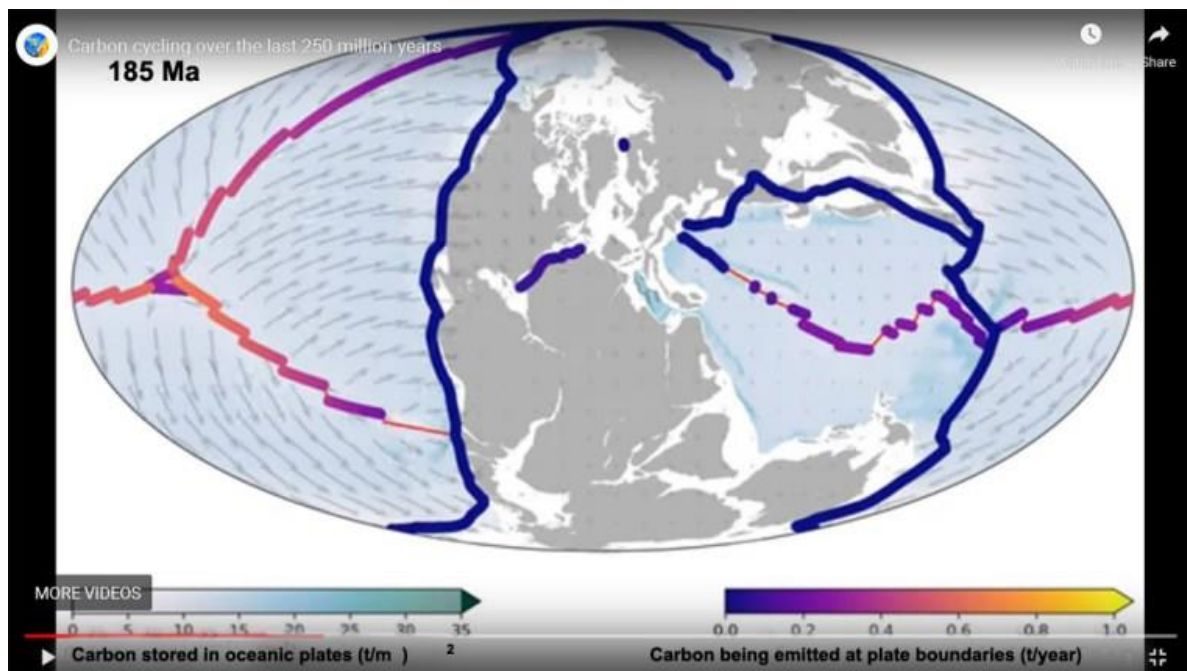
PUBLISHED ON *June 9, 2022*

A central feature of the Earth's climate system is the way that carbon bound in two gases – carbon dioxide (CO₂) and methane (CH₄) – controls the amount of incoming solar energy that is retained by the atmosphere. Indeed, without one or the other our home world would have been locked in fridity since shortly after its formation: a sterile, ice-covered planet. The 'greenhouse effect' has been ever-present because the material from which the Earth accreted contained carbon as well as every other chemical element from hydrogen to uranium. Naturally reactive, it readily combines with hydrogen and oxygen to form methane and carbon dioxide, which would have escaped the inner Earth as gases to enter the earliest atmosphere as a 'comfort blanket', along with water vapour, another greenhouse gas. Their combined effects have remained crudely balanced so that neither inescapable fridity nor surface temperatures high enough to boil-off the oceans have ever occurred in the last 4.5 billion years. Earth has remained like the wee bear's porridge in the Goldilocks story! Even so, global climate has fluctuated again and again from that akin to a steamy greenhouse, through long periods of moderation to extensive glacial conditions, including three that extended from pole-to-pole – 'Snowball' Earths – during in the Precambrian. During the Phanerozoic the Earth has entered three long periods of generally low global temperatures, in the Ordovician, the Carboniferous and during the last 2.5 Ma that allowed polar ice caps and sea-ice to extend a third of the way to the Equator. These were forced back and forth repeatedly by cyclical influences apparently triggered by astronomically controlled changes to Earth's orbital and rotational parameters – the Milankovich Effect. Anthropogenic emissions of greenhouse gases in vast and increasing amounts now threaten to disrupt natural climate variation, effectively overthrowing the gravitational influences of distant giant planets that have controlled climate changes that shaped our own evolution since the genus *Homo* first emerged.

Bubbles of air trapped in cores through the ice sheets of Antarctica and Greenland record decreased volumes of land ice as CO₂ content increased and the opposite during glacial episodes. Somehow in step with the astronomical forcing the Earth released greenhouse gas to warm the climate and drew it down to bring on cooling. Since all life forms are built from carbon-rich compounds and some extract it from the environment to build carbonate hard parts, climate and life on land and in the oceans are interlinked. In fact life and death are involved, because once dead organisms and their hard parts are buried before being oxidised in sediments on land, as in peat and ultimately coal, and on the ocean floors as limestones or carbonaceous mudstones, atmospheric carbon is sequestered. Exposed to acid water containing dissolved CO₂ from the atmosphere or to oxygen, respectively, the two forms of carbon in solid form are released as greenhouse gas once more. Both take place when sedimentary deposits are exhumed as a result of erosion and tectonics. Another factor is the abundance of available nutrients, themselves released and distributed by erosion and agents of transportation. At present surface waters of the most distant parts of the oceans contains plenty of such nutrients, except for a vital one, dissolved iron. So they are wet 'deserts'. It seems that during the much dustier times of glacial episodes iron in fine form reached far out into the world's oceans so that phytoplankton at the base of the food chain 'bloomed' and so did planktonic animals. Dead organisms 'rained' to the ocean floor so drawing down CO₂ from the atmosphere and decreasing the greenhouse effect. The surface parts of the carbon and rock cycles are extremely complex and

climatologists have yet to come to grips with modelling its future climates convincingly. Yet the carbon cycle and much deeper parts of the rock cycle are interwoven too.

Carbon in sedimentary rock can be heated by burial, and some can be subducted to great depths at destructive plate margins together. The same applies to in ocean-floor basalts that have been permeated by circulating sea water through hydrothermal circulation to form carbonates in the altered volcanic rock. In both cases carbon stored for hundreds of million years can be released by metamorphism in orogenic belts at zones of continental collision and deep below island arcs. Carbon from mantle depths that has never 'seen the light of day' is also added to the atmosphere when magmas form below oceanic constructive margins, hot spots and subduction zones, and where magmas flood the continental surface. Consequently, plate tectonics and deep mantle convection have surely played a long-term role in the evolution of our planet's climate system. Geoscientists based in Australia and the UK have used geochemical data to reconstruct the stores of carbon in oceanic plates and thermodynamic modelling to track what may have happened to it and the climate through the last 250 Ma (Müller, R.D. *et al.* 2022. [Evolution of Earth's tectonic carbon conveyor belt](#). *Nature*, v. 605, p. 629-639; DOI: 10.1038/s41586-022-04420-x). Their review is an important step in understanding what underpins climate on a geological time scale, onto which much shorter-term surface influences are superimposed.



The amount of carbon being outgassed as CO₂ each year along plate boundaries in the early Jurassic (185 Ma) shown in dark purple (low) to yellow (high). Also shown in shades of blue is the accumulation of carbon stored in each square metre of the ocean plates. Plate motions are shown as grey arrows (credit: Müller, R.D. *et al.* Clip from video in Supplementary Information)

At mid-ocean ridges basaltic magma wells up from mantle depths and loses much of its content of dissolved CO₂. The annual outgassing at ridges, which depends on the global rate of plate formation, has varied from 13 to 30 million tonnes of carbon (MtC yr⁻¹) since the start of the Mesozoic Era 250 Ma ago. Similarly, there is greenhouse-gas escape from volcanic arcs above subduction zones, estimated to have ranged from 0 to 18 MtC yr⁻¹. As an oceanic plate moves away from its source various processes sequester CO₂ into the oceanic crust and upper mantle through accumulation of

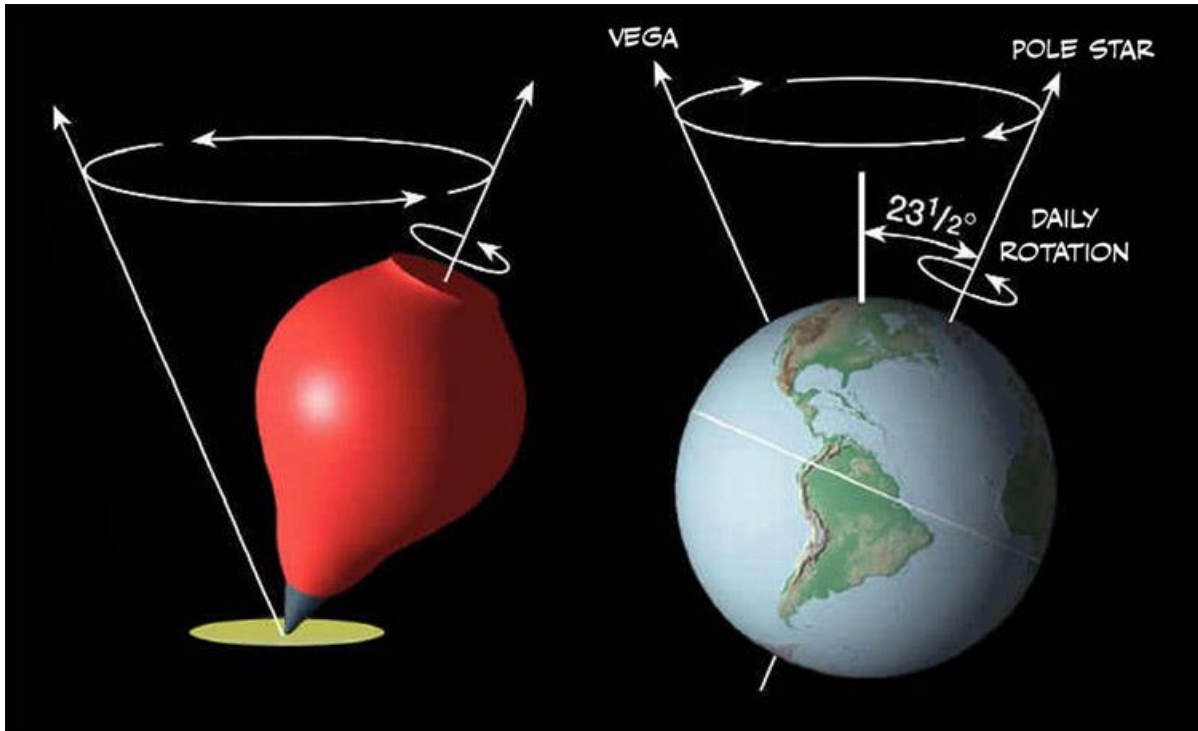
deep-sea sediments and hydrothermal alteration of basaltic crust and peridotite mantle (ranging from 30 to 311 MtC yr⁻¹). Of this influx of carbon into oceanic plates between 36 to 103 MtC yr⁻¹ has gone down subduction zones in descending slabs. Between 0 to 49 MtC yr⁻¹ of that has been outgassed by arc volcanic activity or absorbed into the overriding plate. The rest continues down into the deep mantle, perhaps to form diamonds. Overall, when the rate at which oceanic plates grow is rapid and plate motion speeds up, outgassing should be high. When plate growth slows, so does the rate of CO₂ release. Variations in plate growth can be estimated from the magnetic reversal stripes above the ocean floors. The authors have released an [animation of the break-up of Pangaea](#) (well worth watching at full screen – you can skip the ad at the start), with the rate of carbon emission at ridges and volcanic arcs being colour-coded. Also shown is the storage of carbon within oceanic plates as time passes.

A new twist to Pleistocene climate cycles

PUBLISHED ON [June 17, 2022](#)

The combined gravitational pulls of the sun and moon modulate variations in local tidal range. High spring tides occur when the two bodies are opposed at full moon or in roughly the same direction at new Moon. When the positions of sun and moon are at right angles (1st quarter and 3rd quarter) their gravitational pulls partly cancel each other to give neap tides. Consequently, there are two tidal cycles every lunar month. In a similar way, the varying gravitational pulls of the planets during their orbital cycles impart a repetitive harmony to Earth's astronomical behaviour. But their combined effects are on the order of tens of thousand years. [Milutin Milankovich](#) (1879-1958), a Serbian engineer, pondered on the possible causes of Earth's climatic variations, particularly the repetition of ice ages. He was inspired by 19th century astronomers' suggestion that maybe the gravitational effects of other planets might be a fruitful line of research. Milankovich focussed on how the shape of Earth's orbit, the tilt of its rotational axis and the way the axis wobbles like that of a spinning top affect the amount of solar heating at all points on the surface: the effects of varying *eccentricity*, *obliquity* and *precession*, respectively.

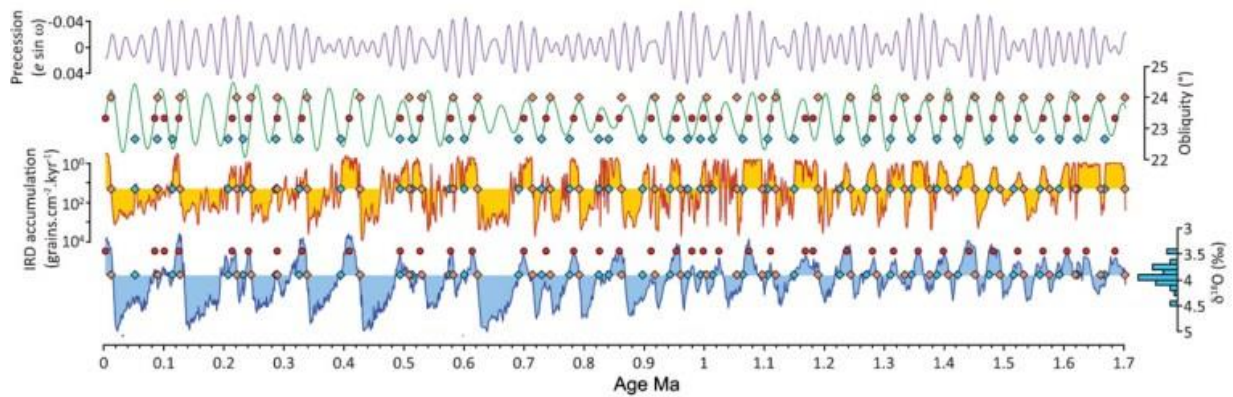
Earlier astronomers had calculated cycles of gravitational effects on Earth of the orbits of Jupiter and Saturn of the three attributes of Earth's astronomical behaviour and found periods of about 100, 41 and 23 thousand years (ka) respectively. The other 3 inner planets and the much more distant giants Uranus and Neptune also have gravitational effects on Earth, but they are negligible compared with those of the two nearest giant planets, because gravitation force varies with mass and inversely with the square of distance. Sadly, Milankovich was long dead when his hypothesis of astronomical climate forcing was verified in 1976 by frequency analysis of the record of oxygen isotopes in foraminifera found in two ocean sediment core from the Southern Indian Ocean. It revealed that all three periods interfered in complex ways during the Late Pleistocene, to dominate variations in sea-surface temperatures and the fluctuating volume of continental ice sheets for which δ¹⁸O is a proxy (see: [Odds and ends about Milankovich and climate change](#); February 2017).



Precession of the axis of a spinning top and that of the Earth. At present the northern end of Earth's axis points to what we now call the Pole Star. Around 11.5 ka from now it will point to the star Vega

This was as revolutionary for climatology as plate tectonics was for geology. We now know that in the early Pleistocene glacial-interglacial cycles were in lockstep with the 41 ka period of axial obliquity, and since 700 ka followed closely – but not perfectly – the 100 ka orbital eccentricity forcing. The transitional period between 1.25 and 0.7 Ma ([the Mid-Pleistocene Transition](#) or MPT) suggested neither one nor the other. Milankovich established that axial tilt variations have the greatest influence on solar heating, so the early 41 ka cycles were no surprise. But the dominance of orbital eccentricity on the last 700 ka certainly presented a puzzle, for it has by far the weakest influence on solar heating: 10 times less than those of axial obliquity and precession. The other oddity concerns the actual effect of axial precession on climate change. There are no obvious 23 ka cycles in the climate record, despite the precession signal being clear in frequency analysis and its effect on solar heating being almost as powerful as obliquity and ten times greater than that of orbital eccentricity. Precessional wobbling of the axis controls the time of year when one hemisphere or the other is closest to the Sun. At one extreme it will be the Northern and 11.5 ka later it will be the Southern. The times of solstices and equinoxes also change relative to the calendar that we use today.

There is an important, if obvious, point about astronomical forcing of climate. It is always there, with much the same complicated interactions between the factors: human activities have absolutely no bearing on them. Climatic 'surprises' are likely to continue!



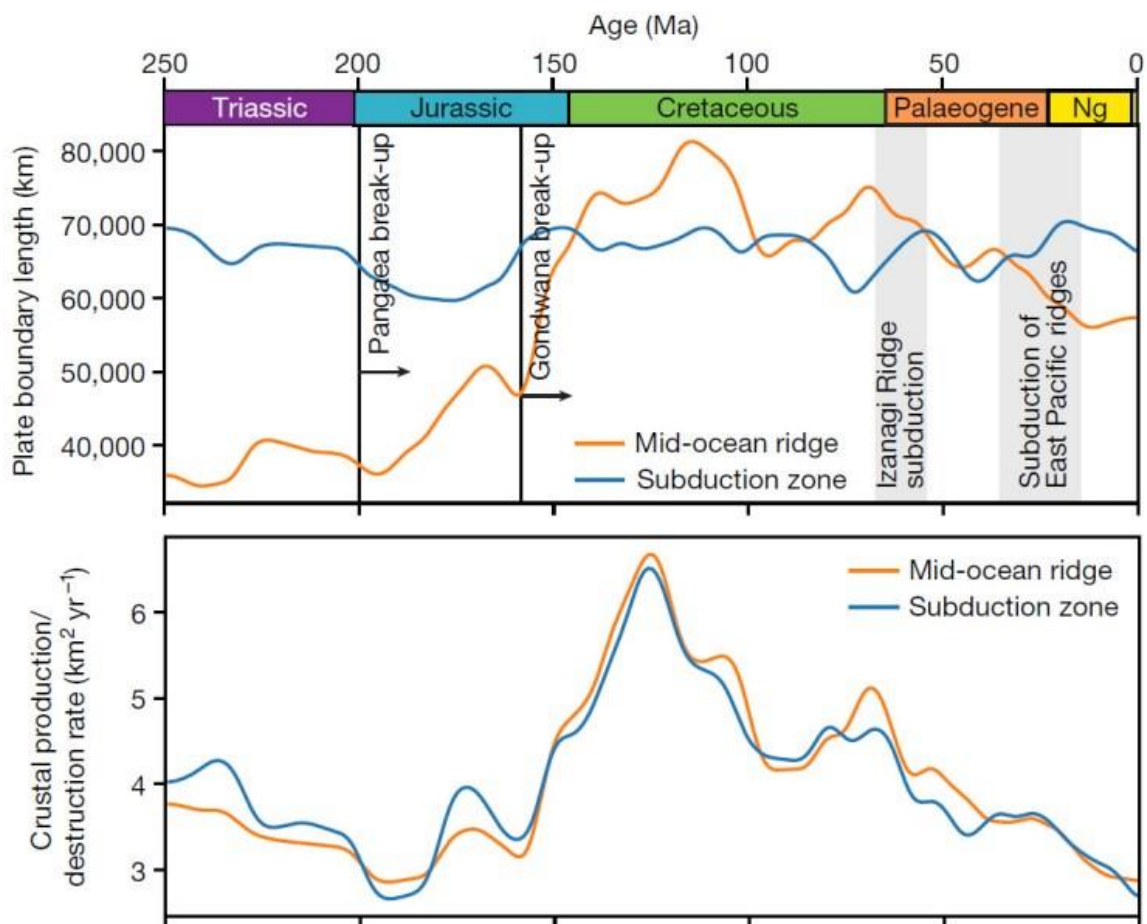
Changes in ice-rafted debris (IRD) since 1.7 Ma in a sediment core from the North Atlantic (orange fill) compared with its oxygen-isotope ($\delta^{18}\text{O}$) record of changes in continental ice cover (blue fill). At the top are the modelled variations in 23 ka axial precession (lilac) and 41 ka obliquity (green). The red circles mark major interglacial episodes, blue diamonds show the onset of significant ice rafting and orange diamonds are terminations of ice-rafting (TIR). (Credit: Barker et al., Fig. 2)

Sea temperature and ice-sheet volume are not the only things that changed during the Pleistocene. Another kind of record from oceanic sediments concerns the varying proportion in the muddy layers of abnormally coarse sand grains and even small pebbles that have been carried by icebergs; they are known as ice-rafted debris (IRD). The North Atlantic Ocean floor has plenty of evidence for them appearing and disappearing on a layer-by-layer basis. They were first recognised in 1988 by an oceanographer called Helmut Heinrich, who proposed that six major layers rich in IRD in North Atlantic cores bear witness to iceberg ‘armadas’ launched by collapse, or ablation, at the front of surging ice sheets on Scandinavia, Greenland and eastern Canada. [Heinrich events](#), along with [Dansgaard-Oeschger events](#) (rapid climatic warming followed by slower cooling) in the progression to the last glacial maximum have been ascribed to a variety of processes operating on a ‘millennial’ scale. However, ocean-floor sediment cores are full of lesser fluctuations in IRD, back to at least 1.7 Ma ago. That record offers a better chance of explaining fluctuations in ice-sheet ablation. A joint European-US group has investigated their potential over the last decade or so (Barker, S. *et al.* 2022. [Persistent influence of precession on northern ice sheet variability since the early Pleistocene](#). *Science*, v. 376, p. 961-967; DOI: 10.1126/science.abm4033). The authors noted that in each glacial cycle since 1.7 Ma the start of ice rafting consistently occurred during a time of decreasing axial obliquity. Yet the largest ablation events were linked to minima in the precession cycles. In the last 700 ka, such extreme events are associated with the terminations of each ice age.

In the earlier part of the record, the 41 ka obliquity ‘signal’ was sufficient to drive glacial-interglacial cycles, hence their much greater regularity and symmetry than those that followed the Mid-Pleistocene Transition. The earlier ice sheets in the Northern Hemisphere also had consistently smaller extents than those after the MPT. Although the records show a role for precession in pre-MPT times in the form of ice-rafting events, the lesser effect of precession on summer warming at higher latitudes, compared with that of axial obliquity, gave it no decisive influence. After 700 ka the northern ice sheets extended much further south – as far as 40°N in North America – where summer warming would always have been commensurately greater than at high northern latitudes. So they were more susceptible to melting during the increased summer warming driven by the precession cycles. When maximum summer heating induced by axial precession in the Northern Hemisphere

coincided with that of obliquity the ice sheets as a whole would have become prone to catastrophic collapse.

It is hard to say whether these revelations have a bearing on future climate. Of course, astronomical forcing will continue relentlessly, irrespective of anthropogenic greenhouse gas emissions. Earth has been in an interglacial for the last 11.5 ka, since the Younger Dryas; i.e. about half a precession cycle ago. The combination of obliquity- and precession-driven influences suggest that climate should be cooling and has been since 6,000 years ago, until the Industrial Revolution intervened. Can the gravitational pull of the giant planets prevent a runaway greenhouse effect, or will human effects defy astronomical forces that continually distort Earth's astronomical behaviour?



Length of mid-ocean ridges (orange) and subduction zones (blue) through the last 250 Ma (top). The areas of oceanic crust produced at ridges and consumed by subduction (bottom) (credit: Müller, R.D. et al., Figs 1a, 1c)

Before Pangaea began to break up at the end of the Triassic (200 Ma) the total length of mid-ocean ridges was at a minimum of about 40 thousand km. Through the Jurassic it never exceeded 50,000 km, but rose to a maximum of 80,000 km during the Cretaceous then declined slowly to the current length of 60,000 km. Throughout the last 250 Ma the length of subduction zones stayed roughly the same at about 65 thousand km – not always in the same places – although the overall rate of subduction changed in line with the rate of oceanic plate growth (the volume that is added must be balanced roughly by the amount that returns to the mantle). Between the end of the Jurassic and the mid-Cretaceous crustal production and destruction doubled, shown by the bottom plot in the figure above. The very fast movement of plates and an increase in the global length of ridges during

Jurassic to mid-Cretaceous times led to a dramatic increase in CO₂ outgassing from ridges so that its content in the atmosphere rose as high as 1200 ppm – more than four times that before the Industrial Revolution. That level resulted in global ‘hothouse’ conditions during the Cretaceous. Another factor behind the Cretaceous climate was a decrease in the global complement of mountains. That led to decreases in erosion and the weathering of silicates by acid rain, thus reducing natural sequestration of carbon.

During the Cenozoic (after 65 Ma) declining ridge outgassing was actually outpaced by that associated with subduction, according to the modelling. That is strange, for by around 35 Ma glaciation had begun on Antarctica as the Earth was cooling, which implies a major, unexpected sink for excess CO₂. The most likely way this might have arisen is through increased erosion and silicate weathering on the exposed continents that consumed CO₂ faster than tectonics was releasing the gas. The length of continental arcs shows no sign of a major increase during the Cenozoic, which might have accelerated that kind of sequestration, but a variety of proxies for signs of weathering definitely suggests that there was an upsurge. Also there was increased storage of carbon on the deep ocean floor, [shown by the video](#). Increased calcium released by weathering to enter ocean water in solution would allow more planktonic organisms to secrete calcite (CaCO₃) skeletons that would then fall to the ocean floor when they died.

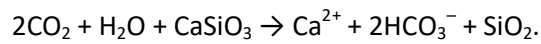
There may be more to be discovered in this hugely complex interplay between tectonics and climate. For instance, when the bottom waters of the oceans are oxygenated by deep currents of cold dense seawater sinking from polar regions, carbon in tissues of sunken dead organism is oxidised to release CO₂. If bottom waters are anoxic, this organic carbon is preserved in sediments. The authors mention this as something to be considered in their future work on the ‘tectonic carbon conveyor belt’.

Climate out of control after the Permian-Triassic mass extinction

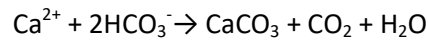
PUBLISHED ON [June 27, 2022](#)

The snuffing out of up to 90 percent of all terrestrial and marine species at the end of the Permian (252 Ma) was the outcome of lethal climatic warming. It probably stemmed from a stupendous episode of flood basalt volcanism and intrusions in what is now Siberia that burned vast amounts of peat or coal in the basin that the flows filled (see: [Coal and the end-Permian mass extinction](#); March 2011). The carbon dioxide so released created planetary hyperthermia and toxic acid rain. For at least five million years Earth was an almost sterile world, a [notable absence being dense vegetation](#) on the land surface – the Early Triassic is devoid of coal, whereas there is plenty of Late Permian age. Much the same slow recovery of life is found in meagre collections of land and marine animal fossils of that age. Yet, other mass extinctions were followed by recovery and species diversification at a much faster pace.

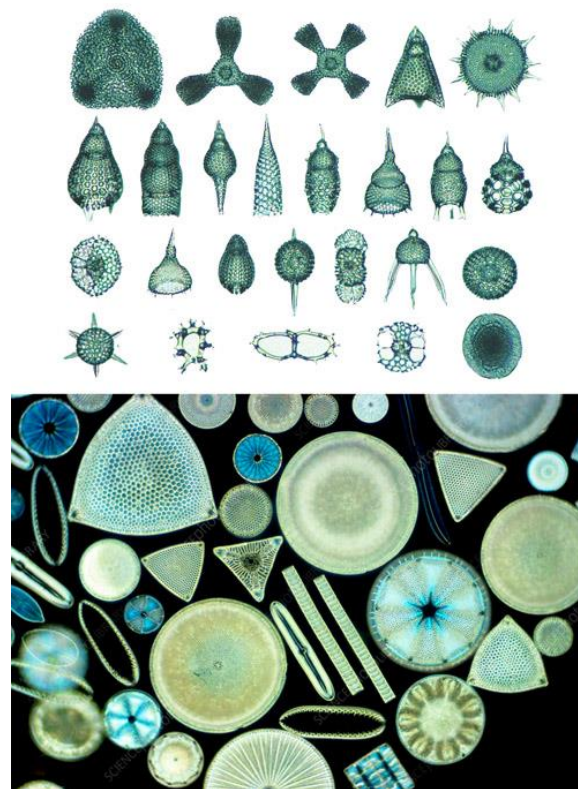
One conceivable explanation could be the near absence of vegetation whose photosynthesis and burial would otherwise draw down CO₂ and the same goes for its marine equivalent phytoplankton. But there is a powerful inorganic means of carbon sequestration: silicate weathering. The chemistry depends on carbon dioxide dissolved in water. For simple silicates it can be expressed as:



The higher the ambient temperature, the faster such reactions proceed. Most silicates are more complex and many common ones, such as feldspars, include aluminium, so that another product of weathering is insoluble, fine-grained clay minerals. So various soluble metal ions (Ca, Mg, K, Na etc), dissolved bicarbonate ions, silica in various guises and clays eventually end up in the sea. Once there, it is possible for them to recombine, as for instance calcium and bicarbonate ions:



Despite some CO₂ gas being released, this reaction results in a net sequestration of carbon in calcium carbonate. Incidentally, the same kind of chemical reaction occurs in the soils produced by weathering. The carbonate may cement soils to form a hard crust of [caliche](#) or 'calcrete'. Chemical weathering enhanced by a hot climate, it might seem, should reduce the greenhouse effect quickly: a feedback mechanism that normally stabilises climate. But that did not happen after the P-Tr extinction event, thereby stressing all remaining life forms. A group of scientists at the University of Waikato in New Zealand have developed a possible explanation for this potentially fatal hazard for life on Earth (Isson, T.T. *et al.* 2022. [Marine siliceous ecosystem decline led to sustained anomalous Early Triassic warmth](#). *Nature Communications*, v. 13, article 3509; DOI: 10.1038/s41467-022-31128-3). It focuses on the silica (SiO₂) released by chemical weathering, which enters the ocean in the form of a colloid: Si(OH)₄, a form of silicic acid known as 'reactive silica'. Under 'normal' conditions, this is removed by organisms, such as [diatoms](#) and [radiolaria](#), and is constantly recycled on a time scale of about 400 years, some contributing to deep-ocean oozes in the form of chert. But, like all other marine organisms, they too were victims of the P-Tr mass extinction.



Examples of marine radiolaria (top)

Reactive silica colloids in seawater also participate in inorganic chemical reactions, combining with dissolved metal ions to form complex hydrated aluminosilicates, i.e. more clay minerals. The reactions change the alkalinity of seawater. As a result dissolved HCO_3^- ions transform to CO_2 gas and water. Despite the complexity of the chemistry that interweaves the carbon and silicon cycles, there is a simple conclusion. If the abundance of silica-secreting marine organisms falls drastically while continental weathering continues to deliver silica, clay-mineral formation on the ocean floor results in release of CO_2 that reverses the effect of enhanced weathering and thus maintains hyperthermal conditions. The other outcome is that less chert and flint granules form. Terry Ison and colleagues examined the varying proportion of chert in cores through Lower Triassic marine sediments. A 'chert gap' characterises the 4 to 6 Ma following the P-Tr boundary event. This can be explained in part by extinction of silica-secreting organisms and by inorganic reactions converting the reactive silica that enhanced weathering delivered to the oceans to clay minerals. This supports the idea that the inorganic part of the silica cycle maintained greenhouse conditions in the absence of organic 'competition' for reactive silica. Many other biogeochemical cycles link biological and chemical processes that combine to affect climate: involving phosphorus, nitrogen and iron, to name but three.

A Lower Jurassic environmental crisis

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Curiously, one of the largest environmental disruptions during the Phanerozoic Eon (i.e. since 541 Ma ago) does not stand out in the way that the 'Big Five' mass extinctions do. Each of them killed off between 70 and 95% of all marine species. The Jurassic was a period of biological recovery from the End-Triassic extinction 201 Ma ago. Throughout its ~50 Ma duration extinction rates were below the average for the Phanerozoic, and they remained relatively low until the K-Pg mass extinction that drew the Mesozoic Era to a close at 66 Ma. Nevertheless, there were significant extinctions, such as the demise of several lineages of [herbivorous dinosaurs](#) towards the end of the Early Jurassic followed by the rise of the familiar, long-necked variety of eusauropods. Marine organisms that secreted hard parts made of calcium carbonate also experienced a collapse then. From time to time during the Jurassic and Cretaceous Periods the oceans lost a great deal of dissolved oxygen, increasing the chances of organic carbon being buried in marine sediments. Such oceanic anoxia resulted in the widespread deposition of [hydrocarbon source rocks](#) in the form of black bituminous muds. Overall, both the Jurassic and Cretaceous [experienced greenhouse](#) climatic conditions, with atmospheric CO_2 levels rising to almost 3000 ppm and oxygen levels significantly lower than the modern 21%. Sea levels rose by up to 200 metres, thought to be due to fast sea-floor spreading and large areas of warm, buoyant oceanic lithosphere.

A notable ocean-anoxia event took place during the Lower Jurassic, around 183 Ma ago at the start of the Toarcian Age. This stratigraphic level was penetrated by a 1.5 km borehole sunk in 2015-2016 at Mochras in North Wales, UK, on the shore of Cardigan Bay. The core provided the thickest and most complete record ever recovered for this event, and has been analysed in exquisite detail using many techniques. The most revealing data have been published by a multinational team led by scientists from Trinity College, Dublin (Ruhl, M. *et al.* 2022. [Reduced plate motion controlled timing](#)

[of Early Jurassic Karoo-Ferrar large igneous province volcanism](#). *Science Advances*, v. 8, article eabo0866; DOI: 10.1126/sciadv.abo0866).

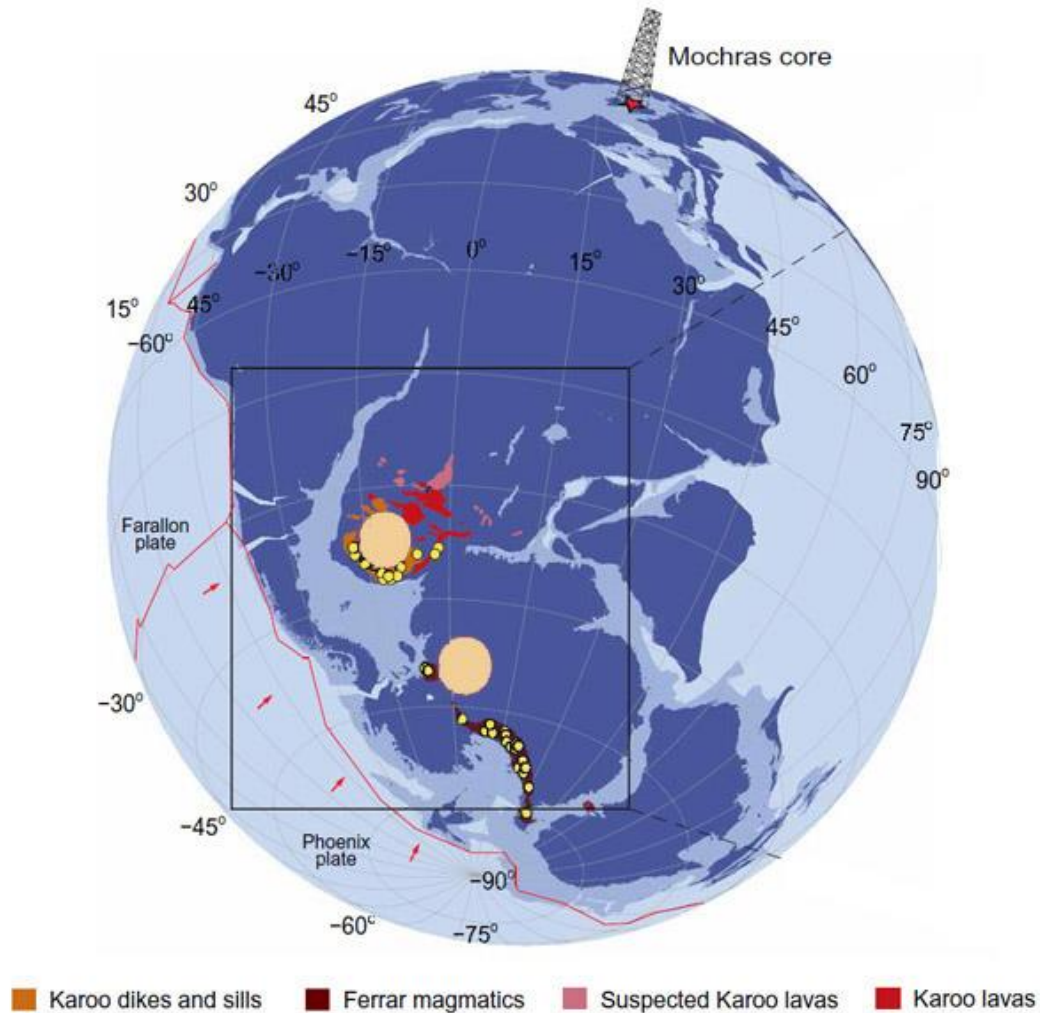


Plate boundaries around Gondwanaland and the Karoo-Ferrar large igneous province in the Early Jurassic (small yellow dots show dated localities). Large pink dots: positions of Tristan de Cunha and Bouvet hotspots at the time (Credit: Ruhl et al. Fig 1A)

At the start of the Toarcian (183.7 Ma) the $^{187}\text{Os}/^{186}\text{Os}$ ratio of the samples begins to rise from 0.3 to almost 0.8 to fall back to 0.3 by 180.8 Ma. Osmium isotopes are [a measure of continental weathering](#), and this 'excursion' surely signifies significant global warming and increases in atmospheric humidity and acidity that broke down rocks at the continental surface. Over the same period $\delta^{13}\text{C}$ rises, decreases to by far the lowest value in the Lower Jurassic, rises again to gradually fall back. The start of the Toarcian seems to have experienced a major release of carbon then a profound sequestration of organic carbon, presumably through burial of dead organisms in the black mudstones that signify anoxic conditions. Remarkably, the 95 m thick Toarcian black-mudstone sequence also reveals a tenfold increase in its content of the element mercury, from 20 to 200 parts per billion (ppb), peaking at the same time (~182.8 Ma) as the most negative $\delta^{13}\text{C}$ value was reached: the acme of carbon sequestration. A coincidence of massive organic carbon burial and

increased mercury in marine sediments also happened at the time of the [end-Permian mass extinction](#), although that does not necessarily imply exactly the same mechanism.

The early Toarcian geochemical trends, however, coincide with the initiation and duration of the Karoo-Ferrar large igneous province, which formed flood basalts, igneous dyke swarms and large volcanic centres in South Africa and Antarctica. That LIP may have emitted mercury, but so too may have increased chemical weathering of the land surface. Whichever, mercury forms an organic compound (methyl mercury) in water bodies. Readily incorporated into living organisms, that could explain the close parallel between the $\delta^{13}\text{C}$ and Hg records in the Jurassic sediment core from Wales. The Karoo-Ferrar igneous activity itself presents a bit of a conundrum, as suggested by Ruhl *et al.* It happened at the very time that there was a 120° change in the direction of motion of the tectonic plate carrying along Africa and, indeed, the Gondwanaland supercontinent during the Jurassic. The directional change also involved local plate movement stopping for a while. According to the authors, it wasn't a fortuitous coincidence of two mantle plumes from the core-mantle boundary hitting the bottom of the continental lithosphere below Africa and Antarctica at this tectonic 'U-turn'. It is more likely that the pause gave existing plumes the opportunity and time to 'erode' the base of the continental lithosphere and rise. Decompression melting would then have produced the voluminous magmas. The two plumes were in place for a very long time and created seamount chains as plates moved over them. Both are still volcanically active: [Tristan de Cunha](#) on the mid-Atlantic Ridge, and [Bouvet Island](#) at a triple junction between South Africa and Antarctica.

So, a venture to unravel a period of profound environmental change during the Early Jurassic, which didn't result in mass extinction, may well have spawned a new model for massive igneous events that did. Ruhl *et al.* suggest that the short-lived Siberian, North Atlantic and East African Rift LIPs each seem to have coincided with short episodes of tectonic slowing-down: LIPs may result in dramatic environmental change, but at the whim of plate tectonics.

See also: <https://scitechdaily.com/surprising-discovery-shows-how-slowing-of-continental-plate-movement-controlled-earths-largest-volcanic-events/>

Milankovich precession and the Palaeocene-Eocene Thermal Maximum

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About 56 Ma ago there occurred some of the most dramatic biological changes since the mass extinction at the Cretaceous-Palaeogene boundary. They included rapid expansion and diversification of mammals and land plants, and a plunge in the number of deep-water foraminifera. Global cooling from the Cretaceous hothouse was rudely reversed by sudden global warming of about 5 to 10°C. Some climatologists have ascribed bugbear status to the Palaeocene-Eocene Thermal Maximum (PETM) as a possible scenario for future anthropogenic global warming. The widely accepted cause is a massive blurt into the Palaeocene atmosphere of greenhouse gases, but what caused it is enthusiastically debated. The climate shift is associated with a sudden decrease in the proportion of ^{13}C in marine sediments: a negative spike in $\delta^{13}\text{C}$. Because photosynthesis favours the lighter ^{12}C , organic matter has a low $\delta^{13}\text{C}$, so a great deal of buried organic carbon may have

escaped from the ocean floor, most likely in the form of methane gas. However, massive burning of living terrestrial biomass would produce the same carbon-isotope signal, but absence of evidence for mass conflagration supports methane release. Methane is temporarily held in marine sediments in the form of gas hydrate (clathrate), an ice-like solid that forms at low temperatures on the deep seafloor. Warming of deep sea water or a decrease in pressure, if sea level falls, destabilise clathrates thereby releasing methane gas: the '[clathrate gun hypothesis](#)'. The main issue is what mechanism may have pulled the trigger for a monstrous methane release.



Massive leak of natural gas – mainly methane – off Sweden in the Baltic Sea, from the probably sabotaged Nord Stream pipeline. (Source: Swedish coastguard agency)

Many have favoured a major igneous event. Between 55.0 and 55.8 Ma basaltic magmatism—continuing today in Iceland – formed the North Atlantic Igneous Province. It involved large-scale intrusion of sills as well as outpourings of flood basalts and coincided with the initial rifting of Greenland from northern Europe (see: [Smoking gun for end-Palaeocene warming: an igneous connection](#); July/August 2004). The occurrence of impact ejecta in end-Palaeocene sediments off the east coast of the US has spawned an extraterrestrial hypothesis for the warming, which could account for the negative spike in $\delta^{13}\text{C}$ as the product of a burning terrestrial biosphere (see: [Impact linked to the Palaeocene-Eocene boundary event](#); October 2016). Less headline-grabbing is the possibility that the event was part and parcel of the Milankovich effect: an inevitability in the complex interplay between the three astronomical components that affect Earth's orbital and rotational behaviour: eccentricity, axial tilt and precession. A group of geoscientists from China and the US, led by Mingsong Li of Peking University, have investigated in minute detail the ups and downs of $\delta^{13}\text{C}$ around 56 Ma in drill cores recovered from a sequence of Palaeocene and Eocene continental-shelf sediments in Maryland, USA (Li, M., Bralower, T.J. *et al.* 2022. [Astrochronology of the Paleocene-Eocene Thermal Maximum on the Atlantic Coastal Plain](#). *Nature Communications*, v. 13, Article 5618; DOI: 10.1038/s41467-022-33390-x).

The study involved sampling sediment for carbon- and oxygen-isotope analysis at depth intervals between 3 and 10 cm over a 35 m section through the lower Eocene and uppermost Palaeocene.

Calcium abundances in the core were logged at a resolution of 5 mm using an X-ray fluorescence instrument. The results link to variations in CaCO₃ in the sediments across the PETM event. Another dataset involves semi-continuous measurements of magnetic susceptibility (MS) along the core. These measurements are able to indicate variations in delivery to the ocean of dissolved calcium and detrital magnetic minerals as climate and continental weathering vary through time. They are widely known to be good recorders of Milankovich cycles. After processing, the Ca and MS data sets show cyclical fluctuations relative to depth within the cores. 'Tuning' their frequencies to the familiar time series of Milankovich astronomical climate forcing reveals a close match to what would be expected if the climate fluctuations were paced by the 26 ka axial precession signal. My post of 17 June 2022 about the [influence of precession over 'iceberg armadas'](#) during the Pleistocene might be useful to re-read in this context. This correlation enabled the researchers to convert depth in the cores to time, so that the timing of fluctuations in carbon- and oxygen-isotope data that the PETM had created could be considered against various hypotheses for its cause. The 'excursions' of both began at the same time and reached the maxima of their changes from Palaeocene values over about 6,000 years. The authors consider that is far too long to countenance the release of methane as a result of asteroidal impact, or by massive burning of terrestrial vegetation. The other option that the beginning of the North Atlantic Igneous Province had been the trigger may also be ruled out on two grounds: the magmatism began earlier, and it continued for far longer. The onset of the PETM coincides with an extreme in precession-related climatic forcing. So Li *et al.* consider that a quirk in the Milankovich Effect could have played a role in triggering massive methane release. This might also explain features of the global calcium record in seafloor sediments as results of a brief period of ocean acidification during the PETM. Such an event would play havoc with carbonate-secreting organisms, such as foraminifera, by lowering the dissolved carbonate ion content on which they depend for their shells: hence their suffering considerable extinction. Of course, the other elements of astronomical forcing – eccentricity and axial tilt – would also have been operating on global climate at the time. The long-term 100 and 405 ka eccentricity cycles may have played a role in amplifying warming, which may have resulted in increased burial of organic carbon and thus the amount of methane buried beneath the seabed.